Assessing spatial distribution of soil erosion in a karst region in southwestern China: A case study in Jinfo Mountains

H Y Zhou¹,2, X Y Pan¹,3 and W Z Zhou¹,4

¹ School of Geographical Sciences, Southwest University, Chongqing 400715, China
² No.1 Experimental Middle School Attached to Sichuan Normal University, Sichuan 61000, China
³ Yonye Saiboneng Land Surveying and Planning Company, Wuhan 40061, China

E-mail: zhouwz@swu.edu.cn

Abstract. Soil erosion is serious with rocky desertification areas appearing in mountainous Karst regions in southwest China due to a conspicuous contradiction between man and the land resource. Land use and land cover play significant roles in regional soil erosion by water. This paper aimed to quantify regional soil erosion and to explore relationships between soil erosion and land use/land cover in order to locate high risk areas requiring soil conservation. Based on GIS, the Revised Universal Soil Loss Equation (RUSLE) was employed for erosion assessment for a typical Karst region, Jinfo Mountain region in southwest China, using local parameters. Spatial distribution of topsoil erosion was analyzed and relationships between soil erosion and land use/land cover changes (LULC) were statistically explored and discussed for regional erosion control. The overall values were under 25 t.ha.a, with the medium erosion areas accounting for 12.7% and the intense and very intense erosion areas totalled about 6%. The relations between soil erosion and LULC are complicated in this Karst mountainous region. Generally, the amount of ground cover, soil conservation measures, and cultivation disturbance have played critical roles in topsoil loss in the Jinfo mountain region. The reduced ground cover levels accompanying greater cultivation disturbance lead to higher erosion intensity in each landscape, and vice versa.

1. Introduction

Soil erosion is one of major global environmental problems causing negative impacts that limit the sustainable development of land resources [1]. It is a cumulative process that depends on factors such as land use, vegetation cover, climate, topography, and on soil physical properties such as texture, organic matter, structure and porosity. Among these, land use and land cover are two of the most important factors that influence the occurrence and intensity of surface runoff and soil erosion [2, 3]. Land cover can improve some physical–chemical properties of the soil through both physical protection of the soil surface, the contribution of organic matter from the plant canopy and the root system [4], and by the increased soil structural stability due to increasing soil organic carbon and aggregation [5]. Land uses which change the type and coverage of vegetation contribute not only to the changes of the runoff and both the physical and chemical properties of soil, but also the development of the soil erosion. Soil erosion causing the loss of fertile soil constrains the structure and distribution of the land use which intensify the contradiction between human and land resource [6]. Rational land use /land cover changes can greatly improve soil properties [7] and reduce soil erosion [8, 9]. Scholars have explored the relationship between LULC and soil erosion from different
perspectives using different methods[10-13], such as analysis of driving factors in the process of soil erosion by observation stations data[14], effect of LULC on soil erosion and sediment transport by the decision support system and GIS[15], regional land use change contributing to reducing soil erosion using models[16], and spatial relationships between natural and socio-economic indicators and the index of soil erosion risk[17].

Nevertheless, studies on the relationship between soil erosion and LULC in Karst regions are fewer than in other areas. The studies on soil erosion in Karst region mainly focused on the characteristics [18], cause [19], process [20], and erosion risk assessment[21]. Studies on soil erosion of limestone hill slopes in semi-arid or arid areas have been carried out from the perspective of the hydrology based on statistical and parametric models [22-24]. New methods have been introduced in studies of soil erosion in Karst area, such as $^{137}$Cs tracer [18] and fuzzy modeling [21]. Human activities on land use and management have been considered as one of main influential factors in Karst regions [19].

