Hydrological impacts of reforestation with eucalyptus and indigenous species in southern China

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ABSTRACT - Tree growth, climate, litter biomass and understorey cover, throughfall and stemflow, surface runoff, soil erosion, soil moisture and water table depth were monitored over a 10-year period in three catchments in southern China. These three catchments belong to a series of rehabilitating heavily degraded lands, and comprise bare land, eucalyptus plantation and mixed forest. Both forest types ameliorated their microclimate compared to bare land, including increased absolute humidity and reduced maximum temperature near the ground. The mixed forest canopy had higher rainfall interception capacity and generated less stemflow than the eucalyptus forest. Surface runoff was greatest in bare land, and least from mixed forest. Soil erosion of bare land was 5 and 129 times higher than that from the eucalyptus and mixed forest catchments respectively, and contained a higher proportion of coarse sediments. Water table depth averaged 30 cm deeper beneath mixed forest and 80 cm deeper beneath eucalyptus forest, compared with bare land. The results support the use of eucalyptus as a pioneer species in the rehabilitation of degraded lands in southern China, demonstrate the additional hydrological benefit of encouraging succession to a mixed forest ecosystem.

Key words: microclimate, reforestation, soil erosion, soil moisture, stem flow, surface runoff

INTRODUCTION

The origins of reforestation programs in southern China can be traced back to 1950, soon after the creation of the People's Republic of China. 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). The key problem of vegetation restoration in this region is to ameliorate the degraded environment to allow plant survival and redevelopment of forest ecosystems (MURPHY, LUGO, 1986; BROWN, LUGO, 1994). This requires reduction of 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 requires 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. After improvement of the environment by the artificial forest, some local species can be transplanted to it 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).

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 eucalyptus are of particular importance (YU, 1994, 1995). In addition to an important economic role as a source of construction timber, pulpwood, eucalyptus oil, honey and other products (BAI, GAN, 1996), eucalyptus are widely planted for ecological values including that of pioneer species for rehabilitation of degraded ecosystems (YU, 1994, 1995; MIDGLEY, PINYOPUSARERK, 1996) and as typhoon shelter for crops and villages (TURNBULL, 1981; BAI, GAN, 1996).

The success of eucalyptus 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 raised concern 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, 1997b), due to loss of high intensity rainfall during the wet season as surface runoff with concomitant problems of erosion, siltation and flooding (CHEN, WANG, 1992; PARHAM, 1993). During the dry season, groundwater bores are an important source of water for domestic, agricultural and manufacturing uses. Water shortage during this period limits both the capacity for production of crops, and the capacity for urban development.

This paper examines the impacts of reforestation on environmental conditions in a degraded area of coastal western Guangdong province. Reforestation there since 1959 has created a range of artificial ecosystem types, from the original degraded land, through economic plantations of *Eucalyptus exserta* and *Pinus massoniana,* to artificially developed mixed forest. These vegetation types may be seen as representing different stages of succession (GUEVARA *et al.*, 1986), and their amelioration of the water and heat environment are related to the success of rehabilitation. Studies of the effects of vegetation on environment have focussed on a comparison of hydrology and microclimate in *E. exserta* plantation, bare land and subtropical mixed forest.

MATERIALS AND METHODS

The study area

The studies were conducted in three experimental watersheds located on coastal highland near Xiaoliang in Dianbai County, Guangdong Province (21° 8′ N, 110° 54′ E). Mean annual rainfall in the region was 1455 mm in 1981-1990, with distinct dry (October to March) and wet (April to September) seasons. Total rainfall during the dry and wet seasons was 17% and 83% of the annual total, respectively. Rainfall in the region is mainly associated with convectional storms and typhoons, and the intensity often exceeds 16 mm h^{-1}. The annual average temperature is 23° C. The soil is a typical laterite derived from granite (YU, ZHOU, 1996). The topography of the three watersheds is generally of low relief, with altitude variations of 10 to 20 m.

