Impacts of eco-restoration on suspended sediment load in the upper Yangtze River of China

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Abstract Vegetation coverage is of great importance to the ecosystem and plays a key role for soil conservation, runoff and sediment yields. Long-term gauging data indicate that eco-programs in the upper Yangtze basin launched since 1989 have increased vegetation coverage through massive afforestation and soil-water conservation measures. The accumulated planting area of 5.3 million hectares has increased catchment forest coverage from 11% in 1978, to 34% in 2010. The mean annual sediment load of 2.78×10^8 t since 1989 is evidently less than that of 5.23×10^8 t before 1989 (a 47% reduction). Comparing the vegetation coverage situation and the sediment regime during 1999–2002 to those of 1984–1998, shows that the riverine suspended sediment load decreased 1.10% per 1% increase in forest coverage. Since 2003, the sediment load has sharply declined due to rapid construction of reservoirs in the upper reaches.

Key words afforestation; ecological programmes; sediment load; soil erosion; the upper Yangtze River

INTRODUCTION

Soil erosion ranks as one of the most serious environmental problems throughout the world, for it occurs widely in various ecosystems, and its effects are pervasive and long lasting (e.g. Morgan, 1995; Pimentel, 1997). Vegetation cover, especially forest cover, can effectively protect soil from erosion. Tree leaves and branches can intercept a part of the rainfall and diminish rainfall energy, and tree roots can increase water infiltration rate so that surface flow erosion is also reduced. Forest ecological monitoring data demonstrate that the integrated water retention potential of forest vegetation ranges from 40.93 to 165.84 mm, with a median of 103.40 mm; that is, forest vegetation can retain 100 mm rainfall each time at the average level (Zhang, 2002). In addition, forest vegetation can change the temporal runoff distribution on the slope and peak flow in the stream. It is estimated that 2% of forest coverage increase can reduce the peak flow by 1% and the peak flow reduction approaches the maximum of 40-50% when the forest coverage reaches 100% of a small watershed scale. Furthermore, the vegetation growth may greatly influence soil properties to improve the anti-erosion ability of the soils (Tang et al., 1993; Primentel & Kounang, 1998). As a result, in stable forest ecosystems, soil erosion rates are very low, ranging from 0.004 to 0.05 t ha⁻¹ year⁻¹ (Roose, 1988; Lal, 2001), while on cultivated bare slopes, soil erosion rates are up to 500 t ha⁻¹ year⁻¹ (Tang, 2004).

The Yangtze River has become of worldwide concern due to the impacts of the Three Gorges Project. The reach from the headwaters to Yichang is called the upper Yangtze River. There have been an increasing number of publications focused on the sediment load dynamics and its relation to human activities and natural factors (e.g. Gu & Douglas, 1989; Higgitt & Lu, 1999; Zhang & Wen, 2004; Lu, 2005; Yang *et al.*, 2006; Wei *et al.*, 2011). A shortage of forest resources and the fragile environment makes the upper Yangtze basin an area susceptible to serious natural disasters such as soil erosion, flood and drought. Catastrophic floods and serious mountain hazards in 1981 and 1998 aroused public concern regarding ecological problems and spurred the Chinese Central Government to launch a campaign of the "Forest-sheltered Yangtze". Since then, reforestation efforts have been put into practice guided by scientific knowledge, together with other comprehensive measures and policies, such as watershed management and restoration, abandonment of steep croplands, and natural forest protection plans. This has resulted in efficient improvement of the ecosystem, indicated by both on-site landscapes and professional analyses of biodiversity (Xu *et al.*, 2006; Zhao *et al.*, 2010; Cao, 2011). Most of these ecological programmes

were orientated to soil erosion control, leading to a great impact on land surface processes. However, how vegetation coverage changes affect the catchments' surface processes of soil erosion and sedimentation, and further the regional climatic and eco- systems remains largely unknown. The present paper analyses the coupling relation between vegetation changes and river sediment load using long-term gauging data.

MATERIALS AND METHODS

Study area

The upper Yangtze is the name given to the 4300-km long river upstream from Yichang, which has a total drainage area of 1×10^6 km² and a population of 155 million. It extends 24–36°N latitude and 90–112°E longitude, with an altitude range between 400 and 5100 m (Wei *et al.*, 2011). The mainstream is generally called the Jinsha River, and is joined by four major tributaries: the Yalong, Min, Jialing and Wu rivers. The complex mountainous terrain, combined with the monsoon-driven uneven precipitation system leads to potential risks to topsoil erosion. It is estimated that 35% of the basin is affected by soil erosion, which has resulted in degradation of the water quality and the riparian ecosystem (Wen *et al.*, 2002). Since 1989, the Central Government has launched a number of eco-restoration programmes in this area such as Grain-for-Green programme, which has led to positive results in sediment yield reduction.