The Karst region of southwestern China is the largest Karst region in the world as well as one of the most fragile ecotones [25]. With high and steep mountains, low vegetation coverage, high precipitation intensity and variability, conspicuous contradiction between human activities and the land resource, soil erosion is serious and even karst rocky desertification areas appear in the southwestern China. As an ultimate state of soil erosion, rocky desertification means collapse of the ecology and environment, and it is hard to restore because of its low rate of soil formation, thin solum, low soil erosion tolerance and fragile ecosystem. Improper land use may cause severe soil erosion and Karst rocky desertification. So it is important to quantify regional soil erosion and to explore relationships between soil erosion and LULC in order to locate the critical areas for conservation in this region. The objectives of this paper were to quantify the characteristics and spatial differentiation of soil erosion in the Jinfo mountain region and to explore the relationships between soil erosion and LULC in Southwestern China.

2. Materials and methods

2.1. Study area
The Jinfo Mountain region which is one of typical Karst areas in southwestern China covers about 1260.58 km$^2$, lies between 106° 54´ E~107° 27´ E and 28° 46´ N~29° 30´ in Nanchuan district of Chongqing municipality, the southeast boundary of Sichuan Basin with elevation from 500m~1000m. The topography in this area is complicated with hills and slots composed of karst monadnocks and terraces in the north, with folded mountains with high steep cliffs, valleys and karst caves in the south. The subtropical humid monsoon climate in this area gives it not only abundant heat but also wide variation in its annual and seasonal rainfall patterns. Typically, mean annual temperature is about 9.5 ºC and the mean precipitation is about 1390 mm annually with most rain occurring from May to October when the temperature is relatively high. Rain with heat at the same period has accelerated karst development. The main soil types are yellow brown soil, yellow soil, limestone soil, purple soil and paddy soil. The main land use types are forestlands, hill dryland, and hill paddy land. The geography in the Jinfo mountain is a typical pattern of the Karst region in southwestern China.

2.2. Data sources
The Landsat-5 TM (2010-08-19) remote sensing image was geometrical precise adjusted by reference to the DEM with a resolution of 1:50,000. The NDVI was derived from the remote sensing image by the index calculating in the spectral enhancement tool. The local land use map with 1:25,000 scale was obtained from the Bureau of Land and Resource of Nanchuan County and classified into 8 types, i.e. dryland, paddy field, woodland, garden-plot, grassland, bare land, construction land, and water area. Slope map of study area was produced by the surface analysis module tool in ArcGIS 9.3 software according to its Digital Elevation Model (DEM). Precipitation data recorded by nearby weather observation stations was interpolated into raster precipitation data and adjusted according to the DEM. Soil texture and organic matter data come from the second Chinese soil survey data.
2.3. Soil Erosion Model

The Revised Universal Soil Loss Equation (RUSLE) [26], formula 1, explains how climate, soil, topography, and land use affect rill and inter rill soil erosion caused by raindrop impact and surface runoff. It has been extensively used to estimate soil erosion loss and to assess soil erosion risk.

\[
A = R \times K \times L \times S \times C \times P
\]  

(1)

where \( A \) is the annual soil erosion module (t ha\(^{-2}\) a\(^{-1}\)), \( R \) the rainfall erodibility factor (MJ mm ha\(^{-2}\) h\(^{-1}\) a\(^{-1}\)), \( K \) the soil erodibility factor (t ha\(^{-1}\)), \( L \) the slope length (m), \( S \) the slope gradient (%), \( C \) the crop management factor, and \( P \) the erosion control practice factor. Factors \( C \) and \( P \) are dimensionless.

The grid map of soil erosion in 2010 was produced according to the RUSLE equation using grid calculator in ArcGIS 9.3 software. Then the soil erosion class map and soil erosion intensity classification were obtained according to SL 190-2007 standards [27] and the spatial differences in annual soil erosion were analyzed. The relationships between LULC and soil erosion were explored in the study area.

