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Changes in Ecosystem Service of Soil Conservation Between 2000 and 2010 and Its Driving Factors in Southwestern China

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Abstract: Human activities significantly alter ecosystems and their services; however, quantifying the impact of human activities on ecosystems has been a great challenge in ecosystem management. We used the Universal Soil Loss Equation and county-level socio-economic data to assess the changes in the ecosystem service of soil conservation between 2000 and 2010, and to analyze its spatial characteristics and driving factors in the southwestern China. The results showed that cropland in the southwestern China decreased by 3.74%, while urban land, forest, and grassland areas increased by 46.78%, 0.86%, and 1.12%, respectively. The soil conservation increased by 1.88×10^{11} kg, with deterioration only in some local areas. The improved and the degraded areas accounted for 6.41% and 2.44% of the total land area, respectively. Implementation of the Sloping Land Conversion Program and urbanization explained 57.80% and 23.90% of the variation in the soil conservation change, respectively, and were found to be the main factors enhancing soil conservation. The 2008 Wenchuan earthquake was one of the factors that led to the degradation of soil conservation. Furthermore, industrial adjustment, by increasing shares of Industry and Service and reducing those of Agriculture, has also promoted soil conservation. Our results quantitatively showed and emphasized the contributions to soil conservation improvement made by implementing ecological restoration programs and promoting urbanization. Consequently, these results provide basic information to improve our understanding of the effects of ecological restoration programs, and help guide future sustainable urban development and regional industrial restructuring.
Keywords: soil conservation; ecosystem service; Sloping Land Conversion Program (SLCP); ecological restoration; urbanization; southwestern China

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1 Introduction

Human activities such as land reclamation, water resource utilization, and urbanization significantly change ecosystems and their services (Ouyang and Zheng, 2009). They principally affect land by changing habitats, ecosystem structures, and biogeochemical cycling (Zheng *et al.*, 2003). The impacts of human activities on ecosystem services can be divided into positive impacts, such as ecosystem management, ecological conservation, and ecological restoration, and negative impacts, such as cultivation and cropping, hydrological disruption, and over-grazing (Zheng *et al.*, 2003; Rey Benayas *et al.*, 2009). Whether ecosystem services can be maintained depends on which impacts are most prevalent at any given time. Exploring the influences of human activities on ecosystem services is critical, as it is the foundation for maintaining and preserving these vital ecosystem

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services. These influences are also important for sustainable regional development. However, quantitatively assessing the impact of human activities on ecosystems is challenging for ecosystem management projects.

The emergence of widespread environmental and ecological degradation has prompted the Chinese government to implement a series of ecological conservation and construction projects in response to the reduction in ecosystem services. These projects also aim to restore, and even enhance, the ecosystem structures and functions through ecological rehabilitation and reconstruction. The Sloping Land Conversion Program (SLCP), also known as the 'Grain for Green Project', is one of the largest ecological rehabilitation efforts as its vast area (1897 counties within 25 provinces) and considerable financial investment (~2.2×10^{11} yuan (RMB) at the end of 2010) (Xu *et al.*, 2006; Liu *et al.*, 2008). It primarily aims to control the serious levels of soil erosion and desertification in China, especially in the western China, by converting sloping cropland and degraded rangeland back to forest and grassland (Xu *et al.*, 2006). Studies in the Loess Plateau showed that implementation of the SLCP gradually recovered the vegetation cover and also considerably enhanced soil conservation and carbon sequestration (Lyu *et al.*, 2012). This led to a considerable drop in severe soil erosion (Fu *et al.*, 2011). Despite ecological protection efforts, ecosystems are still suffering severe damage from natural disasters and human activities, leading to ecological function deterioration. For example, the Wenchuan earthquake in Sichuan Province, China in 2008 caused heavy casualties and property losses, and seriously damaged local ecosystems (Zhang and Wang, 2008), which sharply reduced water retention, soil conservation, carbon sequestration, and other ecosystem services (Wang *et al.*, 2012; Yang *et al.*, 2013). During the last century, in the middle and lower reaches of the Changjiang (Yangtze) River, unsustainable human activities such as conversion of lakes to croplands, building of sluices, and construction of embankments considerably reduced the flood regulation provided by lakes and led to an increase in the flood frequency (Li *et al.*, 2005; Yang *et al.*, 2010). Evaluating the effectiveness of regional ecosystem restoration, especially under the influence of natural and anthropogenic damage, is another great challenge for ecosystem management.

