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Hydrological impacts of reafforestation with eucalypts and indigenous species: a case study in southern China

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Abstract

Restoration of forest ecosystems on degraded lands in the subtropical area of southern China may be achieved by planting exotic pioneer species followed by enrichment planting with indigenous species and promotion of understorey establishment. A 10-year study was conducted in a degraded area of coastal western Guangdong Province to quantify the effectiveness of eucalypts and subtropical mixed forest for ameliorating microclimate and reducing surface runoff and erosion, and to examine the importance of understorey and litter layer development in achieving these effects.

Tree growth, climate, litter biomass and understorey cover, throughfall and stemflow, surface runoff, soil erosion, soil moisture and watertable depth were monitored in three unreplicated catchments containing bare land, *Eucalyptus* plantation and mixed forest, respectively. Litter was regularly removed from most of the *Eucalyptus* catchment, but allowed to accumulate in a section fenced to limit access.

Both forest types increased absolute humidity and reduced maximum temperature near the ground compared to bare land. The mixed forest canopy intercepted more rainfall and generated less stemflow than the *Eucalyptus* forest. Surface runoff was greatest from bare land, and least from mixed forest. Annual runoff from the forested catchments (but not the bare land) decreased over 10 years of measurement. Runoff from the protected area of the *Eucalyptus* catchment also decreased as litter accumulated and an understorey developed.

Soil erosion from bare land was greater than from the forested catchments, and its surface runoff carried a higher proportion of coarse sediments. Soil moisture content was highest in the bare land catchment, but did not show a long-term trend in the vegetated catchments. Watertable depth averaged 30 cm deeper beneath mixed forest and 80 cm deeper beneath *Eucalyptus* forest, compared with bare land.

The results of this case study support the use of eucalypts as a pioneer species in the rehabilitation of degraded lands in southern China, but demonstrate the importance of allowing litter accumulation and understorey development beneath the tree canopy and the additional hydrological benefit of encouraging succession to a mixed forest ecosystem.

Keywords: Reafforestation; Microclimate; Surface runoff; Soil erosion; Soil moisture; Watertable

1. Introduction

The origins of modern reforestation programs in southern China can be traced back to 1950, soon after the creation of the People's Republic of China.

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Initially the objective of forest establishment on bare and degraded lands was primarily for timber production without consideration of environmental issues, and in some areas serious soil erosion was caused. Since 1975 the emergence of new markets for forest products and increasing awareness of the need for environmental protection and improvement have promoted increased efforts at reforestation with a more complex set of management objectives, in some areas including the restoration of degraded natural ecosystems (Chen et al., 1995).

Previous studies have shown the importance of water and heat as limiting factors for the rehabilitation of degraded lands in the subtropical area of southern China (Janzen, 1988; Myers, 1989; Parham, 1993; Zhou, 1997a). Restoration of vegetation here requires amelioration of the degraded environment to allow plant survival and redevelopment of forest ecosystems (Murphy and Lugo, 1986; Brown and Lugo, 1994). This requires reduction of surface runoff and soil erosion, improvement of soil permeability and water storage, increasing atmospheric humidity and limiting solar radiation at the soil surface.

In the sterile environment of severely degraded lands, restoration of original ecosystems is a multi-step process. The first stage is to establish some pioneer tree species that can survive in the harsh conditions, to make an artificial forest. In the protected environment of the artificial forest, some local species can be added by enrichment planting to further ameliorate the microclimate and soil conditions, creating niches for invasion by further indigenous species. This process has been found effective for rehabilitation of heavily degraded land in China, and recommended for wide application (Parham, 1993; Yu, 1994, 1995; Corlett, 1999).

Successful selection of pioneer tree species is clearly of critical importance to the success of restoration. In southern China, the species adopted include several *Eucalyptus* species, *Pinus massoniana* and *Acacia mangium*, but eucalypts are of particular importance (Yu, 1994, 1995). In addition to their ecological value as pioneer species (Yu, 1994, 1995; Midgley and Pinyopusarerk, 1996), eucalypts have an economic role as a source of construction timber, fuelwood, pulpwood, *Eucalyptus* oil, honey and other products, and as typhoon shelter for crops and villages (Turnbull, 1981; Bai and Gan, 1996).

The success of eucalypts as pioneer species arises from their capacity for vigorous growth and deep rooting on sites of low fertility. However, strong competition for water and other resources may limit subsequent success in establishing indigenous trees and understorey species under the eucalypt canopy, and prevent natural succession beyond a eucalypt dominated community. The ability to compete successfully on water-limited sites has also raised concerns that excessive water consumption by eucalypt plantations may deplete water supplies by reduction of runoff and groundwater recharge, in China and elsewhere (Kallarackal, 1992). Surface and underground water resources in southern China are often limited in spite of the moderately high annual rainfall of the region (Zhou, 1997a), due to loss of high intensity rainfall during the wet season as surface runoff with concomitant problems of erosion, siltation and flooding (Chen and Wang, 1992; Parham, 1993).

The effectiveness of eucalypts as a pioneer species for site rehabilitation may also be reduced by intensive collection of leaf and branch litter as a source of fuel. In some rural areas, plantation litter is regularly collected by householders for cooking and heating. As a result the formation of a litter layer and understorey in plantations close to villages is often prevented, with negative impacts on the organic content of the soil and development of soil microbe populations (Ding et al., 1992).

This paper draws together results from several subprojects previously reported in part in Chinese language journals, to make a comprehensive comparison of hydrology and microclimate in eucalypt plantation, bare land and subtropical mixed forest in a degraded area of coastal western Guangdong Province. The objectives were to quantify the effectiveness of eucalypts and mixed forest for ameliorating the climate and reducing surface runoff and erosion, and to examine the importance of understorey and litter layer development in achieving these effects.