2.4. Soil erosion intensity

Researchers demonstrated that the index of soil erosion intensity can reflect the soil erosion intensity on different land use [28, 29]. The index of soil erosion intensity is calculated by using equation 2.

\[
E_j = 100 \times \sum_{i=1}^{n} C_i \times A_i / S_j
\]  

(2)

where \( E_j \) refers to soil erosion intensity index of the \( j \) kind of land use, \( C_i \) refers to the \( i \) grade value of the soil erosion intensity, \( A_i \) refers to the area of \( i \) grade soil erosion intensity in \( j \) kind of land use, \( S_j \) refers to the area of the \( j \) kind land use, \( n \) refers the total grade of soil erosion intensity. The value of \( E_j \) was multiplied 100 times for statistical purposes. The soil erosion intensity was classified into six grades as very low, mild, medium, intense, very intense and severe which were assigned with the values of 1, 2, 3, 4, 5, 6 respectively in which the larger the value, the more intense the soil erosion. Then the response relationship between soil erosion and land use was analyzed quantitatively according to the soil erosion intensity index.

2.5. Validation

To check the performance of the RUSLE model, we set up four 10x5m observing plots, two for dryland and two for grassland, in the study area. Each plot had been set a dam to deposit sediment and to let out water. The field observations were from January to December in 2010 and the sediment was sampled, air-dried and weighed at the end of each season. The annual soil erosion of every plot was totaled from seasonal sediment to test the simulated site data.

2.6. Statistics of soil erosion characteristics

The soil erosion module, the area and percentage of different soil erosion intensity in different land use were obtained with statistic according the land use map and the soil erosion map of study area. Two special land covers, bare rocks and water areas had no soil erosion due to lacking soil on their surface.

3. Results and discussion

3.1. The spatial distribution of soil erosion

The annual soil erosion was classified into very low, mild, medium, intense, very intense and severe erosion grades while soil erosion rates were less than 5, 5-25, 25-50, 50-80, 80-150 and more than 150 t ha a\(^{-1}\) respectively according to the SL 190-2007 standards (Table 1). The soil erosion intensity in the study areas are mainly very low, accounting for 61.9% of the study area. Secondly, mild and medium erosion areas accounted for 19.3% and 12.7% respectively. The intense and very intense erosion areas
were small comparatively and summed to about 6%. The severe erosion areas were few and covered only 2.3 ha in the study area.

Table 1. The statistics of annual soil erosion of study area

| erosion grade | standard for erosion/t.ha.a | erosion area/ha | percentage of erosion area |
|---------------|-----------------------------|-----------------|----------------------------|
| very low      | <5                          | 78057.1         | 61.9                       |
| mild          | 5-25                        | 24322.1         | 19.3                       |
| medium        | 25-50                       | 15983.4         | 12.7                       |
| intense       | 50-80                       | 6901.2          | 5.5                        |
| very intense  | 80-150                      | 792             | 0.6                        |
| severe        | >150                        | 2.3             | 0.0                        |

Figure 1. The soil erosion map

Figure 2. The erosion intensity grade map

The soil erosion (Figure 1) and erosion intensity grading (Figure 2) maps demonstrate that the distribution of soil erosion was different in space in terms of geographical environment and land use. According to statistics, the annual average erosion rate is about 11.3 t/ha, which is a little more than the tolerance level set for the southwest China by the Ministry of Water Resources of China. The total annual erosion quantity is about 142.4 x10^4 tons in the study area. The mass values were under 25 t.ha.a and the maximum erosion rate amounted to 176.4 t.ha.a. Horizontally, the erosion intensity increases from the middle to the surroundings in the study area. Vertically, it increased from the peak of Jinfo Mountain not only to the west but also northeast and southeast. In general, the soil erosion intensity in the east and southeast mountains are mainly mild and medium which are higher than other areas. Conversely, most of the soil erosion intensity in the west and middle region is very low and lower than other areas.