The bare soil watershed (area 3.7 ha) had been virtually devoid of vegetation for at least four decades before reforestation efforts began in 1959 because of severe soil erosion. 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 in 1964. Before that time, its surface was also totally bare and eroded, and its soil chemical and physical properties were similar to those of the control catchment (PARHAM, 1993; YU, 1994; YU, ZHOU, 1996). The eucalyptus forest grew vigorously until 1972 and more slowly thereafter. In 1976 the plantation was harvested, with branches and leaves left on the site. The plantation was regenerated by coppice regrowth on the cut stumps followed by thinning to leave single stems at a spacing of 2.5 x 2.5 m. By 1990, light attenuation by the eucalyptus canopy was 76% and average tree height was 13 m, with 90% of trees between 12.7 and 13.5 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 (1536 m^2) was fenced off to limit access and prevent litter removal, while the rest of the area remained open as before (Fig. 1). By 1994, the understorey cover rate (average ratio of understorey canopy area to ground area) was about 65% on the protected area, with averaged height of 1.5 m. The third watershed (6.4 ha) was also initially established as *E. exserta* plantation, similar to that described above. In 1975 the plantation was thinned to 400 trees per hectare and indigenous species were planted at irregular spacing over the whole catchment. The species include *Aphanamixis polystachya, Cassia siamea, Albizia odoratissima, Aquilaria sinensis, Santalum album, Leucaena leucocephala* cv. Salvador and *Acacia auriculaeformis.*

A topographical map of the area including the three catchments is shown in Fig. 1.

Climate

A weather station was installed in each catchment and in the protected area, on a tower extending 4 m above the canopy. For mixed forest catchment, an observation tower with the top 4 m above the canopy was erected. Measurements of radiation, (including gross, net and reflected radiation), rainfall, wind speed and direction, relative humidity and air temperature were recorded daily at 0800, 1400 and 2000. Similar measurements (except for rainfall) were collected at 1.5 m above ground, and soil temperature was measured near the base of each tower at depths of 0 cm, 5 cm, 10 cm, 15 cm and 20 cm. In all three catchments, hourly climate observations were also collected continuously over 24 hours for 2 or 3 days of each month.

Surface flow and soil erosion

The runoff from all three catchments was monitored by measurement weirs with stream flow recorders on the ephemeral streams emanating from each and recorded automatically for every precipitation event during 1981-1990. A separate monitored subcatchment (1536 m^2) was set up in 1986 for the protect-