Southwestern China is highly biodiverse and produces a wide range of ecosystem services, which strongly support and underpin the development of the Changjiang River Basin, the Zhujiang (Pearl) River Basin, and other important watersheds in China. The Southwest China is also known for its severe soil erosion and tendency for rocky desertification (Jiang *et al.*, 2014). This is due to the exposed carbonate rocks combined with high solubility, a low physical weathering rate, and consequently, a slow soil formation rate (Wang *et al.*, 2004; van Beynen, 2011; Jiang *et al.*, 2014). In some areas, long-term soil erosion has left little erodible soil, which has produced a desert-like landscape with exposed bedrock (as the ultimate state of soil erosion) (Wang *et al.*, 2004). Soil erosion and rocky desertification have threatened the ecological security and sustainable development of this region (van Beynen, 2011). Fortunately, the government has recently launched a series of ecological construction projects in the southwest, such as the SLCP, the Natural Forest Protection Program, the Rocky Desertification Combating Program, and the Shelterbelt Development Program in the Changjiang River and Zhujiang River basins. At the same time, large-scale and rapid urban development was promoted under the 'Go West' policy, which has resulted in clear changes to the regional land cover (Han, 2010).

In this paper, the Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1978) and county-level socioeconomic data were used to assess changes in the ecosystem service of soil conservation in the southwestern China between 2000 and 2010, and to analyze the spatial characteristics and impact factors causing these changes. We determined how implementing the SLCP and promoting urbanization contributed to soil conservation improvement. Finally, we provide basic information that will improve our understanding of the effects of ecological restoration programs and help guide future sustainable urban development and regional industrial restructuring.

2 Materials and Methods

2.1 Study area

The study area is located in the southwestern hinterland of China (Fig. 1), including the Sichuan Basin, the Yunnan-Guizhou Plateau, and the southeastern Tibetan Plateau. It covers four provinces (municipalities): Chongqing, Sichuan, Guizhou, and Yunnan, and contains 436 counties. It has a total area of 1.13×10^8 ha and accounts for 11.75% of China's land area. The principal geomorphic formations are plateaus, mountains, hills, and basins, with the area of mountains and hills exceeding 80% of the total land area. In addition, karst landforms, such as trough valleys, peak-cluster depressions, and rift basins are widely distributed, particularly in the Yunnan-Guizhou Plateau and parts of Sichuan and Chongqing, and account for 28.92% of the total area. Because of the complicated and diverse terrain, there are boreal, temperate, subtropical, and tropical climates, with a humid subtropical monsoon climate dominating the study area. Annual precipitation averages ≥ 1000 mm in most parts, and occurs mainly in frequent heavy rainstorms.

The major land cover types in the southwestern China are forest, cropland, and grassland. The forest is located primarily in the Hengduan Mountains and at the western margin of the Sichuan Basin. Croplands are located mainly in the Sichuan Basin and grasslands are concentrated mainly in the western Sichuan Plateau (Fig. 1).

2.2 Data

The Digital Elevation Model (DEM) used in this study was from the Shuttle Radar Topography Mission (SRTM) with a resolution of 90 m. The soil map and associated soil attributes (including the mass percentages of clay, silt, sand, and soil organic matter) were obtained from the second National Soil Survey of China, with a resolution of 1∶1 000 000. Both the ecosystem categories and the vegetation coverage data (2000, 2010) were produced by the Institute of Remote Sensing Applications, Chinese Academy of Sciences, using satellite Landsat 5 Thematic Mapper (TM) images and Moderate Resolution Imaging Spectroradiometer (MODIS) data, with resolutions of 30 m and 250 m, respectively. The ecosystems were categorized into forest, shrub, grassland, wetland, cropland, urban land, desert, and bare land. Beijing Normal University provided the average annual rainfall erosivity data from 1980 to 2010 from 603 meteorological stations. The administrative divisions were provided by the Satellite Environment Center, Ministry of Environmental Protection.