Data collection

The annual suspended sediment load and water discharge for the upper Yangtze basin was monitored by the Yichang hydrological station; the Jinsha River data were collected from the Pingshan station, and Jialing River data were obtained from the Beibei station. This sediment load and water discharge monitoring data (1954–2009) was provided by the Yangtze Water Conservancy Committee. The area changes of forest clearance and plantation, and the forest coverage rates were based on statistical data (1955–2010) provided by the National Forest Bureau.



Fig. 1 Sketch map of the study area.

RESULTS AND DISCUSSION

Ecological programmes launched in the upper Yangtze basin and LUCC changes

To guarantee the safety of water quality and the Three Gorges Project (TGP), the State listed the upper Yangtze basin as a National Key Soil Conservation Project (NKSCP) and has provided financial support since 1989. In 1991, the Soil and Water Conservation Law of the People's Republic of China came into effect. Since then, soil erosion has been considered as one of the most serious environmental issues in China and soil conservation has been incorporated into the strategies of sustainable development and Western Region Development. In the past three decades, a proactive fiscal policy has been adopted by the Chinese Government to invest in large-scale ecological project construction and several ecological programmes for soil conservation and ecological improvement in the upper Yangtze basin have been launched (Table 1).

These programmes have increased forest area and managed soil and water resources. For example, by the end of 2005, along the river 3531 small catchments were favoured by the NKSCP, with an area of 7.46×10^4 km². Within the first six periods of NKSCP (from 1989 to 2005), the programme had converted 6000 km² of slopeland to terraced farming, planted 210 000 km² of forests and 8000 km² of fruit orchards for soil-water conservation, and cultivated 2900 km² of grassland. Twenty-two thousand km² of land was designated as non-grazing conservation land, and 135 km² of farmland was converted to conservation tillage. The NKSCP has improved the

Program name	Start year	Regions in the upper Yangtze involved	Progress	Main soil conservation practices
National Key Soil Conservation Project in the Yangtze Basin	1989	The lower Jinsha River basin & Bijie area, southern Gansu & Shanxi provinces, the middle and lower Jialing River basin as well as the Three Gorges area, some counties with serious soil erosion in the south Mt. Dabie, totalled 197 counties in 10 provinces.	Soil erosion in more than 3000 small watersheds with area of 84 000 km ² is controlled.	Terracing sloping farmland; planting fruit orchards for soil conservation; planting trees and grasses; non- grazing conservation; check dam; water storage pond; drainage ditches.
The Construction Project of Shelter-forest System in Upper- middle Yangtze Basin	1989	The Three Gorges area, the Jialing River basin, the middle-lower Jinsha River basin and other 10 key areas, totalled 271 counties in 11 provinces.	Afforested an area of 6.74×10^6 ha; forest coverage rate increased by 5% more than 1989.	Forestation; fostering young forest; improvement of low- yield forest.
Natural Forest Protection Project	1998	Provinces of Sichuan, Yunnan, Guizhou, Hubei, Chongqing municipality, Tibet autonomous region.	The forest coverage increases 3.7%; and a net increase of forest volume reaches about 0.725 billion m ³ .	Stop deforestation; closing hillsides to facilitate forestation; aerial seeding; artificial forestation.
Grain-for-Green Project	1999	Initially launched in Sichuan, Shaanxi, Gansu provinces as a pilot, officially started in 2001 and then expanded nationwide.	75% of sloping farmland and 46% of desertified farmland are covered by forests and grasses with an area of 26.87×10^6 ha.	Returning farmland to forest production; forestation on barren mountains; closing hillsides to facilitate forestation.
Ecological Restoration Pilot Project for Soil Conservation	2001	40 counties, distributed in provinces of Yunnan, Guizhou, Sichuan, Gansu, Shaanxi and Hubei.	An area of 3079.1 km ² has been finished.	Closing hillside and forbidding grazing; ecological migration; using alternative energy.
Project of Soil Conservation by the World Bank Loan	2006	38 counties in the four provinces of Yunnan, Guizhou, Hubei and Chongqing.	About 3104 km ² soil erosion area has been controlled.	Returning farmland to forests and grasslands; planting fuel-wood forest; check dam construction; constructing small water conservancy projects.

Table 1 Ecological programmes launched in the upper Yangtze basin.

agricultural production conditions and ecological environment in the seriously-eroded areas within the upper Yangtze basin. Forest coverage changed from 33.8% to 56.2%, and the sediment trapping capacity increased to 5.1×10^8 t in these areas. The erosion rate declined from 3832 t km⁻² year⁻¹ to 1900 t km⁻² year⁻¹, a 50.4% reduction (CIECC, 2007). In conclusion, the project has contributed significant benefits in reducing soil loss.