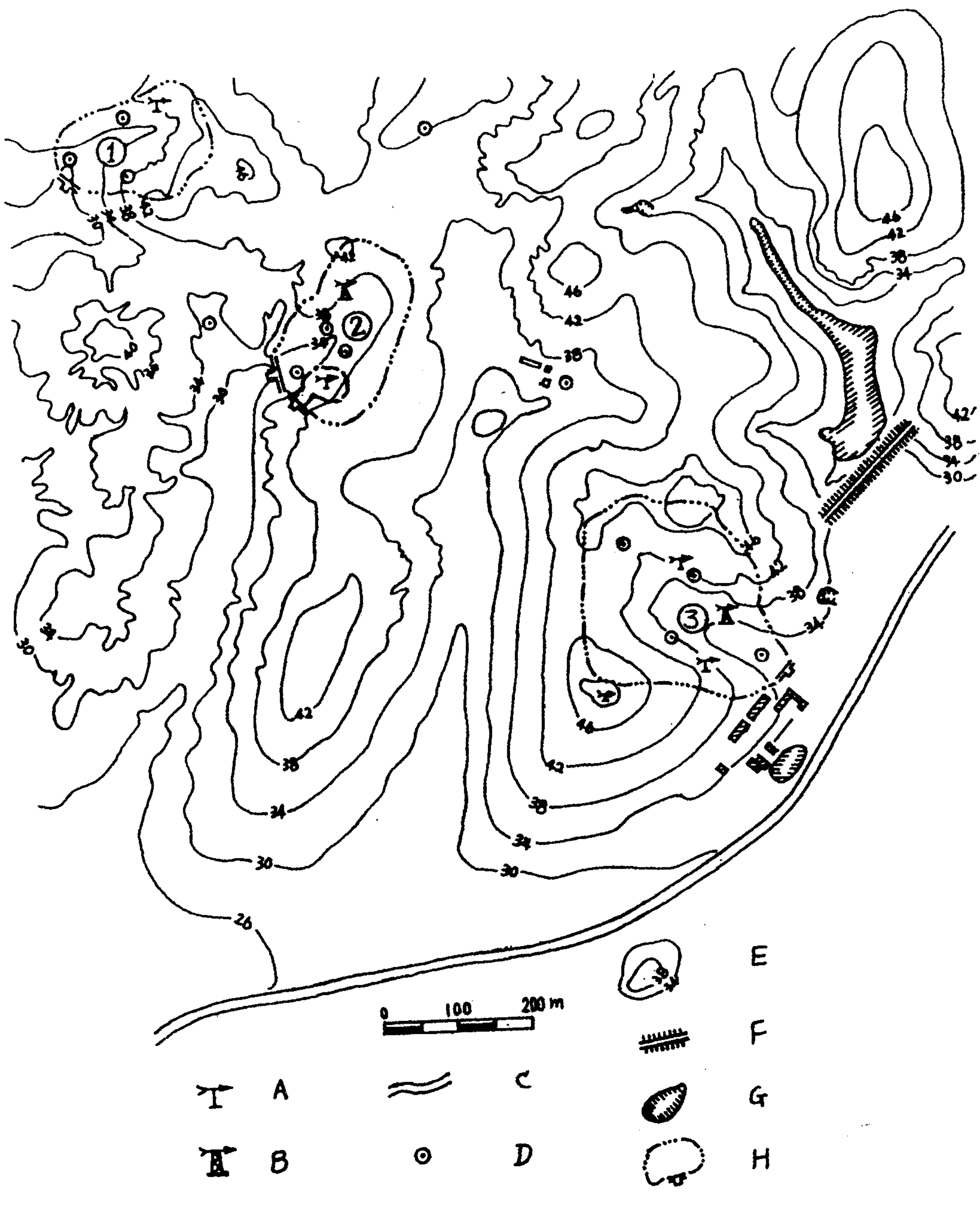

Fig. 1
Topographical map of the Xiaoliang experimental area. ③ Bare land catchment; ② Eucalyptus catchment; ♣ Mixed forest catchment; A: Meteorologic measurement point; B: Observation tower; C: Highway; D: Water table observation well; E: Contour; F: Dam; G: Reservoir; H: boundary and outlet weir of catchment or subcatchment.
Mappa topografica dell'area sperimentale di Xiaoliang. ③ suolo nudo; ② foresta di eucalipto; ♣ foresta mista; A: stazione meteorologica; B: torre di osservazione; C: autostrada; D: pozzetto di controllo del livello di falda; E: curve di livello; F: diga; G: bacino di riserva; H: delimitazioni degli sbarramenti con relativi sbocchi dei bacini o sub-bacini imbriferi.

ed area, using a ditch to lead the runoff out of the catchment. The recorded water flow over each weir in liters 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) x 100%.

The amount of storm flow 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, 1975; SINGH, 1988). Hydrographs for each precipitation event were used to estimate the amount of storm flow following LINSLEY (1975). Storm flow in mm was 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, 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 litre 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}).

Soil and groundwater measurements

Because the topography of the area generally has low relief and the forest was uniform for the two forest catchments, only three locations were selected for soil monitoring in each catchment, located in upper, middle and low slope positions. From 1986, an additional location was selected within the protected area of the Eucalyptus catchment.

At each location soil bulk density was measured at three depths (0-15 cm, 60-80 cm and >120 cm) using a steel cylinder of 80 mm diameter, once each year in October from 1981 to 1990. Soil water content was initially determined gravimetrically on samples collected at 10 cm depth intervals to 200 cm in depth, once per month during 1981-1985. From 1986, soil water content was measured by neutron probe. Three groundwater monitoring wells were installed in each catchment, again located in upper, middle and lower slope positions. Watertable depth was manually recorded at intervals of 5 days and averaged for each month.

Throughfall and stemflow monitoring

Throughfall in the forested catchments was collected by a single trough with a horizontal area of 6 m^2. Water gathered by the trough was channelled to a V-shaped outlet and a fluviograph was used to record the water level in the outlet channel (ZHOU, 1997). 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 to sample throughfall (GASH, 1978; VERTESSY, 1993).

Ten trees adjacent to each site where through fall was monitored were selected for stem flow measurement (GASH, 1978; LEE, 1980), spanning the range of diameters of the whole plantation. For the mixed forest, nine species of trees of average diameter were selected. They were *Eucalyptus exserta* (two trees), *Aphanamixis polystachya, Cassia siamea, Albizia odoratissima, Aquilaria sinensis, Santalum album, Leucaena leucocephala* cv. salvador, *Acacia auriculaeformis,* and *Pinus massoniana.* Stem flow was collected by an open PVC tube wrapped around the stem, and led to a tipping bucket rain gauge. The average stem flow for each stand was calculated from the data recorded by the rain gauges as:

S_c: stand stemflow (mm); A_g: area of a rain gauge (m^2); A_{ci}: canopy projected area of tree number i (m^2); S_{mi}: recorded data for rain gauge number i (mm).