2.3 Methods

2.3.1 Model description

Soil conservation is the reduction of soil erosion via

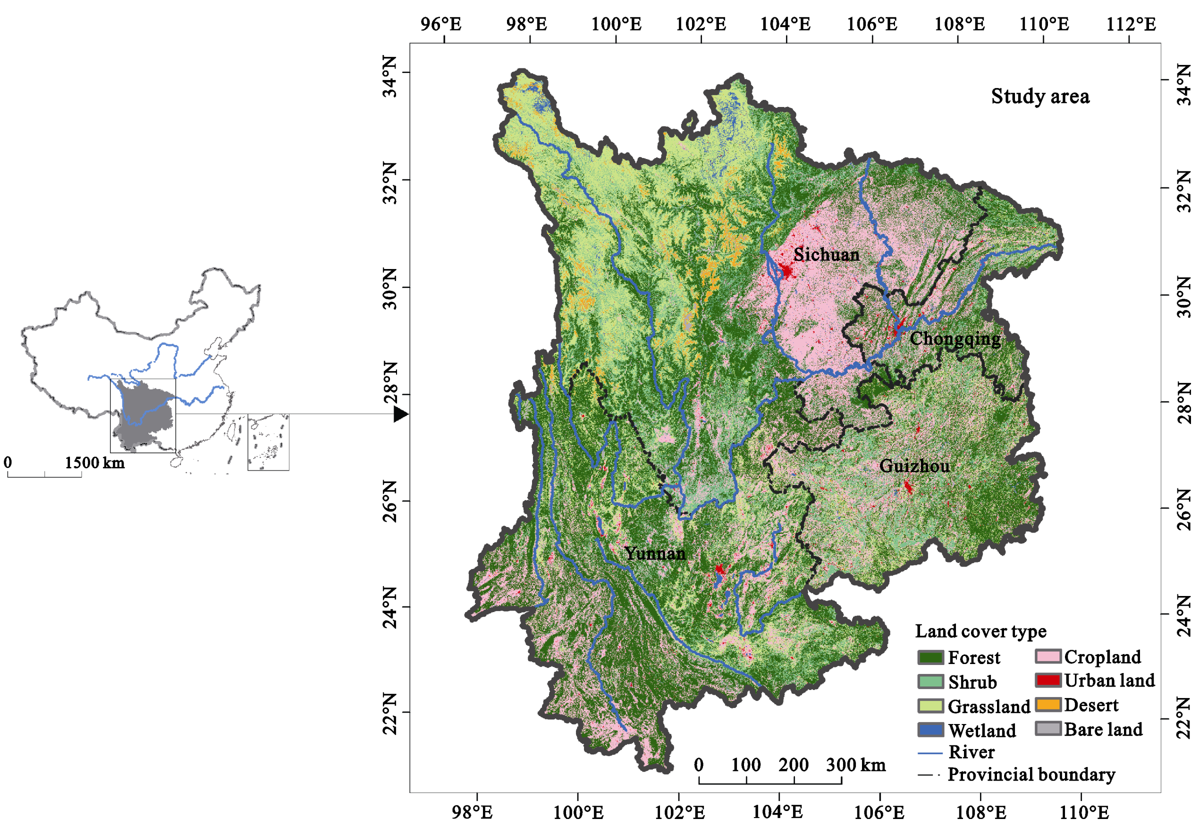

Fig. 1 Location and land cover distribution map for southwestern China

ecosystem structures and processes, and can be expressed as the difference between potential and actual soil erosion. According to the USLE, soil erosion is closely related to rainfall, soil, topography, and vegetation and the soil conservation model can be expressed as:

$$SC = R \times K \times LS \times (1 - C) \quad (1)$$

where *SC* represents the soil conservation capacity (t/(ha·yr)); *R* is the rainfall erosivity factor (MJ·mm/(ha·h·yr)); *K* is the soil erodibility factor (t·ha·h/(ha·MJ·mm)); *LS* is the topographic factor; and *C* is the vegetation cover factor.

For *R* factor, we used the average annual rainfall erosivity data (1980–2010), which were generated by Beijing Normal University using the Daily Rainfall Erosivity model (SCO, 2010). For *K* factor, the Erosion/Productivity Impact Calculator was used for the calculations, and the research conducted by Zhang *et al.* (2008) was used for the revision. For *LS* factor, we integrated the relevant research on gentle slopes and steep slopes, and performed calculations using different slope segments (Rao *et al.*, 2014). For *C* factor, values were assigned after referring to domestic and foreign literature (Liu *et al.*, 1999; Wei *et al.*, 2002; Carter and Eslinger, 2004), with different ecosystem types and vegetation coverage considered (Rao *et al.*, 2014).