2. The study area

The studies were conducted in three unreplicated experimental watersheds located on coastal highland

Fig. 1. Location of the Xiaoliang study area within Guangdong Province of southern China.

near Xiaoliang (Fig. 1) in Dianbai County, Guangdong Province (21°8′N, 110°54′E). Mean annual rainfall in the region is approximately 1500 mm, with distinct dry (October to March) and wet (April to September) seasons. Rainfall in the wet season is mainly associated with convective storms and typhoons, and the intensity often exceeds 16 mm h^{-1}. The annual average temperature at Xiaoliang is 23 °C.

A topographical map of the area including the three catchments is shown in Fig. 2. The topography of the three watersheds is generally of low relief, with altitude variations of 10–20 m. The *Eucalyptus* and bare soil watersheds have a generally south-westerly aspect, while the mixed forest has a south-easterly aspect. The soil of all three watersheds is a typical laterite derived from granite (Yu and Zhou, 1996).

The bare soil watershed (area 3.7 ha) had been virtually devoid of vegetation for at least four decades because of severe soil erosion before reforestation efforts began in 1959. This watershed has been maintained as a control for studies of environmental amelioration in the surrounding area.

The *Eucalyptus* (*E. exserta*) plantation watershed (3.8 ha) was established on bare eroded land in 1964, harvested in 1976 and regenerated by coppice regrowth followed by thinning to leave single stems at a spacing of 2.5 m × 2.5 m. By 1990, canopy cover was 76% and average tree height was 13 m. No understorey developed under the growing forest, due to repeated disturbance and intensive removal of forest litter by local residents for fuel. In 1986, a section of the plantation (1.5 ha) was fenced off to limit access and prevent litter removal (Fig. 2). By 1994, a shrub and herb understorey had established on about 65% of the protected area, with average height of 1.5 m.

The third watershed (6.4 ha) was also initially established as *E. exserta* plantation, but in 1975, the plantation was thinned to 400 trees ha^{-1} and indigenous species were planted at irregular spacing. The species include *Aphanamixis polystachya, Cassia siamea, Albizia odoratissima, Aquilaria sinensis, Santalum album, Leucaena leucocephala* cv. Salvador and *Acacia auriculaeformis*.

3. Methods

3.1. Climate

A weather station was installed in each catchment and in the protected area, on a tower extending 4 m above the canopy. Measurements of above-canopy radiation, rainfall, wind speed and direction, relative humidity and air temperature were recorded daily at 08.00, 14.00 and 20.00. Temperature and relative humidity were also recorded at 20, 50 and 150 cm above ground, and soil temperature was measured near the base of each tower at depths of 0, 5, 10, 15 and 20 cm.

3.2. Throughfall and stemflow

Throughfall in the *Eucalyptus* and mixed forest catchments was collected by troughs with a horizontal area of 6 m^2, and measured using a fluviograph (Zhou, 1997b). Because the *E. exserta* trees were evenly spaced and both the mixed forest canopy and *Eucalyptus* canopy were uniform, a single trough in each catchment was considered sufficient (Gash, 1978; Vertessy et al., 1993).

Ten trees adjacent to each site where throughfall was monitored were selected for stemflow measurement (Gash, 1978; Lee, 1980), to represent the range of diameters and species present in each catchment. Stemflow was collected by an open PVC tube wrapped around the stem, and led to a tipping bucket rain gauge. The average stemflow for each stand was calculated from the data recorded by the rain gauges as