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

Litter biomass and understorey cover

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

RESULTS

Seasonal variation in rainfall and solar radiation

Monthly means of net radiation and rainfall over 10 years (1981-1990) are shown in Fig. 2. Wet season rainfall in the study area is 82.9% of the total, while radiation during the same period is 65.8% of the annual total. Prolonged warm dry conditions during the dry season may promote soil crusting, increasing runoff and rendering the soil surface susceptible to erosion by rainstorms in the following wet season.

Temperature and humidity near the soil surface

Fig. 3 shows daily mean soil and air temperatures at several levels above and below the soil surface, averaged over ten years of observations (1981-1990) for the three catchments and over four 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 (UA) were usually lowest. Temperatures in the mixed forest were similar to those of bare land in the dry season, but similar to the eucalyptus catchment UA in the wet season. Thus the mixed forest had the least temperature variation, with relatively warm winter temperatures and cool summer temperatures. In all 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, which may imply that proximity to the land surface influences temperatures within this zone. The only exception is in July over bare land, when temperature was elevated within 0.5 m above the land surface.

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 higher in the mixed forest than in the eucalyptus UA and bare land catchments, and varied less between seasons. The pattern of RH variation with height above the surface may result from variations in both temperature and absolute humidity.

Absolute humidity (AH) (g m^{-3}), calculated from the

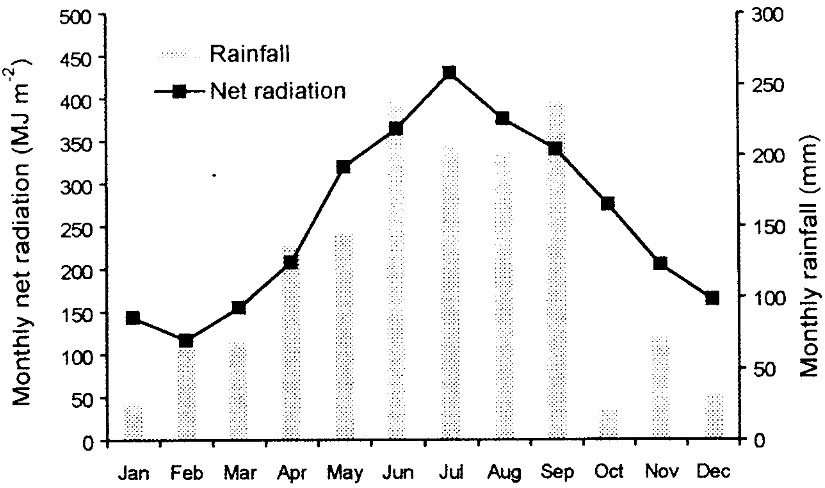

Fig. 2
Monthly distribution of rainfall and net solar radiation averaged over ten years at Xiaoliang.
Medie decennali mensili delle precipitazioni e della radiazione solare netta in Xiaoliang.