Due to the extensive distribution of karst areas, which are characterized by developed karst fractures, we used an adjustment coefficient for correction, according to Wei (2011). In karst areas, most of the precipitation infiltrates into the underground river system through surface cracks, and consequently, overland flow occurs only occasionally and is far less than in non-karst areas. Additionally, the thin soil layer and the small amount of erodible soil make soil erosion in karst areas much lower than in non-karst areas (van Beynen, 2011; Jiang *et al.*, 2014).

2.3.2 Redundancy analysis

The relationships between human activities and the soil conservation offered by ecosystems were analyzed via redundancy analysis (RDA), which was performed by CANOCO 4.5 (Biometris-Plant Research International, Wageningen, The Netherlands). This analysis is usually used to study the impact of environment on species. Here, 'species' data were represented by data of *change in soil conservation capacity* (*CSCC*) and *area of soil conservation improved* (*ASCI*). 'Environment' data were selected based on regional features and the focus of concern, and were represented in this study by *area of forest converted from cropland* (*AFC*), *area of grassland converted from cropland* (*AGC*), *change in urban population* (*CUP*), *change in rural population* (*CRP*), *change in urban area* (*CUA*), and *change in shares of GDP* from *Agriculture* (*CGA*), *Industry* (*CGI*) and *Service* (*CGS*). The first two environmental variables reflect the efforts invested in the SLCP, while the others reflect the rate of urbanization. Data analysis and processing were performed at the county-level and all the changes in variables represented absolute differences between 2000 and 2010. Furthermore, both 'species' and 'environment' data were standardized beforehand in order to eliminate dimension effects.

3 Results

3.1 Land cover changes

The dominant land cover types in the southwestern China are forest, cropland, and grassland, which account for 38.02%, 23.90%, and 18.50% of the land area, respectively, and together make up 80.42% of the land area. The decrease in cropland and the increase in urban land, forest, and grassland were the major changes in land cover from 2000 to 2010 (Table 1). Cropland decreased by about 1.05 × 10^6 ha (3.74%). Urban land (including artificial surface and urban green space) expanded the most during this period, with an increase of 4.0 × 10^5 ha (46.78%). Forest and grassland increased by 3.6 × 10^5 ha (0.86%) and 2.3 × 10^5 ha (1.12%), respectively, while changes in other land cover types were relatively small.

3.2 Soil conservation changes

The spatial distribution of the soil conservation offered by various ecosystems was highly heterogeneous. Areas with high soil conservation capacities were located

Table 1 Area change in land cover between 2000 and 2010 in southwestern China (10^6 ha)

Category	Area change	Category	Area change
Forest	0.36 (0.86)	Cropland	−1.05 (−3.74)
Shrub	−0.06 (−0.37)	Urban land	0.40 (46.78)
Grassland	0.23 (1.12)	Bare land	0.01 (0.92)
Wetland	0.09 (6.49)		

Note: negative numbers mean decline of area; numbers in the brackets are area percentages of change (%)

mainly in the hills surrounding the Sichuan Basin, the Hengduan Mountains, Wuliang Mountain, Ailao Mountain, Miaoling Mountain, and other mountain areas, while flat areas, such as the Sichuan Basin, Yunnan-Guizhou Plateau, and the western Sichuan Plateau, had poor soil conservation capacities (Fig. 2a).

Overall, soil conservation was enhanced, except for some local degradation. The areas of improved land and degraded land occupied approximately 6.41% and 2.44% of the total land area, respectively. Spatially, regional soil conservation improvements were widely distributed, with the Dalou Mountain, Daba Mountain, and Miaoling Mountain improving considerably. Regions with degraded soil conservation were primarily concentrated in the Minshan Mountain and Qionglai Mountain, to the west of the Sichuan Basin, and in the southern Yunnan Valley in the southernmost part of the study area (Fig. 2b). Quantitatively, the soil conservation in southwestern China increased by 1.88×10^{11} kg over the decade, with a relative increase of 0.36%.