3.2. The analysis of relationship between soil erosion and LULC

Table 2 shows the statistics of annual soil erosion characteristics of different land use. From the soil erosion map, grassland had the highest estimated erosion rate, amounting to 15.7 t.ha.a, followed by the woodland and garden plot which were 12.9 and 12.4 t.ha.a respectively and had fairly high soil erosion rates. Grassland was usually distributed in areas with relatively high slope and low cover levels where the topsoil is easily eroded by runoff. The woods in woodlands are usually mixed conifers and broadleaf trees which grow in the subtropics. With low ground cover, the topsoil in those woodlands was eroded by raindrops from broadleaf on which produce influx. On the other hand, some
of woodlands were returned from slope farmland and planted some young trees with low vegetation cover since projects of returning farmland for forest and grass was enforced by the government in cultured land areas with slope which were more than 25 degree recent years. The returned woodland area amounted to 11775 hm$^2$ from 2000 to 2010 in the study area. As for the garden plots, beside the raindrop conflux erosion from broad leaves of trees, frequent disturbance by cultivation cause the relatively high erosion. This may be the result of human activity such as weeding and fertilization which not only improve the growth of the fruit tree or the tea tree but also decrease the vegetation cover which may cause soil erosion over topsoil. The annual soil erosion module of dryland was 10.3 t·ha·a$^{-1}$ and lower than that of grassland, woodland and garden plot due to low slope and preferable erosion control practice. The erosion rate of dryland in the study area was different from those studied results that dryland had the most erosion rates in Loess Plateau of China [8, 30]. The erosion modules of paddy field and construction land, where the erosion protection control is best in those land use and land cover, is 5.7 and 3.3 t·ha·a$^{-1}$ respectively.

The index of soil erosion intensity $E_j$ showed the impacts of soil erosion by water on different land uses/land cover in the study area. Like the mean soil erosion module, the index of the soil erosion intensity on construction land was 120.5, which was smaller than those on other land uses. The paddy field had a middle erosion intensity index that was 144.6. While the indexes of grassland, garden plot, dryland and woodland were fairly high and amount to 183.9, 183.9, 168.5, and 167.7 respectively. Although having different mean erosion modules, the woodland and dryland had approximate indexes of soil erosion intensity.

| Table. 2 | The soil erosion characteristics of different land use |
|---------|---------------------------------------------------------|
| dryland | paddy field | woodland | garden plot | grassland | construction land |
| erosion rate (t·ha·a$^{-1}$) | 10.3 | 5.7 | 12.9 | 12.4 | 15.7 | 3.3 |
| $E_j$ | 168.5 | 144.6 | 167.7 | 174.0 | 183.9 | 120.5 |
| very low area (hm$^2$) | 7645.9 | 8848.8 | 51495.6 | 1019.9 | 3060.9 | 4496.1 |
| mild area (hm$^2$) | 9912.1 | 5335.1 | 7969.6 | 608.8 | 780.3 | 558.4 |
| medium area (hm$^2$) | 1389.4 | 397.6 | 12230.3 | 390.6 | 1139.2 | 168.3 |
| intense area (hm$^2$) | 107.8 | 127.4 | 5937.7 | 43.1 | 451.1 | 52.3 |
| very intense area (hm$^2$) | 9.3 | 13.3 | 696.3 | 2.4 | 46.2 | 8.0 |
| severe area (hm$^2$) | 0 | 0.1 | 1.9 | 0 | 0 | 0.1 |

In the study area, the erosion intensity of very low and mild accounted for the main area and the intense, very intense and severe intensity were small in the six kinds of land use and land cover. But the proportion of erosion intensity area varies for one land use/land cover. The very low intensity accounted for 40.1%, 60.1%, 65.7%, 49.4%, 55.9% and 85.1% respectively in dryland, paddy field, woodland, garden plot, grassland and construction land. The mild intensity had 52.0%, 36.2%, 10.2%, 29.5%, 14.2% and 10.6% respectively in those types of land use and land cover. Nevertheless, what was noteworthy was that more than half of the dryland had mild erosion intensity. Although the average erosion rate is relatively low in the woodland, garden plot and grassland, the medium intensity took up 15.6%, 18.9% and 20.8% respectively, and the intense class did 7.6%, 2.1% and 8.2% respectively. For those land uses and land cover, the very intense erosion is no more than 1% and the severe intensity areas were hardly any in the study area. For the grassland and woodland, the terrain with escarpment and poor ground cover had led to medium and intense intensity. As for the garden plot, low cover rate and frequent disturbance by cultivation had contributed to the topsoil loss. So those areas in woodland, garden plot and grassland would be the critical ones to prevent soil from water erosion in the study area.
4. Conclusion

