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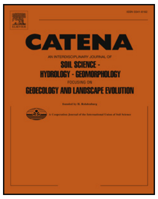

Temporal analysis on quantitative attribution of karst soil erosion: A case study of a peak-cluster depression basin in Southwest China

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ABSTRACT

In karst areas, soil erosion is a significant problem, seriously impeding sustainable socioeconomic development. A thorough understanding and quantitative identification of the influencing factors are essential for soil erosion protection and rocky desertification management. This study identifies the dominant factors (and interactions) influencing soil erosion and its spatiotemporal variability in a karst basin, the Sancha River Basin, China. The geographical detector method was used to conduct the quantitative attribution analysis, based on the modified universal soil loss equation model for karst environments. The results revealed that karst soil erosion exhibited a notable decreasing trend over the past 36 years ($p < 0.01$), decreasing from 16.70 t ha^{-1} a^{-1} in 1980 to 12.22 t ha^{-1} a^{-1} in 2015. The geographical detector results indicated significant differences in the strength of the association between influencing factors (or factor combinations) and karst soil erosion. Land use type was the dominant factor, followed by slope; a combination of land use type and slope was the dominant interaction factor, explaining at least 74% of the karst soil erosion distribution. Land use change dominated karst soil erosion dynamics in the 1980s and 1990s, and rainfall variability dominated in the 2000s. In addition, karst soil erosion showed high spatial heterogeneity, and the strength of the association differed substantially among diverse geomorphological types due to differences in the inner characteristics of each. These findings suggest that the characteristics of different geomorphological types should be considered for effective management and prevention of soil erosion at a regional level, and that steep croplands, especially with slopes higher than 15°, should be prohibited in karst areas. The methodology and framework can be used to better understand the relationships between soil erosion and its influencing factors in karst areas.

1. Introduction

Soil erosion is a global environmental and ecological problem (Borrelli et al., 2017; Martinez-Casasnovas et al., 2016), severely impeding sustainable socioeconomic development (Kefi et al., 2011). On-site and off-site problems related to soil erosion have been observed (Guo et al., 2015), including loss of soil productivity, water pollution, eutrophication and turbidity, flooding, and landslides (Ouyang et al., 2010; Vanacker et al., 2003; Yao et al., 2016). Determining the influencing mechanisms of soil erosion is instrumental for managing this problem. In karst areas, soil erosion is the main factor causing rocky desertification (Wang, 2003), but highly complex geological structures, diverse topography, and humid climates hinder soil erosion control (Tian et al., 2016; Febles-Gonzalez et al., 2012; Feng et al., 2016). Several studies have concentrated on karst soil erosion assessment and the identification of driving forces, including rainfall, terrain, vegetation cover, land use type, soil physical properties, and other factors (Xu and Long, 2005; Yan et al., 2017; Xu and Peng, 2008; Zheng and Wang, 2016). For example, Febles-Gonzalez et al. (2012) noted that soil losses surpassed the permissible erosion threshold in karst regions of Havana, Cuba; Peng and Wang (2012) found that soil loss exhibited significant variation under different rainfall and land use regimes, and; Xiong et al. (2012) confirmed that geomorphology controls soil erosion at a macroscopic scale. Although most studies have identified one or more influencing factors of soil erosion, quantitative attribution analyses of single and multiple interacting factors are lacking. These analyses are an urgent and basic requirement for researchers and policy makers to develop soil protection measures for karst areas.

Understanding the dynamic principles of soil erosion under long-term data series is the basis for its effective control (Irvem et al., 2007;

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Ouyang et al., 2010). Temporal variability in soil erosion may be affected by the compensation effect, which is the alternation of events that transport sediment (source-limited) with those that break down the sediment (transport-limited regimes) (Kim et al., 2016). In addition, the frequency, magnitude, and specific sequence of the driving climatological events increase the uncertainty of erosion estimates (Campbell, 1992). However, few studies have stressed the importance of the temporal scale for soil erosion (Boix-Fayos et al., 2006), and most research has been conducted for only limited periods (< 10 years). In karst areas, most studies have performed investigations of soil erosion evolution with scattered time points (Zeng et al., 2011). For example, Zeng et al. (2017) recently studied the soil erosion evolution in karst geomorphology in southwest China in 2000, 2005, and 2013. However, studies based on discontinuous time series may inaccurately reflect the characteristics of soil erosion change. Hence, dynamic simulations of soil erosion and the identification of the determinants of soil erosion variability are necessary.

Karst soil erosion can be estimated using several methods, such as runoff field monitoring (Peng and Wang, 2012), runoff plot experiments (Dai et al., 2017), isotopic tracing (Bai et al., 2013) and mathematical models (Zeng et al., 2017). Among these methods, models are most appropriate for simulating soil erosion at a relatively large spatial scale. The revised universal soil loss equation (RUSLE), a popular empirical model, has been widely used in low-slope regions as well as for complex topographical landscape units (Sun et al., 2013; Zeng et al., 2017). The RUSLE model has also been used extensively in karst areas, such as southwest China (Chen et al., 2017; Feng et al., 2016; Li et al., 2016) and Cuba (Febles-Gonzalez et al., 2012). However, these applications ignored karst features, including less erodible soil in areas with severe rocky desertification, and erosion-resistant bedrock outcrops, and thus may have overestimated karst soil erosion (Feng et al., 2016; Zeng et al., 2017). Slow soil formation rates and severe soil erosion cause rocky desertification, which is characterized by extensive exposure of basement rocks (Wang et al., 2004). Outcropping bedrock can absorb rainfall after long-term weathering, and reduce the surface runoff velocity (Xiong et al., 2012). Further, underground infiltration and the resistance of outcropping bedrock cause discontinuous overland flow and sediment deposition patterns (Feng et al., 2016). Due to this discontinuity, the slope length (L) factor may be smaller for karst areas than non-karst areas. Hence, the RUSLE model should be calibrated to accurately simulate karst soil erosion by considering outcropping bedrock and rocky desertification.