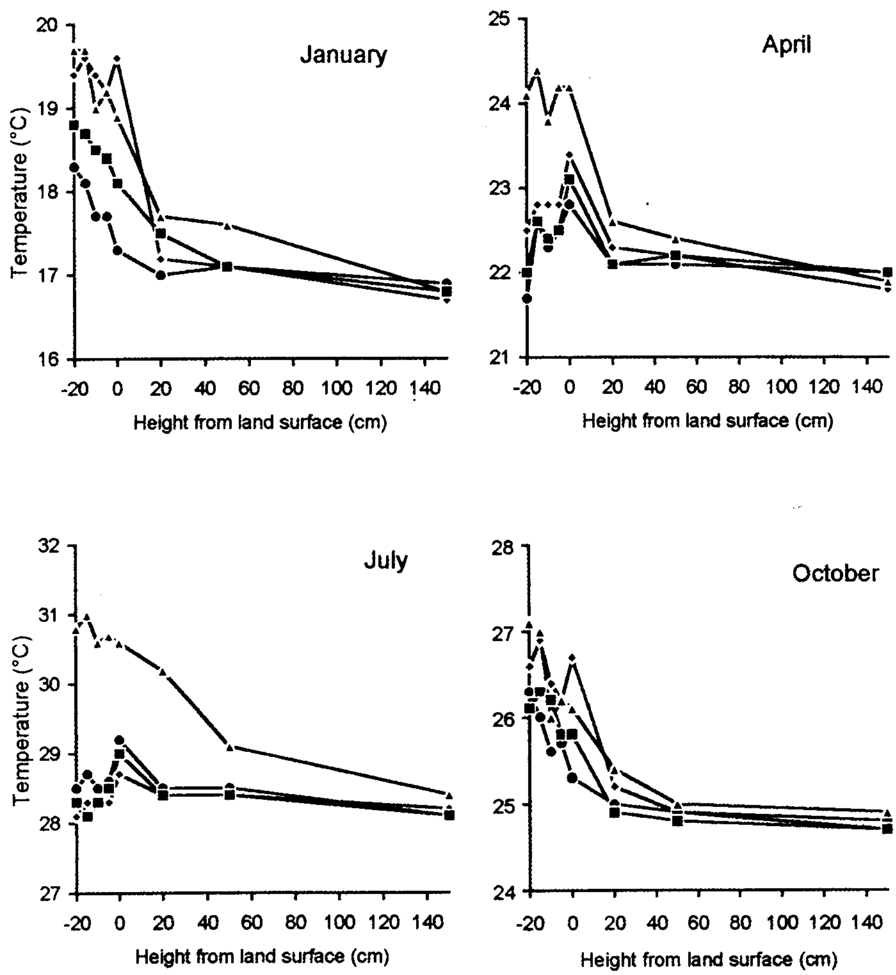

Fig. 3
Daytime mean temperature measured near the soil surface in the three catchments. —♦— Mixed forest; —●— Eucalyptus plantation (unprotected); —■— Eucalyptus plantation (protected); —▲— Bare land.
Temperature medie diurne misurate a diverse altezze dalla superficie del terreno nei tre bacini imbriferi. —♦— Foresta mista; —●— piantagioni non protette di eucalipto; —■— piantagioni protette di eucalipto; —▲— suolo nudo.

observations of mean air temperature and relative humidity (%), varied with height above the soil surface for the four experimental sites (Fig. 4). AH in bare land decreased continuously with height in all seasons, especially in July and April. In the vegetated catchments AH tended to reach a maximum at about 0.5 m above the surface.

Throughfall and stemflow

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:

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

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

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

$P_S = 0.083\ R - 0.046$ (n = 266 and $r > 0.92$), for eucalyptus trees $P_S = 0.068\ R - 0.066$ (n = 335 and $r > 0.88$), for mixed forest trees.

The results show the mixed forest has higher interception and less stem flow than the eucalyptus forest (Fig. 5). Considering that the recorded historic maximum rainfall in a rain event was less than 100 mm (ZHOU, 1997a), the maximum interception capacity of the two forest types is approximately 8 mm and 12 mm in a rain event for eucalyptus and mixed forests, respectively. The stem flow results also reflect the higher interception capacity of the mixed forest. Stem flow occurred in the eucalyptus forest when rainfall exceeded approximately 0.6 mm, but the corresponding minimum rainfall for stem flow in the mixed forest was 1.3 mm.

Surface runoff

Surface runoff differed considerably among the three catchments. Tab. 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. Surface runoff from the bare land catchment was greatest, followed by the eucalyptus catchment while runoff from the mixed forest was very low. These results reflect qualitative differences in the condition of the soil surface and vegetation cover. The mixed forest had a well-developed understorey with three or more layers of vegetation. Differences in aspect and topography among the