$$P_s = \frac{A_g}{\sum_{i=1}^{10} A_{ci}} \times \sum_{i=1}^{10} S_{mi}$$

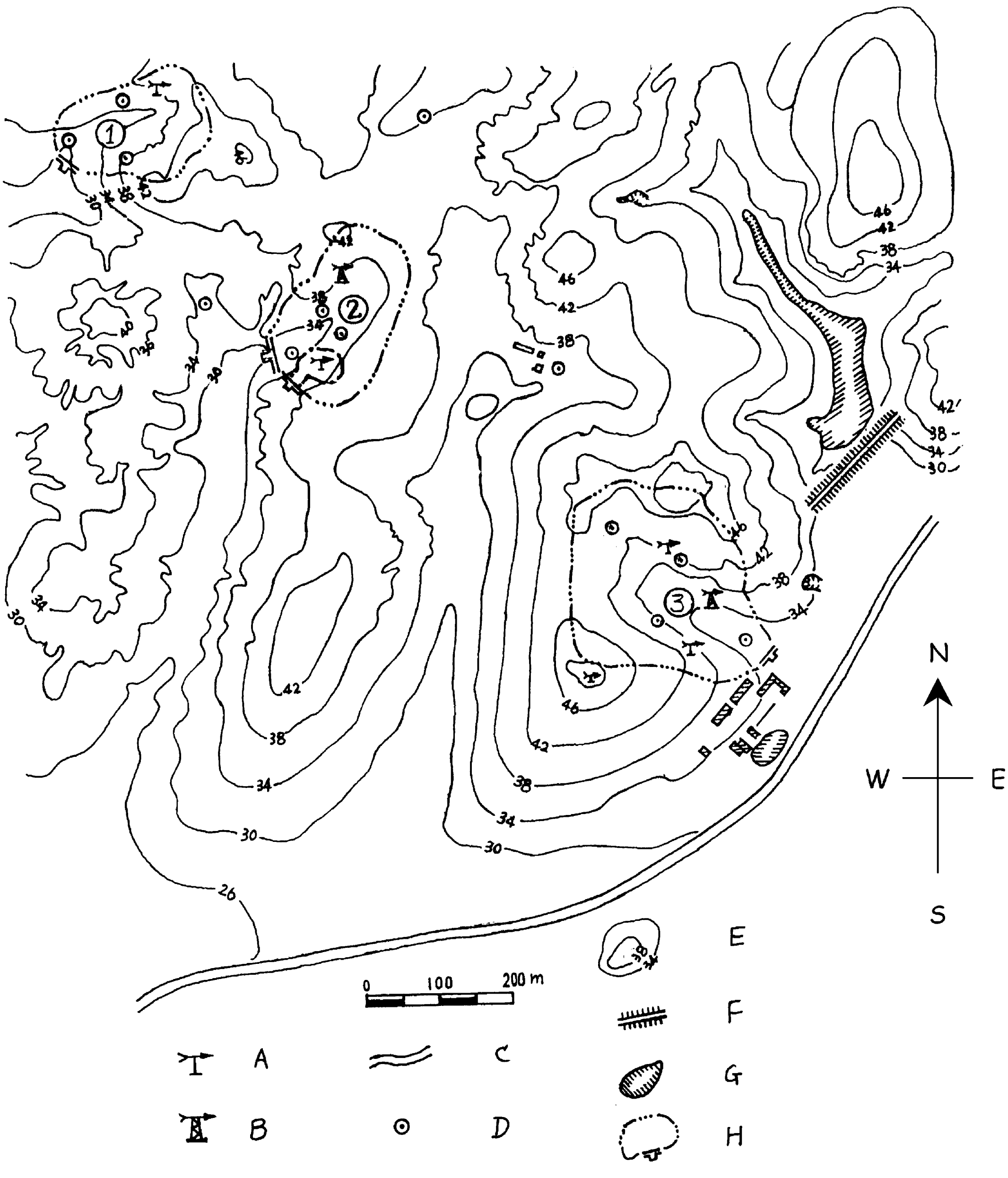

Fig. 2. Topographical map of the Xiaoliang experimental area: bare land catchment ①; *Eucalyptus* catchment ②; mixed forest catchment ③. A: meteorologic measurement point; B: observation tower; C: highway; D: watertable observation well; E: contour; F: dam; G: reservoir; H: boundary and outlet weir of catchment or subcatchment.

where P_s is the stemflow (mm), A_g the area of a rain gauge (m^2), A_{ci} the canopy projected area of tree number i (m^2), and S_{mi} the recorded data for rain gauge number i (mm).

3.3. Litter biomass and understorey cover

Since 1986 onwards, litter accumulation and understorey cover were assessed at 2-year intervals in the protected area of the *Eucalyptus* catchment. Litter was collected from ten plots each 1 m × 1 m square, then dried and weighed. At the same time, the understorey cover percentage of the whole area was visually estimated.

3.4. Surface flow and soil erosion

Runoff was monitored by measurement weirs with streamflow recorders on the ephemeral streams emanating from each catchment and recorded automatically for every precipitation event during 1981–1990. A separate monitoring weir was set up in 1986 for the protected area, using a ditch to lead the runoff out of the catchment. The recorded water flow over each weir in litres was divided by the catchment area in m^2 to express runoff in mm. A surface runoff coefficient was calculated as surface flow (mm)/precipitation (mm) × 100%. Stormflow in mm was estimated by analysis of hydrographs following Linsley et al. (1975), and expressed as a percentage of incident rainfall for each catchment.

Soil removed from the catchments in surface runoff was assessed separately as suspended solids and bed load (Singh, 1988; Zhou et al., 1995; Yu and Zhou, 1996). Bed load was deposited in a pool located upstream of each weir, and was measured manually by weighing soil dredged from the pool after each rainfall event. Suspended solids were determined as the product of runoff volume and concentration of suspended solids for each rain event. In each month, at least one rain event was selected to sample for determination of suspended solids concentration. Three 1 l samples (beginning, peak stage and ending) were taken during the rain event and combined, then filtered to determine the weight of suspended solids in the runoff. It was assumed that the value would be the same for all runoff in a month. Soil erosion rates were characterized as kg of suspended and deposited sediment per unit of catchment area, per mm of rainfall (kg ha^{-1} mm^{-1}).

3.5. Soil and groundwater measurements

Soil conditions were monitored in upper, middle and low slope positions of each catchment and within the protected area of the *Eucalyptus* catchment. At each location soil bulk density was measured at 0–15, 60–80 and >120 cm in October each year. Soil water content was determined gravimetrically on samples collected at 10 cm intervals to 200 cm, once per month during 1981–1985. Since 1986, soil water content was measured by neutron probe.

Watertable depth was manually recorded at intervals of 5 days in groundwater monitoring wells located in upper, middle and lower slope positions of each catchment.

4. Results

4.1. Rainfall and microclimate

Monthly means of net radiation and rainfall over 10 years (1981–1990) are shown in Fig. 3. Mean annual

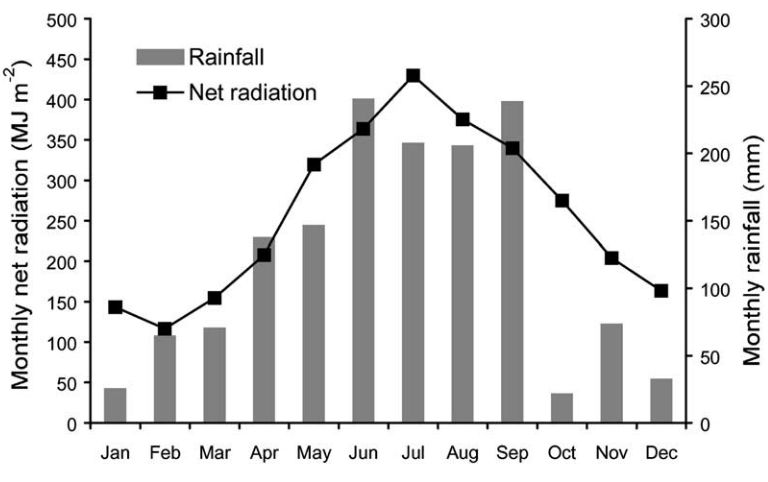

Fig. 3. Seasonal distribution of rainfall and net solar radiation averaged over 10 years at Xiaoliang.

rainfall for the period was 1455 mm, of which 82.9% fell during the wet season. Net radiation during the wet season averaged 65.8% of the annual total.