The goal of this study is to identify the dominant factors influencing soil erosion and temporal variability in karst areas in southwest China. To achieve this goal, we performed the following analyses: (1) calibration of the RUSLE model for karst areas by considering karst rocky desertification, and discontinuous surface runoff caused by outcropping bedrock; (2) quantitative identification of the dominant factors affecting the distribution of soil erosion, and (3) quantitative evaluation of the dominant factors affecting the variability of soil erosion.

2. Methods

2.1. Study area

The study area, the Sancha River Basin (SRB), is located in Guizhou Province, southwest China (Fig. 1), with an area of 4860 km^2. The Sancha River, with a length of 325.6 km, is a first order tributary of the Wujiang River. The basin is characterized by karst peak-cluster depressions, where carbonate is widely distributed. It experiences a subtropical monsoon climate, with rainfall concentrated between May and October, and has an annual mean rainfall of 1100 mm. The changing climate, complex topography, and high levels of human activity make the ecosystem highly fragile. Unsustainable land use combined with the fragility of the ecosystem cause serious rocky desertification, and rocky desertification with thin soil overlying bedrock is a common landscape in this area.

2.2. Data

The RUSLE model requires both environmental and anthropogenic data, including rainfall, a digital elevation model (DEM), a soil dataset, and land use type. Rainfall data from 1980 to 2015 were acquired from the National Meteorological Information Center (http://data.cma.cn). A raster gridded yearly rainfall dataset was interpolated using the ANUSPLIN 4.2 software (Hutchinson, 2001) with data from 28 meteorological stations in the SRB and its surrounding areas. A high-resolution DEM (9 m, Google Earth ver. 6.0.3) was applied to simulate the topographic factor. The soil dataset, including soil type and physical properties at a 1-km spatial resolution, was obtained from the Harmonized World Database ver. 1.1 established by the Food and Agriculture Organization of the United Nations and the International Institute for Applied System Analysis. The data set was provided by the Cold and Arid Regions Sciences Data Center at Lanzhou, China (http://westdc.westgis.ac.cn). Land use data (30-m resolution) for the years 1980, 1990, 1995, 2000, 2005, 2010 and 2015, were provided by the Data Center for Resources and Environmental Sciences, Chinese Academy of Sciences (RESDC) (http://www.resdc.cn). In addition, lithology and geomorphology data were used to explore the power of the determinant for soil erosion from data acquired by the RESDC. The lithology map was classified into ten types (Fig. S1a) and the geomorphology was classified into five types (Fig. S1b, Table S1). Rocky desertification data were provided by the State Forestry Administration (http://www.forestry.gov.cn/).

2.3. Methods

2.3.1. The RUSLE model

The RUSLE model (Renard et al., 1997), revised from the USLE model (Wischmeier and Smith, 1978), has been widely used to simulate soil erosion worldwide, supported by GIS and remote sensing methods. The equation is as follows:

$$A = R \times K \times LS \times C \times P \tag{1}$$

where A is the annual soil erosion module ($\mathrm{t\,ha^{-1}\,a^{-1}}$), R is the rainfall erosivity factor ($\mathrm{MJ\,mm\,ha^{-1}\,h^{-1}\,a^{-1}}$), K is the soil erodibility factor ($\mathrm{t\,hm^{2}\,h\,MJ^{-1}\,mm^{-1}\,hm^{-2}}$), LS is the slope aspect factor, C is the land cover and management factor, and P is the conservation measure factor.

The RUSLE model does not differentiate between the enough erodible soil areas and the less erodible soil areas (serious rocky desertification areas) and thus usually overestimates the results in karst areas, requiring modification to improve its accuracy with regard to less erodible soil in serious rocky desertification areas (Xiong et al., 2012). A previous study showed that increased bedrock bareness results in decreased soil erosion (Wang et al., 2010b). This can be explained by the following factors a) outcropping bedrock with many joints, fissures, and pores can absorb rainwater, especially after long-term weathering (Xiong et al., 2012), and b) bedrock has interception and gathering effects, reducing the velocity of surface runoff (Kheir et al., 2008; Wang et al., 2010b). Dai et al. (2017) studied the relationship between soil erosion and the bedrock bareness rate in a karst area using artificial rainfall simulation tests to simulate the dual hydrological structure with surface bed rock bareness and underground pore fissures (Fig. S2). They found that the coefficient of association (R) between surface sediment and the bedrock bareness rate was -0.076 ($p < 0.01$). Based on this result, we modified the RUSLE model to simulate karst soil erosion using the coefficient of determination (R^2), which measured how well soil erosion might be constructed from bedrock bareness. Therefore, Eq. (1) can be modified as follows:

$$A = (1 - 0.076^2 \times a) \times R \times K \times LS \times C \times P \tag{2}$$

where a is a correctional coefficient. The data were acquired from mean