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Reconstructing recent changes in sediment yields from a typical karst watershed in southwest China

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ABSTRACT

Southwest China is characterized by shallow soils with low soil loss tolerance (30–68 t km^{-2} yr^{-1}), and this region is one of the largest contiguous karst areas in the world, notorious for its highly eroded landscapes. However, reliable information on soil erosion rates in these karst watersheds is limited due to the highly heterogonous landscape. Karst depressions are a unique geomorphologic pattern in southwest China which can trap eroded sediment similar to a reservoir or dam, and may provide a great opportunity for sediment yield estimation if the sediment chronology can be properly determined. This study used karst depression sediment deposits to reconstruct the changes in sediment yields over the past 60 years from a typical karst watershed in southwest China. Three sediment cores were collected from the depression to measure the changes in ^{137}Cs and ^{210}Pb$_{ex}$, clay, silt, and sand contents, and soil organic carbon at different depths. The results indicated that the three common ^{210}Pb$_{ex}$ dating models - Constant Sedimentation (CFCS), Constant Initial Concentration (CIC), and Constant Rate of Supply (CRS) - were not applicable to karst depressions, while a modified CRS model that used ^{137}Cs age marker as reference improved determination of the sediment chronology. From 1949 to 2015, the sediment yields initially increased and then sharply decreased to a low value, which might represent a general trend of soil erosion dynamics in karst watershed of southwest China. It was noteworthy that the mean soil erosion rate after the "Grain for Green" project of 1999 was only 80 t km^{-2} yr^{-1}, which also is greater than the soil loss tolerance in karst regions. This study demonstrates the potential for use of ^{137}Cs and ^{210}Pb$_{ex}$ to evaluate the temporal variation in sediment yield in a typical karst watershed of southwest China and may improve karst watershed management.

1. Introduction

Soil erosion is one of the most serious environmental concerns in the world since it can cause on-site degradation of a natural resource base, and downstream off-site problems such as sedimentation, siltation and eutrophication of water way and enhance flooding (Pimentel et al., 1995; Quinton et al., 2010; Borrelli et al., 2017). As one of the largest contiguous karst areas in the world, southwest China is experiencing severe soil erosion due to its special hydrogeological conditions, low soil loss tolerance, and unsuitable land use (Peng and Wang, 2012; Jiang et al., 2014). In southwest China, a porous rock matrix, fissures, fractures, and a network of solution conduits embedded in karst aquifers create complex hydrogeological conditions, which greatly influence soil erosion (Hartmann et al., 2014; Martin et al., 2016; Li et al., 2017b). This region is characterized by thin soils overlaying highly irregular epikarst surfaces with high infiltration rates (Feng et al., 2014; Li et al., 2017c). Surficial karst processes enlarge carbonate rock fissures, resulting in increased bedrock permeability (Wilcox et al., 2007; Hartmann et al., 2012; Li et al., 2017d). As a result, precipitation drains quickly to soil-epikarst systems through numerous fissures and fractures, and then drains to recharge groundwater systems via the conduits (Dai et al., 2017; Wu et al., 2017). Eroded soils from hillslopes can generally fill in the karst conduits and block the drainage outlets in karst depressions (Zhang et al., 2011; Li et al., 2017c). Due to this highly heterogonous landscape, the soil erosion processes in karst regions are complicated.

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Generally, the carbonate rocks are highly soluble and do not produce much soil (Feng et al., 2014). The mean soil formation rate in karst areas is approximately 11 t km^{-2} yr^{-1}, which is up to 100 times less than the purple soil in the non-karst areas of southwest China (Jiang et al., 2014). This low soil formation rate in karst areas is mainly due to the low concentrations of insoluble components in carbonate rock, especially limestone (Li et al., 2017a). In pure carbonate rocks, it would require 2000–8000 years to form 1 cm soil by dissolving 25 m thick of carbonate rocks (Jiang et al., 2014; Li et al., 2016). These low soil formation rates from the carbonate bedrocks had led some studies to suggest that the soil loss tolerance of the karst areas is only 30–68 t km^{-2} yr^{-1} (Peng and Wang, 2012). It will be extremely difficult to recover the soil layer in this karst area once the soil is lost.

With the economic development and population growth, land use practices such as deforestation, over-grazing, and farming activities are commonly occurring in karst areas of southwest China, especially in hillslopes with shallow soil layers (Peng and Wang, 2012; Jiang et al., 2014). These areas have relatively steep terrains, with the slopes of most watersheds areas measuring 25° or more (Li et al., 2010). The unfavorable land use practices, steep slopes, and abundant rainfall cause severe soil erosion (Li et al., 2016). In 1999, the Chinese government realized the seriousness of this issue and began to implement the “Grain for Green” scheme to achieve sustainable development of the socio-economic environment by controlling soil erosion and restoring the disturbed ecosystem (Wang et al., 2016; Yang et al., 2017). A reliable evaluation of recent changes in soil erosion rates is of paramount importance to effectively control soil loss and reasonably manage watersheds.