Fig. 4 shows daily mean soil and air temperatures at several levels above and below the soil surface, averaged over 10 years of observations for the three catchments and over 4 years (1986–1990) for the protected area of the *Eucalyptus* catchment. Temperatures in the bare land catchment were highest at all times of the year, and those in the *Eucalyptus* catchment unprotected area were usually lowest. The mixed forest had the least annual temperature variation, with relatively warm winter temperatures and cool summer temperatures.

The decrease in temperature with height above the surface was accompanied by a tendency for relative humidity (RH) to increase with height. RH was always highest in the mixed forest catchment, and varied less between seasons. The pattern of RH variation with height above the surface results from variations in both temperature and absolute humidity (Fig. 5). Absolute humidity in bare land decreased continuously with height in all seasons, but in the vegetated catchments it tended to reach a maximum at about 0.5 m above the surface.

The interception of rainfall by the forest canopy (I, mm) was found to be closely related to the rainfall of a rain event (R, mm). The best-fit regression equations are

$$I = 0.65R^{0.55} \quad (n = 378 \text{ and } r > 0.96),$$
for *Eucalyptus* forest,

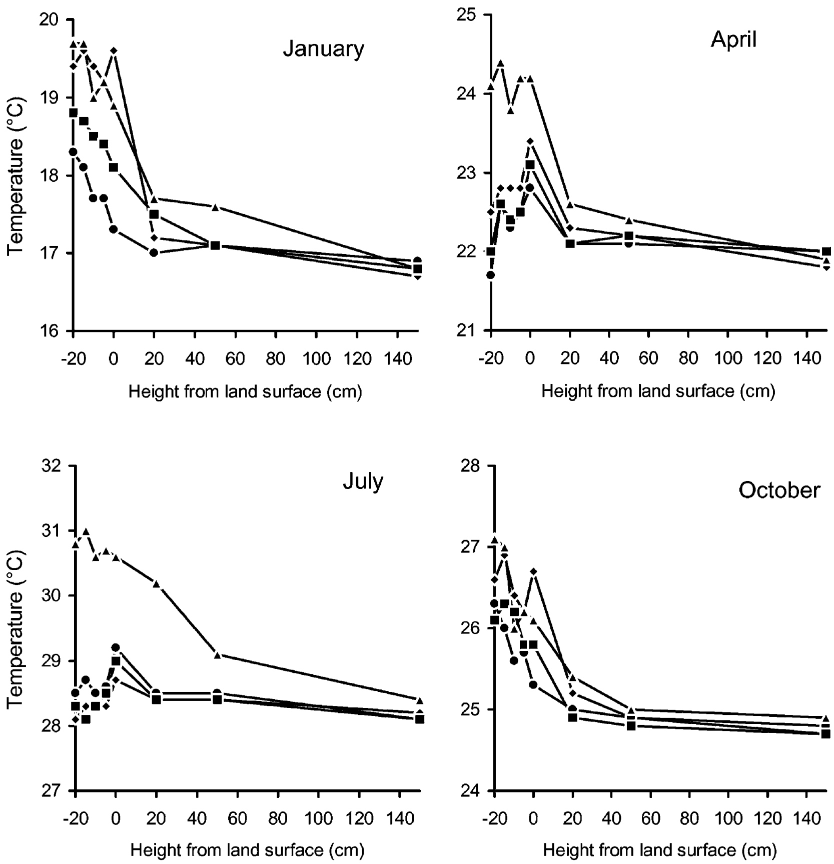

Fig. 4. Daytime mean temperature change patterns near the soil surface in the three catchments: mixed forest (◆); *Eucalyptus* plantation (unprotected) (●); *Eucalyptus* plantation (protected) (■); bare land (▲).

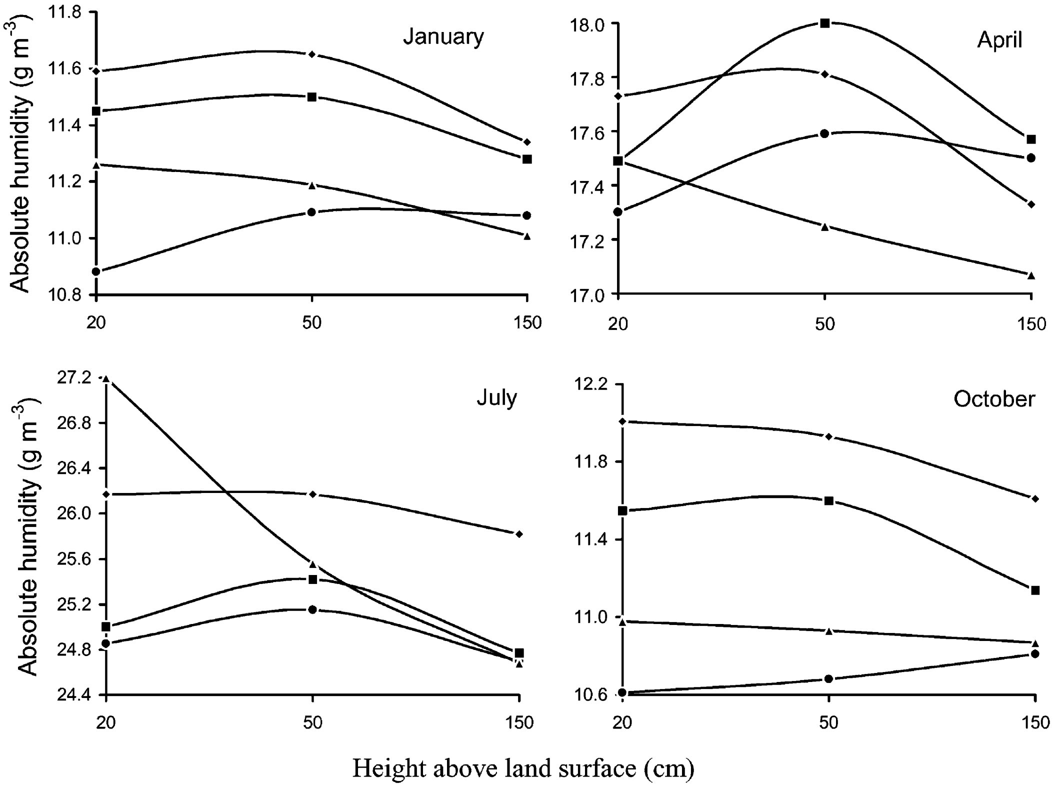

Fig. 5. Daytime mean absolute humidity at 20–150 cm above the land surface in the three catchments: mixed forest (◆); *Eucalyptus* plantation (unprotected) (●); *Eucalyptus* plantation (protected) (■); bare land (▲).