Besides NKSCP, the subsequent Grain-for-Green Project and the Natural Forest Protection Programme are regarded as the world's largest ecological rehabilitation projects. These programmes changed the land use and land cover greatly, further controlled the generation of sediment, which directly reduces sediment yields to the rivers. During recent decades, land use in the study area has changed dramatically. For example, the Grain-for-Green programme, initially started as a pilot programme in Sichuan, Gansu and Shaanxi provinces in 1999, and expanded nationwide in 2001. The programme compensates participating farmers with cash subsidies, grain subsidies, and free saplings for reforestation. Hence, agricultural cropland with a gradient over 25° was easily converted or restored to forestland or grassland. Consequently, the area of the forest increased from 33.47×10^4 km² in the 1970s, covering 33.92% of the total basin, to 33.63×10^4 km², covering 34.09% of the total. The grassland area changed from 34.33×10^4 km² (34.80%) to 35.64×10^4 km² (36.12%), the unused land from 5.35×10^4 km² (5.42%) to 5.54×10^4 km² (5.62%), the wetland from 0.37×10^4 km² (0.38%) to 1.41×10^4 km² (1.43%) and the urban area from 0.06×10^4 km² (0.06%) to 0.52×10^4 km² (0.52%) (Wei *et al.*, 2011). There is no doubt that the above land-use conversion is beneficial for soil erosion control. Zhang et al. (2003) indicated erosion rates of forest and grassland in the upper Yangtze ranging from 310 to 4435 t km⁻² year⁻¹. Where forest coverage was greater than 80%, erosion rates were between 0 and 300 t km⁻² year⁻¹; 700-900 t km⁻² year⁻¹ with forest coverage of 60%; and more than 4000 t km⁻² year⁻¹ with a coverage of less than 30%.

Riverine suspended sediment load variations in response to fluctuations of vegetation coverage

The Yichang hydrological observation station is the virtual end point of the upper Yangtze reach (Fig. 1); therefore it is plausible to use the water discharge and sediment load data to reflect the situation in the entire upper Yangtze basin. The water discharge at Yichang gauging station has changed slightly, but sediment has declined notably over time (Fig. 2(c)). Since the mid-1980s, the sediment load has gradually been decreasing. Dividing 1950–2009 into two periods (pre-1989 and post-1989) is helpful to illustrate the effects of ecological programme implementation (Table 2). The mean annual water discharge of 4180×10^8 m³ after 1989 is 5% less than that of 4391×10^8 m³ before 1989, while the mean annual sediment load decreased by 47% (from 5.23 to 2.78×10^8 t). The Jinsha and Jialing rivers are regarded as the first two large tributaries in the upper reaches in terms of sediment yield. At the Pingshan station on Jinsha River, there were slight increases in both sediment load and water discharge after the late 1970s, but since 2000, a decrease of sediment and water discharge is evident (Fig. 2(a)). The mean annual water discharge and sediment load before 1989 were 1407×10^8 m³ and 2.43×10^8 t, but after 1989, were 1490×10^8 m³ and 2.38×10^8 t, but after 1989 were 1490×10^8 m³ and 2.38×10^8 m³ an 10⁸ t, respectively. Unlike Yichang and Pingshan, both water discharge and sediment load at Beibei station decreased with a notably sharper decrease in sediment load (Fig. 2(b)). The mean annual water discharge and sediment load decreased by 20% (from 701 to 559× 10⁸ t) and 74% (from 1.44 to 0.37×10^8 t).

able 2 Water discharge and sediment load variations in the upper Yangtze.

Station	Pre-1989 MAWD	MASL	Post-1989 MAWD	MASL	Increment MAWD	MASL
Beibei	701	1.44	559	0.37	-142	-1.07
Pingshan	1407	2.43	1490	2.38	83	-0.05
Yichang	4391	5.23	4180	2.78	-211	-2.45

MAWD: mean annual water discharge, $\times 10^8$ m³; MASL: mean annual sediment load, $\times 10^8$ t.



Fig. 2 Time-series of annual sediment load and double accumulated curve of annual runoff and sediment load from 1954 to 2009; (a) observation data at Pingshan Station, the outlet station of the Jinsha River; (b) observation data at Beibei Station, the outlet station of the Jialing River; (c) observation data at Yichang Station, the virtual end of the upper Yangtze River.