The spatial distribution of annual soil erosion by water varied due to the terrain, soil properties, frequency and intensity of rainfall, land cover, land use and its management in the Jinfo Karst Mountain region. Although the annual average erosion is about 11.3 t.ha.a, the maximum erosion rate amounted to 176.4 t.ha.a. The mass values were under 25 t.ha.a, including very low intensity which accounted for 61.9% and mild intensity which accounted for 19.3% of the study area. Medium erosion areas accounted for 12.7%, and intense and very intense erosion areas for about 6%.

The relations between soil erosion and LULC are complicated in the Karst mountainous region. Generally, the ground cover rate, protective measures, and cultivation disturbance had played critical roles in topsoil loss in Jinfo Karst Mountain region. The lower the ground cover rate and the greater the cultivation disturbance, the higher the erosion intensity became in each landscape, and vice versa. In terms of annual erosion rates and indexes of erosion intensity of each land use/land cover, the grassland had the maximum erosion rate and highest index of soil erosion intensity; while there are medium erosion and erosion intensity index for garden plot, woodland and dryland, and low values for paddy field and construction land. It was critical that 52.0% of the dryland was under mild erosion intensity, with 7.3% under medium intensity. What was worth paying more attention to was that there were 15.6%, 18.9% and 20.8% of areas with medium erosion intensity, and 7.6%, 2.1% and 8.2% of intense erosion for woodland, garden land and grassland respectively, although the topsoil erosion rates in most areas with different land use/land cover was under the tolerance level set for the southwestern China by the government. Those areas with relatively high erosion would be the key ones to focus on for prevention of soil loss from water erosion in the study area.

Acknowledgement

The work was financially supported by the Fundamental Research Funds for the Central Universities in China (no. XDJK2014C013). We also thank the two anonymous reviewers for their suggestions.

References

[1] Marques M J, Bienes R, Perez-Rodriguez R, et al. 2008 Soil degradation in Central Spain due to sheet water erosion by low-intensity rainfall events *Earth Surf. Proc. Land* **33** (3) 414 – 423.

[2] Morgan P C 1995 *Soil Erosion and Conservation* Longman, London.

[3] Cerdan O, Le Bissonnais Y, Couturier A, et al. 2002 Modelling interrill erosion in small cultivated catchments *Hydrological Processes* **16** 3215–26.

[4] Bronick C J, Lal R 2005 Soil structure and management: a review *Geoderma* **124** 3–22.

[5] Six J, Elliott E T, Paustian K, Doran J W 1998 Aggregation and soil organic matter accumulation in cultivated and native grassland soils *Soil Science Society of America Journal* **62** 1367–77.

[6] Li R 2011 The research on the process and adjustment of soil erosion in the main water eroded region of China *Bulletin of soil and water conservation* **31**(5) 1-6. In Chinese with English abstract.

[7] Kosmas C, Gerontidis S, Marathianou M 2000 The effect of land use change on soils and vegetation over various lithological formations on Lesvos (Greece) *Catena* **40** 51–68.

[8] Fu B J, Wang Y F, Lu Y H, et al. 2009 The effects of land-use combinations on soil erosion: a case study in the Loess Plateau of China *Progress in Physical Geography* **33** 793–804.

[9] Zhang B, Yang Y S, Zen H 2004 Effect of vegetation restoration on soil and water erosion and nutrient losses of a severely eroded clayey Plinthudult in southeastern China *Catena* **57** 77–90.

[10] Islam K R, Weil R R 2000 Land use effects on soil quality in a tropical forest ecosystem of Bangladesh *Agriculture ecosystems & Environment* **1(79)** 9-16.