3.3 Drivers of soil conservation change

RDA analyses of soil conservation change and human activities are displayed on a biplot (Fig. 3a). The *CSCC* and *ASCI* were significantly positively correlated with *AFC*, *AGC*, *CUP*, *CUA*, and *CGS* ($P < 0.05$), and significantly negatively correlated with *CRP* and *CGA* ($P < 0.01$). The SLCP variables (*AFC* and *AGC*) and urbanization variables (*CUP*, *CRP*, *CUA*, *CGA*, and *CGS*) explained 57.80% ($P < 0.01$) and 23.90% ($P < 0.01$), respectively, of the total variance in soil conservation change (Fig. 3b). *AFC*, a measure of the SLCP effort, described most of the variance (52.00%), followed by *AGC*, *CGS*, *CGA*, *CRP*, *CUA*, and *CUP*, in descending order. Furthermore, there was a clear positive interaction between the SLCP and urbanization, which explained 16.10% of the variance (Fig. 3b).

4 Discussion

Changes in the soil conservation offered by ecosystems and the soil erosion intensity in a region are closely related to changes in land use and land cover (Yang *et al.*, 2003; Feng *et al.*, 2010; Su and Fu, 2013). From 2000 to 2010, decreases in cropland and increases in urban land, forest, and grassland areas were observed in the southwestern China. The major conversions were from cropland to forest, from cropland to urban land, and from cropland to grassland (Fig. 4). Their rates of change (area of specific conversion in proportion to all types of conversions) were 32.60%, 19.67%, and 14.42%, respectively. On gentle slopes, conversion from cropland to urban land predominated, indicating rapid urbanization. On steep slopes, conversions from cropland to forest and from cropland to grassland predominated, which reflects the achievements of the SLCP in recent years. It

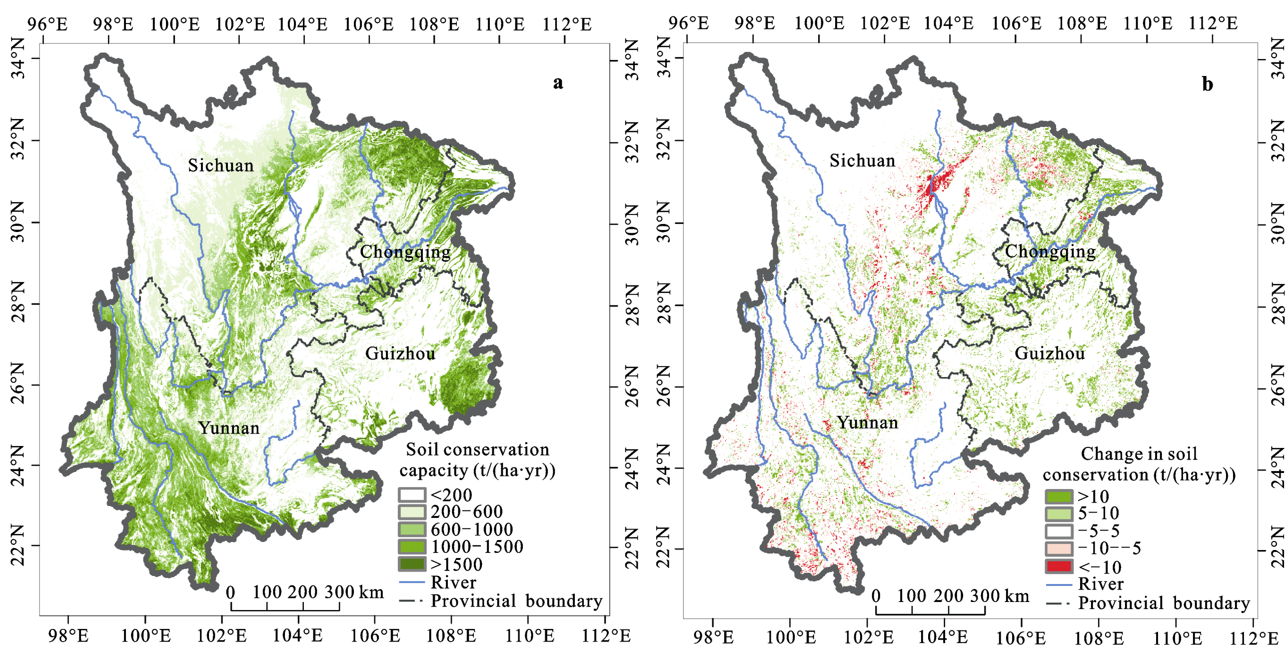

Fig. 2 Spatial pattern (a) and changes (b) of soil conservation capacity between 2000 and 2010