$$I = 0.75R^{0.61} \quad (n = 413 \text{ and } r > 0.90), \text{ for mixed forest.}$$

Stem flow (P_s in mm) was also closely related to R (mm), and the best-fit regression equations are

$$P_s = 0.083R - 0.046 \quad (n = 266 \text{ and } r > 0.92), \text{ for } \textit{Eucalyptus} \text{ trees}$$

$$P_s = 0.068R - 0.086 \quad (n = 335 \text{ and } r > 0.88), \text{ for mixed forest trees.}$$

The results show the mixed forest has higher interception and less stemflow than the *Eucalyptus* forest (Fig. 6). Considering that the maximum rainfall recorded in a single rain event was less than 100 mm (Zhou, 1997b), the maximum interception capacity of the two forest types may be estimated as approximately 8 and 12 mm in a rain event for *Eucalyptus* and mixed forests, respectively. The stemflow results also reflect the higher interception capacity of the mixed forest. Stemflow occurred in the *Eucalyptus* forest when rainfall exceeded approximately 0.6 mm, but the corresponding minimum rainfall for stemflow in the mixed forest was 1.3 mm.

4.2. *Runoff and erosion*

Surface runoff differed considerably among the three catchments. Table 1 shows monthly surface flow coefficients based on rainfall and runoff observations from 958 rainfall events between 1981 and 1990. For the *Eucalyptus* catchment, runoff data are from the unprotected site. The results reflect qualitative differences in the condition of the soil surface and vegetation cover, although differences in aspect and topography among the catchments may have also contributed to the difference in runoff (Fig. 1).

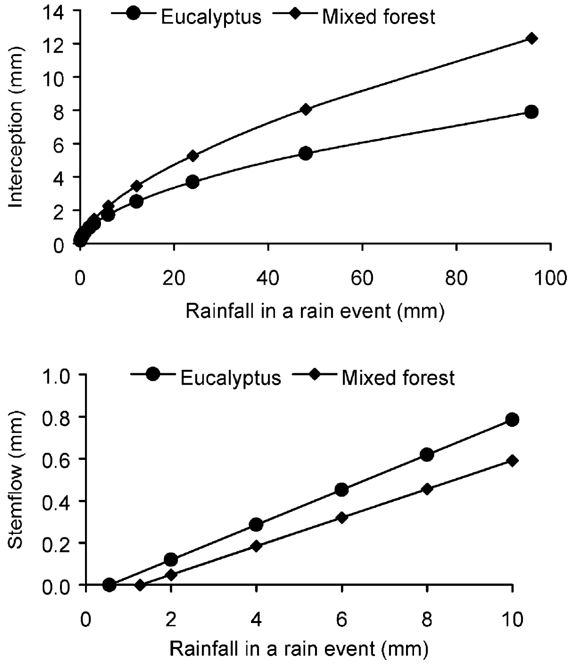

Fig. 6. Interception and stem flow in a rain event for mixed and *Eucalyptus* forests.

Surface runoff coefficients from mixed forest and *Eucalyptus* forest decreased over the period 1981–1990. There was no consistent trend in the annual values of surface runoff from the bare land catchment, but Fig. 7 suggests that it varied in proportion to the yearly rainfall. Stormflow was highest from bare land (Table 2), averaging 10.4% of annual rainfall (20.4% of total runoff). That from the *Eucalyptus* catchment was 6.2% (27.1% of runoff), while the lowest stormflow was from mixed forest at 0.02% of rainfall (0.9% of runoff).

Within the protected area of the *Eucalyptus* plantation, surface runoff decreased (Table 3) as litter accumulated and understorey cover increased (Fig. 8). When the protected area was enclosed in 1986, the runoff there was higher than the average over the whole *Eucalyptus* catchment due to local effects of slope and soil surface crusting. The annual average runoff coefficients of protected and unprotected parts in 1986 were 33.1 and 15.0%, respectively. By 1994, the surface runoff coefficient in the protected area had fallen to 8.6%.

Table 4 shows the annual erosion rate from the three catchments in 1981–1990. Over the 10-year period, the average erosion rate for the mixed forest catchment was 0.3 kg ha^{-1} mm^{-1} of rainfall, including 0.2 kg ha^{-1} mm^{-1} as suspended sediment and 0.1 kg ha^{-1} mm^{-1} deposited at the weir. In the *Eucalyptus* catchment, the erosion rate was 9.1 kg ha^{-1} mm^{-1}, including 5.3 kg ha^{-1} mm^{-1} suspended and 3.8 kg ha^{-1} mm^{-1} deposited sediments. In the bare land catchment, the corresponding rates were 43.7, 19.3 and 24.4 kg ha^{-1} mm^{-1}. The ratios of suspended to deposited sediments were 1.5, 1.4 and 0.7 for mixed forest, *Eucalyptus* and bare land catchments, respectively.

4.3. Soil moisture and groundwater dynamics

Fig. 9 shows soil profile moisture content at 10 cm depth intervals, averaged from all measured values for each point over the study period. In the upper 80 cm, soil water contents for the three catchments were generally similar. Below this depth soil water content in the bare land increased with depth, but in the vegetated catchments, it was constant or decreased with depth to 195 cm.