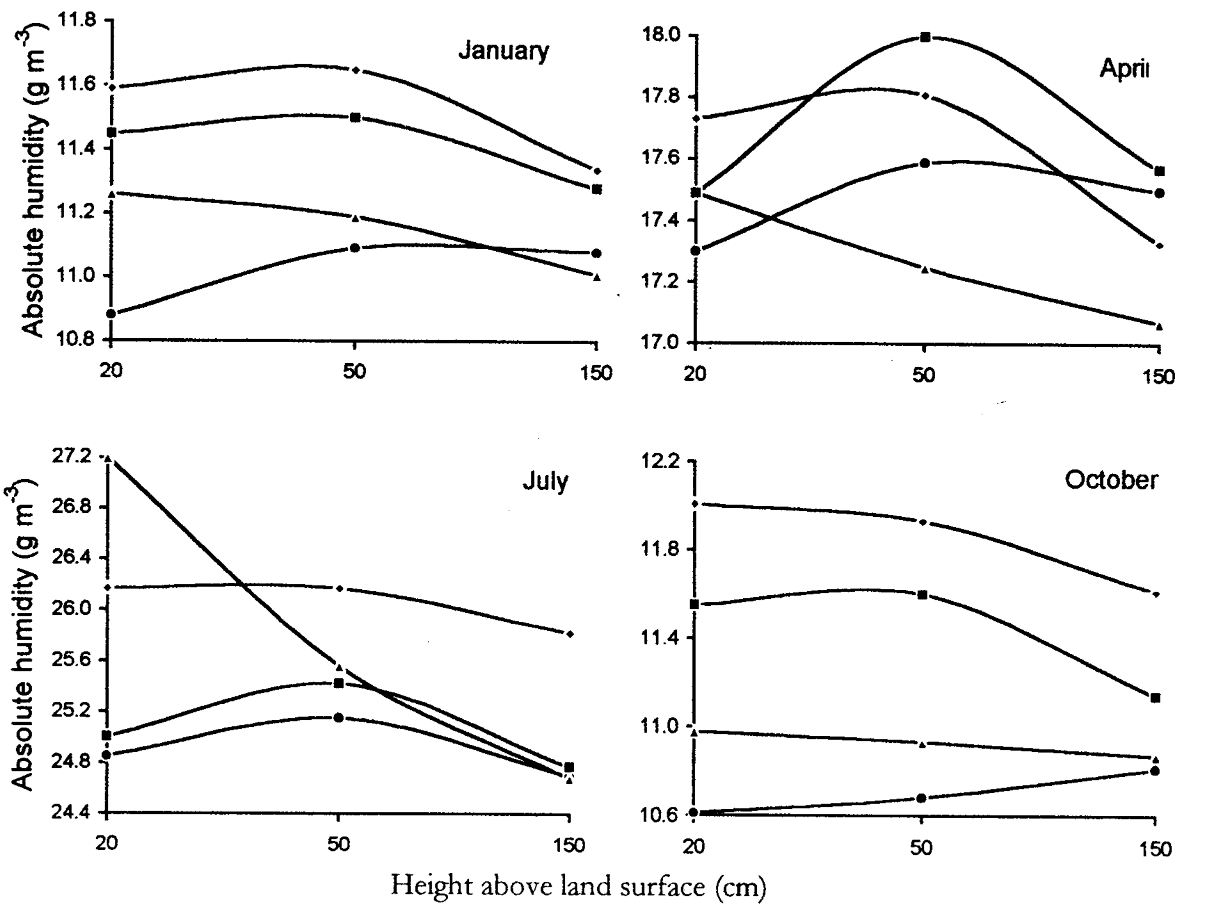

Fig. 4

Daytime mean absolute humidity at 20 to 150 cm above the land surface in the three catchments. —♦— Mixed forest; —●— Eucalyptus plantation (unprotected); —■— Eucalyptus plantation (protected); —▲— Bare land.

Medie diurne di umidità assoluta misurata a 20, 50 e 150 cm dalla superficie del suolo nei tre bacini imbriferi. —♦— Foresta mista; —●— piantagioni non protette di eucalipto; —■— piantagioni protette di eucalipto; —▲— suolo nudo.

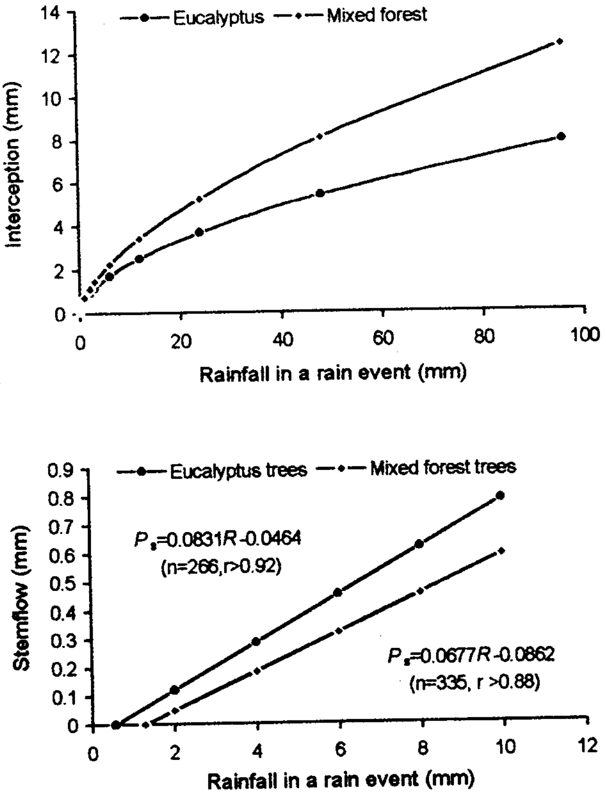

Fig. 5
Interception and stem flow in a rain event for mixed and eucalyptus forests.
Intercettazione della pioggia e *stemflow* in relazione all'intensità delle precipitazioni nelle foreste miste e nelle foreste di eucalipto.