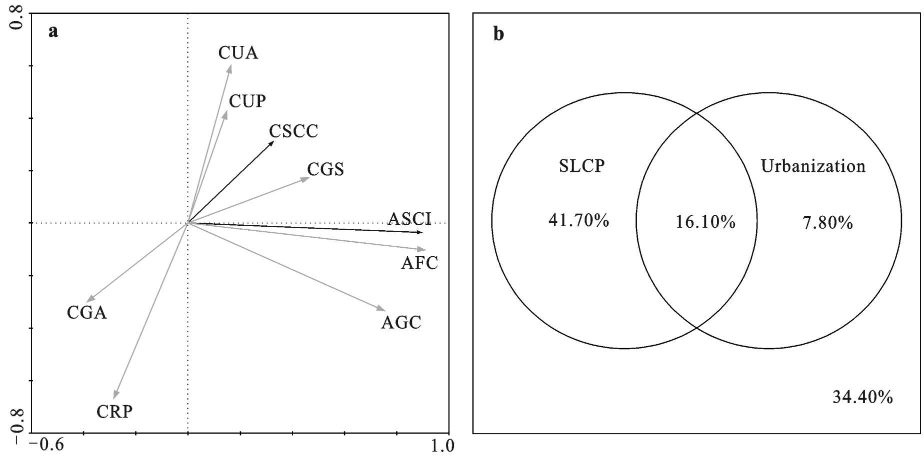

Fig. 3 Redundancy analysis (RDA) results showing relationship between soil conservation change and human activities. a. Changes in soil conservation (displayed with black arrows) was represented by *change in soil conservation capacity* (*CSCC*) and *area of soil conservation improved* (*ASCI*). Human activities (displayed with grey arrows) were categorized into the Sloping Land Conversion Program (SLCP) and urbanization. The former was represented by *area of forest converted from cropland* (*AFC*) and *area of grassland converted from cropland* (*AGC*), while the latter was represented by *change in urban population* (*CUP*), *change in rural population* (*CRP*), *change in urban area* (*CUA*), and *change in shares of GDP* from Agriculture (*CGA*), Industry (*CGI*), and Service (*CGS*). The cosine of angles between arrows approximated the correlation coefficients among variables and the length of arrows was used to compare the magnitude of the effects across variables. b. Variance partitioning revealed the contributions made by the two subsets of variables (SLCP variables, urbanization variables, their shared proportion and the residual variance)

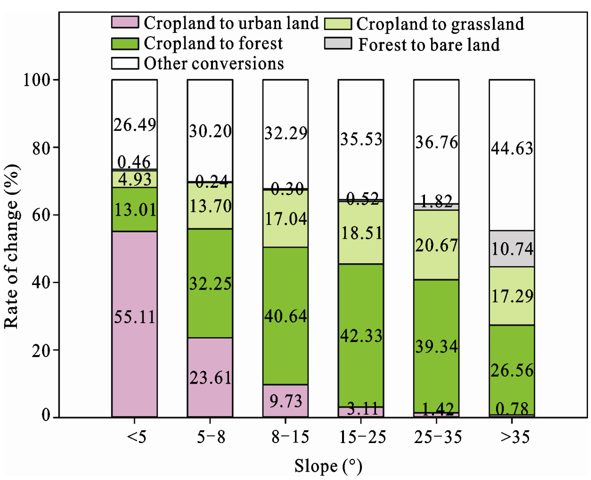

Fig. 4 Land cover conversions on different slopes. Rate of change is the area of specific conversion in proportion to all types of conversions

was reported that SLCP had converted nearly 9.0×10^6 ha of cropland into forest or grassland nationwide before 2007 (Liu *et al.*, 2008). Additionally, conversion from forest to bare land consisted of a considerable proportion (10.74%) on slopes of > 35°, which demonstrated the damage caused by the Wenchuan earthquake in 2008 (Zhang and Wang, 2008; Wang *et al.*, 2012).