Table 1
Mean monthly surface flow and runoff coefficients for the three catchments (1981–1990)

	January	February	March	April	May	June	July	August	September	October	November	December	Full year
Mixed forest (mm)	0.0	0.0	0.2	0.4	0.7	14.4	6.8	18.3	1.2	0.0	0.0	0.0	42.0
Mixed forest (%)	0.0	0.0	0.3	0.3	0.5	6.0	3.3	8.9	0.5	0.0	0.0	0.0	2.9
Eucalyptus (mm)	2.9	7.0	16.1	27.7	42.9	77.3	53.6	50.0	42.6	4.1	6.7	0.0	330.9
Eucalyptus (%)	11.4	10.9	23.0	20.2	29.4	32.2	25.9	23.9	17.9	19.5	9.2	0.0	23.1
Bare land (mm)	7.42	23.7	39.7	44.1	91.3	143.5	125.2	121.4	124.2	10.0	7.4	2.3	740.2
Bare land (%)	31.3	37.0	56.7	32.2	62.5	59.7	60.5	59.2	52.2	47.4	10.1	7.1	50.8

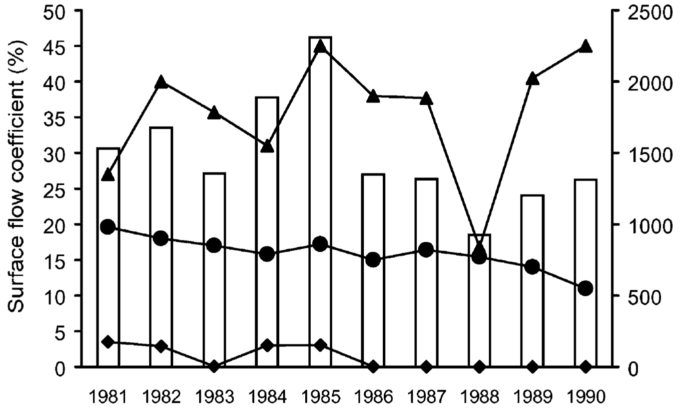

Fig. 7. Yearly changes of surface flow coefficient for the three catchments: mixed forest (◆); *Eucalyptus* plantation (UA) (●); bare land (▲); rainfall (vertical bars).

Table 2
Mean monthly stormflow as a percentage of rainfall for the three catchments (1981–1990)

	January	February	March	April	May	June	July	August	September	October	November	December
Mixed forest	0	0	0.1	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Eucalyptus	3.6	6.4	6.5	11.1	5.5	5.4	6.8	4.9	5.6	3.1	5.8	4.6
Bare land	6.5	5.0	11.0	10.1	13.6	15.3	10.0	11.0	8.3	9.1	4.1	0

Table 3
Monthly surface runoff coefficient (%) from the protected area of the *Eucalyptus* catchment

Year	January	February	March	April	May	June	July	August	September	October	November	December	Mean
1988	25.4	22.1	30.5	31.3	45.7	42.8	50.4	46.6	48.0	24.3	5.3	2.1	31.2
1990	22.3	18.4	28.7	35.6	42.5	36.4	41.7	33.0	40.0	12.2	2.5	1.3	26.2
1992	10.2	9.8	16.6	22.3	25.7	24.0	27.7	21.6	30.1	4.3	1.0	0.4	16.1
1994	6.3	3.8	9.6	11.4	12.9	13.8	14.5	13.0	15.5	2.1	0.5	0.0	8.6

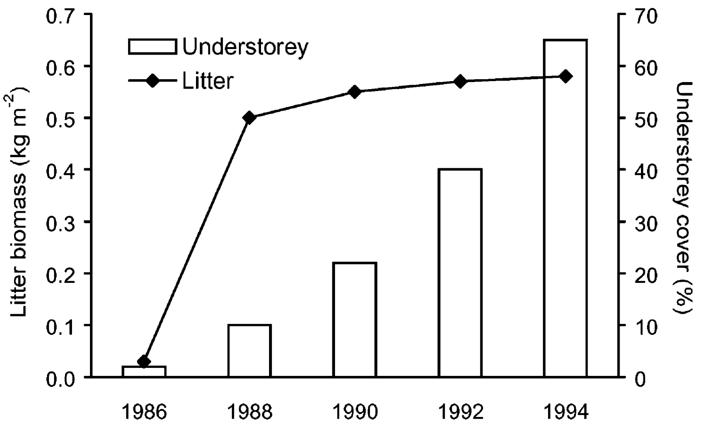

Fig. 8. Yearly changes of understorey cover and litter biomass (LB) on the protected area.

Table 4
Erosion rate of the three catchments in different years (kg ha^{-1} mm^{-1})

	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990
Mixed forest										
Suspended	0.34	0.21	0.02	0.50	1.25	0.00	0.00	0.00	0.00	0.00
Deposited	0.52	0.08	0.01	0.45	0.00	0.00	0.00	0.00	0.00	0.00
Total	0.86	0.30	0.03	0.95	1.25	0.00	0.00	0.00	0.00	0.00
Eucalyptus forest										
Suspended	6.37	5.64	5.87	5.57	6.94	5.76	4.28	1.93	6.52	4.33
Deposited	4.56	3.90	2.58	3.32	4.79	5.08	5.64	2.77	1.74	3.73
Total	10.93	9.54	8.45	8.89	11.74	10.83	9.92	4.70	8.26	8.06
Bare land										
Suspended	19.32	15.27	14.61	17.71	24.61	19.78	29.83	18.47	14.30	19.00
Deposited	20.54	13.01	12.94	13.98	58.66	24.93	24.80	18.66	27.36	28.77
Total	39.86	28.28	27.54	31.69	83.26	44.71	54.64	37.13	41.66	47.77