[11] Adelia N, Nunes, Antonio C, De Almeida, Celeste O A 2011 Impacts of land use and cover type on runoff and soil erosion in a marginal area of Portugal *Applied Geography* **31** 687-699.
[12] Henry A, Mabit L, Jaramillo R E 2013 Land use effects on erosion and carbon storage of the Rio Chimbo watershed, Ecuador Plant and Soil 1-2(367) 477-491.

[13] Ziadat F M, Taimeh A Y 2013 Effect of rainfall intensity, slope, land use and antecedent soil moisture on soil erosion in an arid environment Land degradation & Development 6(24) 582-590.

[14] Ries J B 1995 Geomorphodynamic processes in the eastern central Himalaya - Consequences of land use and soil erosion for the lowlands Mitteilungen der österreichischen geographischen gesellschaft 137 187-202.

[15] Rodda, Stroud M J, Shankar U 2001 A GIS based approach to modelling the effects of land-use change on soil erosion in New Zealand Soil use and Management 1(17) 30-40.

[16] Panagos Christos, Karydas Cristiano, et al. 2014 Seasonal monitoring of soil erosion at regional scale: An application of the G2 model in Crete focusing on agricultural land uses International Journal of Applied Earth Observation and Geoinformation 4 (27) 147-155.

[17] Sabbi A., Salvati L. 2014 Searching for a downward spiral soil erosion risk, agro-forest landscape and socioeconomic conditions in Italian local communities Land Use Policy 41 388–396.

[18] Fu W L, Zhang Z W, Zhang H, et al. 2007 Study on characteristics of soil erosion on Karst Hillslope J. Soil Water Conserve. 21 38–41. In Chinese with English abstract.

[19] Drew D P 1983 Accelerated soil erosion in a karst area: the Burren Western Ireland. Journal of Hydrology 61 113–124.

[20] Jian P, Yue Q X, Ren Z, et al. 2013 Soil erosion monitoring and its implication in a limestone land suffering from rocky desertification in the Huajiang Canyon, Guizhou, Southwest China Environ Earth Sci 69 831–841.

[21] Yang Q Y, Xie Y Q, Li W J, et al 2014 Assessing soil erosion risk in karst area using fuzzy modeling and method of the analytical hierarchy process Environ Earth Sci 71 287–292.

[22] Calvo-Cases A, Boix-Fayos C, Imeson A C 2003 Runoff generation, sediment movement and soil water behaviour on calcareous (limestone) slopes of some Mediterranean environments in southeast Spain Geomorphology 50 269–291.

[23] Imeson A C, Lavee H, Calvo A, Cerdà A 1998 The erosional response of calcareous soils along a climatological gradient in Southeast Spain Geomorphology 24 3–16.

[24] Kheir R B, Abdallah C, Khawlie A 2008 Assessing soil erosion in Mediterranean karst landscapes of Lebanon using remote sensing and GIS Engineering Geology 99 239–254.

[25] Xiao H, Weng Q 2009 The impact of land use and land cover changes on land surface temperature in Karst area of China Journal of Environmental Management 15 115-121.

[26] Wischmeier W H and Smith D D 1978 Predicting Rainfall Erosion Losses USDA Agricultural Research Services handbook 537, Washington, DC.

[27] Ministry of Water Resources of China 2008 Standards for Classification and Gradation of Soil Erosion. Beijing. In Chinese

[28] Wang S Y, Wang G Q, Chen Z X 2005 Relationship between land use and soil erosion in Yellow River Basin Journal of Natural Disasters 14(1) 32-37.

[29] Yao H R, Cui B S 2006 The effect of Land use and its change on soil erosion of the Lancang River watershed in Yunnan Province Acta Scientiae Circumstantiatis 26(8) 1362 -71.

[30] Li Y K, Ni J, Yang Q K, Li R 2006 Human impacts on soil erosion identified using land-use changes: a case study from the Loess Plateau, China. Physical Geography 27(2) 109 – 126.