catchments may have also contributed to the difference in runoff (Fig. 1).
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 surface runoff from bare land varied in proportion to the yearly rainfall distribution.
Storm flow was highest from bare land, averaging 8.7% of annual rainfall (20.4% of total runoff). That from the eucalyptus catchment was 5.8% (27.1% of runoff), while the lowest storm flow was from mixed forest at 0.02% of rainfall (0.9% of runoff).
Within the protected area of the eucalyptus plantation, surface runoff decreased during 1986-1994 (Tab. 2) as litter accumulated and understorey cover increased. 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 in1986 were 33.1% and 15.0%, respectively. By 1994 the surface runoff coefficient in the protected area had fallen to 8.6%.

Soil erosion

Tab. 3 shows the annual erosion rate from the three catchments in 1981-1990. Over the ten 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 (UA), 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 kg ha^{-1} mm^{-1}, 19.3 kg ha^{-1} mm^{-1} 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 (UA) and bare land catchments, respectively, demonstrating the effectiveness of forest cover not only in decreasing the total soil erosion, but also in reducing the proportion of larger sediments removed and deposited in the stream channel.

Soil moisture

Fig. 6 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).
Medie mensili di scorrimento superficiale e relative percentuali nei tre diversi bacini imbriferi (1981-1990).

	Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	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
	(%)	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
	(%)	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
	(%)	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

TABLE 2
Monthly surface runoff coefficient (%) from the protected area of the eucalyptus catchment.
Percentuali mensili di scorrimento superficiale nelle piantagioni protette di eucalipto.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	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

TABLE 3
Erosion rate of the three catchments in different years (kg ha^{-1} mm^{-1}).
Tassi di erosione nei tre bacini imbriferi (kg ha^{-1} mm^{-1}).

Year		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

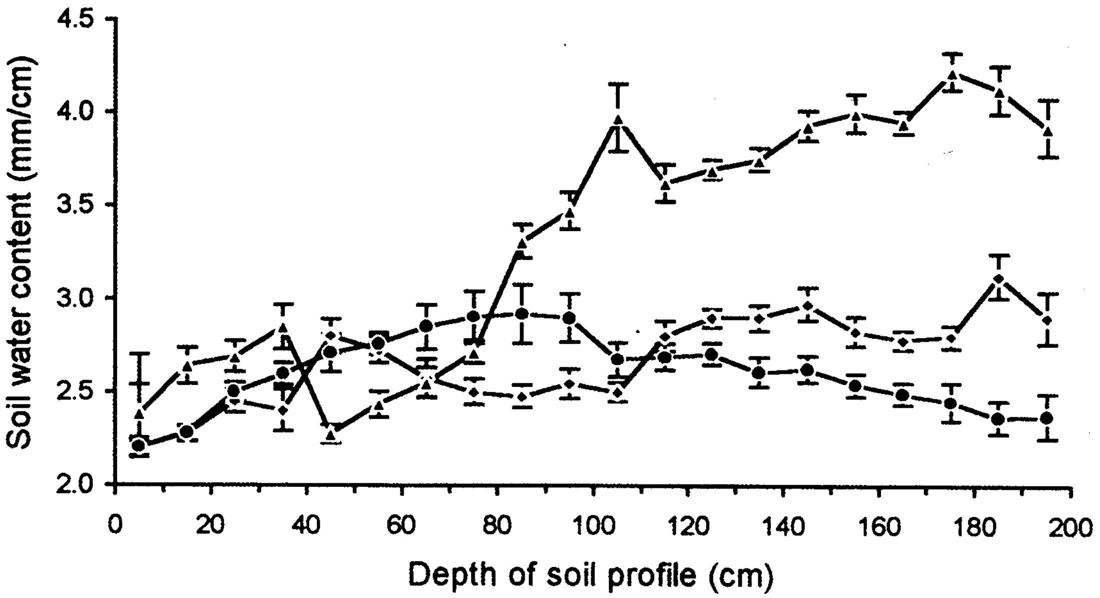

Fig. 6
Soil water content throughout the profile, averaged over 10 years of monthly observation. —♦— Mixed forest; —●— Eucalyptus plantation (UA); —▲— Bare land. Bars indicate ±1 standard error.
Medie decennali mensili dei profili di contenuto idrico del suolo. —♦— Foresta mista; —●— piantagioni di eucalipto (UA); —▲— suolo nudo. Le barre indicano ±1 errore standard.