The fallout radionuclides ^{137}Cs and $^{210}Pb_{ex}$ have been widely used as chronometers of recent deposits to assess the soil erosion rates in reservoirs, lakes, rivers, floodplains, estuaries, and deltas (Ritchie et al., 1975; Appleby et al., 1979; Walling and He, 1997; Albrecht et al., 1998; Ambers, 2001; Terry et al., 2002; Ritchie et al., 2004; Mabit et al., 2008; Du and Walling, 2012; Mabit et al., 2014; Zhang et al., 2015; Zhao et al., 2015; Zhang et al., 2017). ^{137}Cs and $^{210}Pb_{ex}$, however, are unsuitable to evaluate surface soil erosion on carbonate rock hillslopes in karst regions (Zhang et al., 2011). This because ^{137}Cs is absorbed by soil particles rather than by rocks (Walling and He, 1997; Zhang, 2015). Large areas of bare bedrock, discontinuous soil cover, variable soil depth, and varying proportions of gravel results in strong heterogeneity of the soils on karst slopes. Consequently, the classical ^{137}Cs method is unsuitable for investigating the soil erosion in carbonate rock hillslopes in karst areas.

The most typical landscape found in southwest China is the peak-cluster depressions of similar dimensions with overlapping steep hills and ridges surrounding a flat center (Fig. 1) (Feng et al., 2014; Li et al., 2017b). The area of the karst depression ranges from less than 1 ha to several hundred hectares. One or more sinkholes generally exist at the bottom of the depressions (Zhang et al., 2011). The bottoms of some depressions are frequently inundated after rainstorm when the runoff from the contributing watershed cannot quickly drain through the sinkholes, or the sinkholes are filled with sediment (Jiang et al., 2014). This waterlogging results in the transportation of eroded sediment from the surrounding hillslopes by runoff being deposited in karst depressions during rainstorms (Li et al., 2010). Similar to lake sediments, karst depression deposits can provide records of the long-term history of environmental changes (Bai et al., 2013). This makes these depressions a good test for the use ^{137}Cs and $^{210}Pb_{ex}$ techniques for dating sediment yield. Little quantitative research has focused on dating the deposited sediments in karst depressions where the soil erosion process is complicated. Previous studies have estimated the mean soil erosion rate since 1963 or 1979 by dating the ^{137}Cs distribution depths of cores collected from karst depressions (Li et al., 2010; Bai et al., 2013; Feng et al., 2016). However, changes in soil erosion rates in karst depressions in recent years are unknown, which hampers the development of effective regional soil conservation policies for karst watersheds.

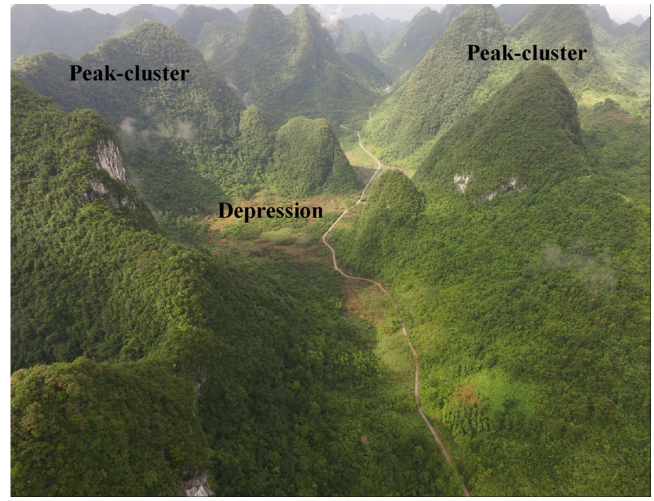

Fig. 1. Typical landscape of karst peak-cluster depression in southwest China.

Therefore, the objectives of this study were to investigate the recent changes in sediment yield for a small karst watershed in southwest China over the past 60 years using depression deposits, and to identify the factors affecting recent temporal patterns in soil erosion. To the best of our knowledge, this maybe the first research to evaluate the temporal variation in sediment yield in karst depressions, and we hope it will provide valuable information to improve soil erosion control in this region.

2. Study area

Experiments were carried out in the Guzhou watershed (24°53′–24°56′ N, 107°55′–107°58′ E). The watershed is in Huanjiang county, Guangxi province, southwest China, near the Huanjiang Observation and Research Station for Karst Ecosystems of the Institute of Subtropical Agriculture, Chinese Academy of Sciences (Fig. 2). This area is located in a subtropical mountainous monsoon climate with the mean annual temperature of 18.5 °C. The mean annual precipitation is 1389 mm and about 70% to 80% of the rain falls between April and September. The watershed has an altitude between 375 m and 816 m with a total area of 1.87 km^2. The Guzhou watershed is composed of a flat depression in the center surrounded by a series of hillslopes. The calcareous soils are mainly derived from limestone containing significant amounts of rock fragments. The soil have an average depth of 10–30 cm on the hillslopes, and about 100 cm in the depression. More than 70% of hillslopes have a gradient greater than 25° and the soil is discontinuous except at the foot of the hillslopes. On the hillslopes, there is a long history of cultivation, which may have contributed soil loss. Due to the inconvenient transportation, and land shortage coupled with serious soil erosion, this area has been designated a national emigration area and the west “Grain for Green” project area since 1999. Thus, the cultivated areas on the hillslope were converted to trees, grass, or natural vegetation restoration to reduce soil erosion and improve soil quality.

The depression, with an area of 0.17 km^2, is mainly covered by crops (corn and soybean), forage grassland (hybrid Napiergrass Guimu-1), and forest (*Zenia insignis* Chun). Due to high groundwater levels and poor drainage capacity of the underground porosities and pipelines, waterlogging generally occurred in the depression during the wet season. In most cases, water detention time was two or three days, or longer, and almost all sediments were deposited in the depression. For example, when an extreme rainfall occurred in 2016, the depression was flooded for more than 10 days (Fig. S1).