General enhancement and local degradation in the soil conservation in southwestern China occurred between 2000 and 2010. The degraded zone accounted for 2.44% of the total land area, primarily in the Minshan Mountain and Qionglai Mountain to the west of the Sichuan Basin, which were part of the Wenchuan earthquake zone. A recent study conducted by Wang *et al.* (2012) showed that after the Wenchuan earthquake, the reduction of soil conservation capacity in the earthquake zone averaged 0.90 t/(ha·yr), which was the most affected among the three key ecosystem services (soil conservation, water retention, and carbon sequestration). This indicates that earthquakes not only destroy the natural vegetation but also degrade the soil conservation offered by ecosystems (Zhang and Wang, 2008; Wang *et al.*, 2012). A reduction in soil conservation was also observed in southern Yunnan Valley, which was the result of the large-scale replacement of tropical rainforest with cash crop forest (Li *et al.*, 2007; Zhang and Zou, 2009). However, the improved zone accounted for 6.41% of the total land area, mainly in the Dalou Mountain, Daba Mountain, Miaoling Mountain, and other mountain areas.

Implementation of the SLCP and urbanization are the major driving forces that promote soil conservation in southwestern China, and explained 57.80% and 23.90%, of the variation in soil conservation change, respectively. The SLCP and similar ecological restoration programs have the ability to increase ecosystem service provision (Chazdon, 2008; Rey Benayas *et al.*, 2009). First, returning cropland to forest and grassland through changing land use patterns can significantly reduce the amount of sloping cropland (most susceptible to erosion and a major source of sediment) (Pimentel *et al.*, 1995; Liu *et al.*, 2008) and effectively increase the distribution of forest and grassland (high soil conservation) (Liu *et al.*, 2008). Second, the increase in biodiversity after restoration is also an important factor in enhancing ecosystem services (Rey Benayas *et al.*, 2009). As a result, the regional soil conservation is improved and soil erosion is considerably reduced (Liu *et al.*, 2008), which is the principal objective of the SLCP (Yin and Zhao, 2012). In southwestern China, where rocky desertification is a serious ecological problem, most ecological restoration efforts are focused on karst areas, which are vulnerable to rocky desertification. The proportion of improved land in karst regions (8.42%) was much higher than that in non-karst regions (5.62%) and higher than the average (6.41%), which was probably the result of regional ecological restoration. In addition, the effects may be even larger over time, since there are time lags in ecological effects and vegetation recovery needs time (Liu *et al.*, 2008). In the meantime, southwestern China experienced rapid urbanization, characterized by extensive urban sprawl, rural-urban migration, and increased Industry and Service shares of GDP (Table 2). It is generally believed that urbanization not only causes environmental problems, such as climate change and pollution (Faulkner, 2004; Grimm *et al.*, 2008; McDonald, 2008; Shen *et al.*, 2008), but also leads to invasion of exotic species and loss of biodiversity (Nagendra *et al.*, 2014). However, urbanization can help increase the soil conservation by reducing soil disturbance from agricultural activities (especially on steep slopes) with the increasing share of Industry and Service (Grau and Aide, 2007; Ricardo and Aide, 2008). Also, urbanization may reduce the pressure on natural ecosystems following the shift to an urban population (Ye *et al.*, 2003; Grau and Aide, 2007), which stimulates ecosystem recovery and soil conservation improvement (Jiang *et al.*, 2003; Ricardo and Aide, 2008). A significant interaction was observed between the SLCP and urbanization. Cropland conversion and ecological resettlement accelerate the development of urbanization, while urbanization also improves the implementation and maintenance of ecological restoration programs (Jiang *et al.*, 2003; Ricardo and Aide, 2008), because people are less dependent on fragile, vulnerable, or damaged ecosystems.

Table 2 Changes in population and industry structures in southwestern China between 2000 and 2010

	Item	2000	2010	Change (2000–2010)
Population (10^6 person)	Urban	50.15	74.74	24.58
	Rural	139.36	113.72	–25.64
GDP (%)	Agriculture	23.18	13.42	–9.76
	Industry	40.52	49.13	8.62
	Service	36.30	37.45	1.15

5 Conclusions

From 2000 to 2010, decreases in cropland and increases in urban land, forest, and grassland have occurred in Southwestern China. Except for some local degradation, the soil conservation offered by ecosystems has generally improved. The improved regions are located primarily in the Dalou Mountain, Daba Mountain, Miaoling Mountain, and other mountain areas, while the degraded regions are concentrated in the Minshan Mountain, Qionglai Mountain, and southern Yunnan Valley. The SLCP and urbanization are recognized as the major drivers behind soil conservation enhancement, while earthquakes negatively affect soil conservation. Thus, we can conclude that implementing ecological restoration programs and promoting urbanization have contributed to soil conservation improvement, and that industrial adjustment, by increasing Industry and Service shares, can also be used to promote soil conservation.

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