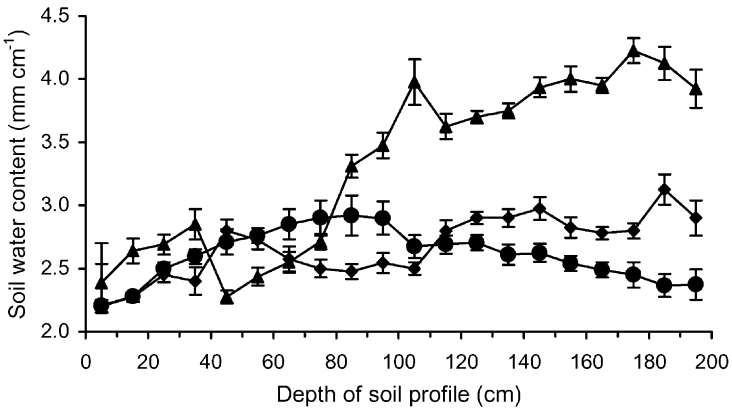

Fig. 9. Soil water content throughout the profile, averaged over 10 years of monthly observation data for each point: mixed forest (◆); *Eucalyptus* plantation (UA) (●); bare land (▲). Bars indicate ±1 standard error.

Fig. 10 shows monthly and annual variation in mean soil moisture content to 195 cm depth. In the bare land catchment, soil water content was always higher than the two forested catchments, but there was little difference between *Eucalyptus* and mixed forest. No long-term trend was apparent in the annual average profile water content of any of the catchments. Analysis of variance showed that soil water content in the protected eucalypt plantation did not differ significantly ($P > 0.05$) from that of the unprotected plantation during the period 1986–1994.

Table 5 lists the relative levels (m, above datum) and average watertable depths during 1983–1989 for the watertable observation wells shown in Fig. 1. The depth to groundwater increases with increasing altitude, indicating a relatively flat watertable and high subsoil hydraulic conductivity. Relative to the bare land catchment, the mixed forest lowered the watertable by 30 cm and the *Eucalyptus* forest lowered it by 80 cm as an average over the 7-year period of observation.

Fig. 11 shows monthly and annual variation in watertable depth in the three catchments. Variation in

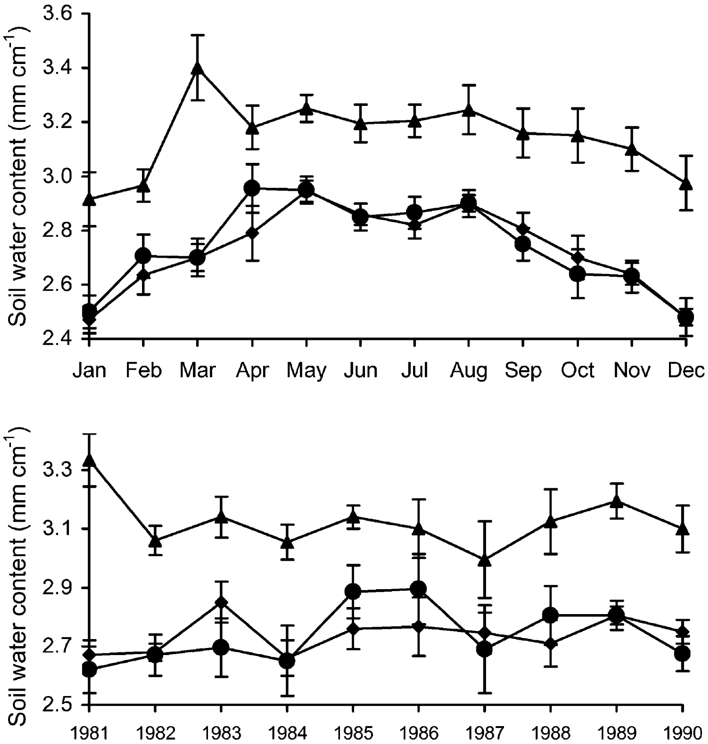

Fig. 10. Monthly and annual changes in mean soil water content of the three catchments: mixed forest (◆); *Eucalyptus* plantation (UA) (●); bare land (▲). Bars indicate ±1 standard error.

watertable depth between wet and dry seasons was greatest in the bare land catchment and least in the *Eucalyptus* plantation. Watertables generally declined during the measurement period, but high rainfall in 1985 (2210 mm, compared with an average of 1455 mm for 1981–1990) raised the watertable by up to 1 m in all catchments in that year. The change in annual mean watertable depth over the 7-year period

Table 5
Average watertable depths for the three catchments during 1983–1989

Catchment	Well altitude (m)	Average depth, 1983–1989 (m)	Relative level of watertable (m)	Mean relative watertable level (m)
Mixed forest				
1	32	3.2	28.8	
2	38	8.7	29.3	29.3
3	44	14.2	29.8	
Eucalyptus forest				
1	32	3.5	28.5	
2	36	7.0	29.0	28.8
3	36	7.1	28.9	
Bare land				
1	30	0.8	29.2	
2	36	6.2	29.8	29.6
3	38	8.1	29.9	