Soil water content in the eucalyptus plantation reached a maximum at 95 cm depth then declined continuously, suggesting that *E. exserta* may absorb water from deeper in the profile than the mixed forest. A zone of lower soil water content existed in mixed forest at 45-115 cm depth, possibly corresponding to the zone of greatest root density and water uptake (YU, 1995). 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. The average soil water content in the wet season were 2.9 mm cm^{-1}, 2.9 mm cm^{-1} and 3.2 mm cm^{-1} for mixed forest, eucalyptus plantation (UA) and bare land, respectively. Corresponding values in the dry season were 2.6 mm cm^{-1}, 2.6 mm cm^{-1} and 3.0 mm cm^{-1}. No long term trend was apparent in the annual average profile water content of any of the catchments. Soil water content in the protected eucalypt plantation did not differ significantly from that of the unprotected plantation during the period 1986-1994.

Locations of the watertable observation wells for each catchment are shown in Fig. 1. Their relative levels (m above datum) and average watertable depths during 1983-1989 are listed in Tab. 4. The depth of groundwater increases with increasing altitude, indicating a relatively flat watertable reflecting high subsoil hydraulic conductivity. The average watertable levels over three wells in each catchment through the whole period were 29.6 m, 28.8 m and 29.3 m for bare land, eucalyptus and mixed forests, respectively. Relative to the bare land catchment therefore, 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. Variation in watertable depth between wet and dry seasons was greatest in the bare land catchment and least in the eucalyptus plantation. In all three catchments, the highest watertable level was reached in August-September.

Watertables generally declined during the measurement period (1983-1989), 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 seven year period did not differ significantly between catchments.

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, 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, 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, 1997). 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, 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

TABLE 4
Average water table depths for the three catchments during 1983-1989.
Profondità media della falda nei tre bacini imbriferi durante il periodo 1983-1989.

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

surface, which may be attributed to evapotranspiration from the understorey. 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.

Because there was no pre-planting calibration period of stream flow 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, WANG (1992) from work in a neighboring experimental region. The surface runoff coefficients for both mixed and eucalyptus (UA) 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, 1975; SINGH, 1988; MYERS, 1989; VERTESSY, 1993; YU, 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.

Storm flow is recognized as a potential damaging agency for ecosystems (LINSLEY, 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 eucalyptus alone had some positive effects on reducing storm flow, 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 storm flow, 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.

Soil moisture content in bare land was higher than in the two vegetated catchments. This may be attributed to water uptake by plant roots, but the soil moisture observations provide no evidence of a difference in water consumption between mixed forest and eucalyptus. There was no long term trend in the annual average profile water content of any of the catchments over a period of ten years.

The water table level in all three catchments generally decreased over the period of observation. Mean water table 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.

Our results support the use of eucalyptus 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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RIASSUNTO - In questo lavoro si è studiato la crescita degli alberi, il clima, la biomassa della lettiera e del sottobosco, *throughfall* e *stemflow*, lo scorrimento superficiale, l'erosione del suolo, il contenuto idrico del suolo e la profondità della falda, in tre diversi bacini imbriferi (suolo nudo, piantagione di eucalipto e foresta mista) ubicati nel sud della Cina durante un periodo di 10 anni. Il microclima di entrambi i tipi di foresta è risultato migliore di quello del suolo nudo, in termini di più elevata umidità assoluta e più bassa temperatura massima misurata a livello del suolo. La foresta mista ha mostrato una maggiore capacità d'intercettazione delle precipitazioni ed ha generato un minore *stemflow* rispetto alla foresta di eucalipto. I valori maggiori di scorrimento superficiale si sono verificati sul suolo nudo, mentre quelli più bassi si sono riscontrati nella foresta mista. Di conseguenza l'erosione del suolo nudo è risultata pari a circa 5 volte quella registrata nella foresta di eucalipto ed a circa 129 volte quella della foresta mista. Inoltre nelle foreste di eucalipto e nelle foreste miste la falda è risultata essere in media più profonda rispettivamente di 30 e 80 cm rispetto a quella presente nel suolo nudo. Dai risultati ottenuti emerge il ruolo positivo svolto dall'eucalipto come specie pioniera nella riabilitazione dei territori degradati nella Cina del sud, ma soprattutto risaltano i benefici idrologici aggiuntivi derivanti dalla successione agli ecosistemi forestali misti.

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