The ecological programmes described previously increased vegetation coverage significantly. For example, the Upper Min River tributary had been a timber-supply base before the 1980s resulting in forest cover declining from more than 50% before 1910 to 18% at the end of the 1970s, but now has a forest cover of more than 36% (National Forest Bureau of China, 2010). Vegetation recovery has been widely recognized as an important driving force to ecosystem restoration. It can generally improve land surface stability and protect soil from erosion (Primentel, 1998) (Fig. 3). The Jialing River is the main source of the suspended sediment of the upper Yangtze River, and also a key area for planting forest for soil conservation (Wei et al., 2011). The forest coverage has risen from 11% in 1978 to 34% in 2010 (Fig. 4(a)). By 2010, the accumulated planting area in the upper Yangtze River was 5.3×10^6 ha (Fig. 4(b)). The suspended sediment concentration of river flow began to decrease since the 1980s. The double accumulated curve of sediment load to water discharge in the past five decades clearly shows a turning point in 1986, indicating that the sediment concentration and load became lower than that before 1986 (Fig. 2). The hydrological observation data in Yichang shows that in upper reaches of the Yangtze River, annual suspended sediment yield was about 640×10^6 t on average from 1950 to 1986, while it was about 380×10^6 t after 1986 (Fig. 2(c)). The sediment concentration decreased to 0.85 kg m^{-3} in the 1990s from 1.14 to 1.24 kg m⁻³ before 1986.



Fig. 3 Soil erosion rates related to vegetation coverage (data from Tang, 1993; Trimble & Mendel, 1995; Cheng *et al.*, 2004; He *et al.*, 2004).

Quantitative impacts of forest coverage on the sediment load decrease

The Elasticity Coefficient is introduced here to quantify the impacts of forest coverage on the sediment load decrease:

$$\delta_f = (\Delta S/S)/(\Delta f/f) = [(S_2 - S_1)/S_1]/[(f_2 - f_1)/f_1]$$
(1)

where δ_f is an index reflecting the contribution of forest coverage change to the sediment load variation; S_1 and S_2 are the mean annual sediment load of two periods to be compared; f_1 and f_2 are the forest coverage of two periods to be compared.

Table 3 is the result of quantifying forest coverage impacts on the sediment load decrement according to formula (1). 1984–1988 is defined as Period 1 to indicate the status of forest coverage and sediment load before the above ecological programmes commenced; 1999–2002 and 2003–2006 are Period 2 and Period 3, respectively. Period 2 is expected to reflect the situation after the eco-programmes began; Period 3 of 2003–2006 is particularly proposed here because the Three Gorges reservoir began to store water in June 2003, and since then the sediment load has reduced dramatically; that is, soil conservation practices combined with the reservoir trapping of sediment load coming from the upper Yangtze.

Item	Period 1 (1984–1988)	Period 2 (1999–2002)	Period 3 (2003–2006)	Δ_{12}	δ_{12}	Δ_{13}	δ_{13}
Forest coverage (%)	19.21	25.00	30.27	5.79	-1.10	11.06	-1.50
Sediment load $(10^8 t)$	5.05	3.38	0.70	-1.67		-4.35	

Table 3 Impacts of forest coverage on the sediment load increment.

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Fig. 4 Riverine sediment load response to the catchment vegetation changes and artificial forestation. (a) changes of vegetation coverage rates in Sichuan Province; (b) accumulated re-forested area in the upper Yangtze River basin; and (c) sediment fluctuation in the upper Yangtze (observations at Yichang Station).

The coefficient δ_{12} of -1.10 indicates that the riverine suspended sediment load decreases 1.10% when forest coverage increases 1%. However, this is true only when Period 1 and Period 2 are compared. The δ_{13} of -1.50 indicates that when forest coverage increases by 1%, the riverine suspended sediment load decreases by 1.50%. Obviously, the absolute value of δ_{13} is greater than that of δ_{12} , which demonstrates that the contribution of forest coverage change to the sediment load variation increased, and this may be enhanced by the dam and reservoirs impacts (e.g. Yang, 2006; Shi & Du, 2009).

CONCLUSION

Since 1989, a number of ecological programmes have been launched to promote soil conservation and ecological improvement in the upper Yangtze basin. These programs have increased vegetation coverage through massive afforestation and soil-water conservation practices. By 2010, the accumulated planted area in the upper Yangtze River was 5.3 million hectares, resulting from an increase in forest coverage from 11% in 1978 to 34% in 2010. The mean annual water discharge of 4180×10^8 m³ after 1989 is less than that of 4391×10^8 m³ before 1989 with a 5% reduction, while the mean annual sediment load decreased by 47% (from 5.23 to 2.78 × 10⁸ t).

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Comparing the situation during 1999–2002 (after ecological programmes started) to that of 1984–1998 (before ecological program started), the riverine suspended sediment load decreased by 1.10% when forest coverage rate increased 1%; however, when the status of 2003–2006 is compared to that of 1984–1988, the contribution of forest coverage change to the sediment load variation increased as indicated by the coefficient δ_{13} of –1.50, partly because the impacts of dam and reservoirs on the sediment load became increasingly evident.

Acknowledgements This work is supported by the National Natural Science Foundation of China (no. 41001168), National Key Technology R&D Program (no. 2011BAD31B03) and Chongqing Education Committee (no. KJ100601).

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