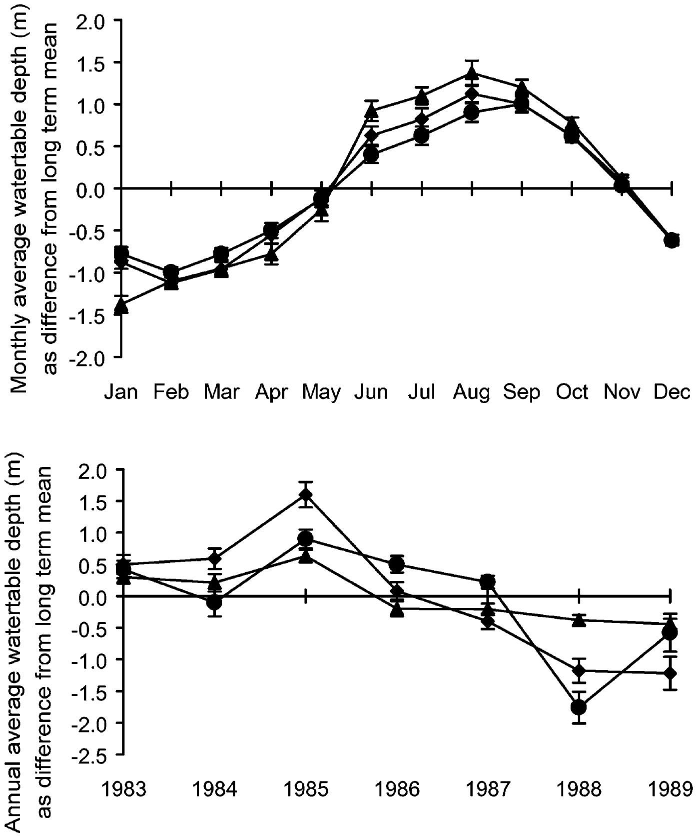

Fig. 11. Monthly and annual variation in watertable depth for the three catchments, as a difference from the long-term mean for each: mixed forest (◆); *Eucalyptus* plantation (UA) (●); bare land (▲). Bars indicate ±1 standard error.

did not differ significantly between catchments (*t*-test, $P > 0.05$).

5. Discussion and conclusions

The coastal region of southern China is subject to a monsoonal climate characterized by distinct wet and dry seasons. Adequate rainfall and relatively warm conditions providing high radiant energy input throughout the year can enable very high productivity from well developed ecosystems in this region (Mecina, 1982; Peng and Zhang, 1995). However, due to the limited capacity of degraded ecosystems to regulate their environment, warm conditions during the season of low rainfall can also make degraded lands more sterile (Parham, 1993; Brown and Lugo, 1994). In the wet season in southern China, storms often cause flooding and heavy soil erosion from bare land, but warm conditions in the dry season may restrict plant survival (Zhou, 1997a). Thus, rehabilitation of barren degraded land there must be a stepwise process (Yu, 1994, 1995).

Both the *Eucalyptus* and mixed forest were found to regulate their microclimate, including the air temperature and humidity near the ground. In all three catchments, air temperature decreased continuously from ground level to 1.5 m above the surface, with the greatest decrease between 0 and 0.2 m. The findings of Murphy and Lugo (1986) similarly suggest an influence of proximity to the land surface extending to this height. Absolute humidity in vegetated catchments reached a maximum at about 0.5 m above the surface, which may be attributed to evapotranspiration from the understorey, litter and surface soil. In the unprotected part of the *Eucalyptus* catchment, where no understorey existed, this characteristic was less apparent, while absolute humidity above bare land decreased continuously with height. The results reinforce the findings reported by Huang et al. (1984) from an earlier study at Xiaoliang.

Because there was no replication of the vegetation treatments and no pre-planting calibration period of streamflow monitoring in the three catchments, the quantitative comparisons of runoff and erosion between catchments are subject to an unknown bias. However, the study design is considered adequate for the purpose of quantifying runoff and erosion from individual catchments and identifying qualitative differences in catchment behavior. Surface runoff differed greatly between the catchments, confirming results reported by Chen and Wang (1992) from work in a neighboring experimental region. The surface runoff coefficients for both mixed and *Eucalyptus* forests decreased over the period 1981–1990, while the coefficient for bare land showed no such trend. Understorey and litter have been shown by many studies to play an important role in reducing surface runoff (Linsley et al., 1975; Singh, 1988; Myers, 1989; Vertessy et al., 1993; Yu and Zhou, 1996). In the protected area of the *Eucalyptus* catchment at Xiaoliang, litter biomass and understorey cover increased over a period of 8 years while the surface runoff coefficient decreased continuously.

The amount of stormflow in runoff from a rain event is an important indicator of the hydrological effectiveness of forest cover and is also important as a key cause of soil erosion (Linsley et al., 1975; Singh, 1988). Stormflow from the *Eucalyptus* catchment as a percentage of rainfall was less than from the bare land, but still considerably more than from the mixed forest catchment with a developed understorey and litter layer. Although the eucalypts alone had some positive effects on reducing stormflow, it is clear that the rehabilitation process for degraded lands must extend beyond this pioneer phase to be fully effective.

Associated with the differences in surface runoff and stormflow, there were large differences in soil erosion among the three catchments. The mean erosion rate from bare land was 5 and 129 times that from *Eucalyptus* and mixed forest catchments, and the ratio of suspended to deposited sediments from bare land was only half the corresponding ratio from vegetated catchments. This implies higher kinetic energy of runoff from bare land, to erode and transport the coarser grained materials deposited in the bottom of the stream channel.

The observation of higher soil moisture content in bare land than in the vegetated catchments may be attributed to water uptake by plant roots. Although the soil moisture observations provide no evidence of a difference in water consumption between mixed forest and *Eucalyptus* plantation, the decreasing water content below 95 cm in the *Eucalyptus* catchment suggests that the *E. exserta* stand may absorb water from deeper in the profile. Differences in the age of the mixed forest and eucalypt root systems may contribute in part to this difference. The zone of low soil water content at 45–115 cm depth below mixed forest may correspond to the zone of greatest root density and water uptake (Yu, 1995). There was no long-term trend in the annual average profile water content of any of the catchments over a period of 10 years.

The watertable level in all three catchments generally decreased over the period of observation. Mean watertable level in the mixed forest catchment was 30 cm lower than the bare land, and in the *Eucalyptus* catchment was 80 cm lower than bare land. These observations may reflect differences in water uptake by the two vegetation types as well as differences in surface runoff between vegetated and bare catchments.

The results from the case study reported here support the use of eucalypts as a pioneer species in the rehabilitation of degraded lands in southern China, but demonstrate the importance of allowing litter accumulation and understorey development beneath the tree canopy. Artificially accelerating succession beyond a *Eucalyptus* monoculture by the introduction of indigenous tree and shrub species has been successful at Xiaoliang, with positive hydrological impacts including major reductions in storm runoff and erosion.

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