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Acid deposition strongly influenced element fluxes in a forested karst watershed in the upper Yangtze River region, China

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ABSTRACT

The hydrological fluxes and associated element input–output budgets were investigated from July 2007 to August 2008 in a forested karst watershed in Guizhou, southwest China. Banning logging in the watershed (mountain closure) has been in practice as an effort to reduce soil erosion and its impact to Yangtze River. The watershed lies in an area heavily affected by acid deposition. Therefore, specific objective of this study was to investigate the impact of acid deposition on elemental fluxes in the forested karst watershed. Weekly bulk precipitation, throughfall, and stemflow samples were collected from two forest plots. Volume and chemistry of streamflow out of the watershed were continuously monitored to determine the concentration and fluxes of elements. The bulk precipitation had low pH value of 4.8 as annual volume-weighted mean and high SO_4^{2-}-S and Ca^{2+} concentrations. Concentrations of elements were higher in throughfall or stemflow than the bulk precipitation. Forested karst watershed had low streamflow but high water discharge through deep seepage, occupying 4.0% and 40.4% of the annual bulk precipitation, representatively. Streamflow had high and constant pH value of 8.3 as annual mean, and was dominated by Ca^{2+} and Mg^{2+}. The annual net input of SO_4^{2-}-S into the watershed was greater than 40 kg S ha^{-1} year^{-1}. The strikingly high rate of output of Ca^{2+} and Mg^{2+}, greater than 250 kg ha^{-1} year^{-1} and 150 kg ha^{-1} year^{-1}, representatively, reflected the fast weathering of carbonaceous rocks, and the strong neutralizing capacity of weathering to acid deposition in the karst watershed. This research indicates that acid deposition strongly influenced the export of nutrients out of the karst watershed and can accelerate transformation of the local land form.

1. Introduction

Karst covers about 550,000 km^2 of the land area in the upper Yangtze River region in southwest China and occupies over 74% of Guizhou Province (Piao et al., 2000; Zhang et al., 2006). Banning logging in watersheds (mountain closure) that supply water to the Yangtze River was considered an effective way for natural forest restoration (Xue and Fang, 2002), and thus, has been in practice since the launch of the "Natural Forest Protection Program" and the "Grain for Green Project" (a State campaign to restore an ecological balance by turning the low-yielding farmland back into forests and pasture) in China (Liu and Diamond, 2005; Liu et al., 2008). This practice resulted in rapid expansion of secondary forests in the karst area in the upper Yangtze River region.

Understanding the impact of mountain closure on forested watersheds is critical in guiding future policy development. Past studies focused mostly on forest policy, desertification, and vegetation succession after mountain closure in the karst region (Liu and Diamond, 2005; Liu et al., 2008; Wang et al., 2004; Yu et al., 2002). Forest ecosystems in the karst region have been shown to be fragile due to the generally shallow soil layer and the impoverishment in soil fertility (Wang, 2002; Yuan, 1997). Unfortunately, there is limited information on tree growth and nutrient cycling in relation to restoration of the forest ecosystems in the karst region. It remains unclear whether the forest ecosystems can be successfully reestablished solely by natural processes following mountain closure.

In forest ecosystems, nutrient elements are moved by meteorological, geological, and biological vectors from inputs to outputs (Bormann and Likens, 1967; Likens and Bormann, 1995). Throughout those processes, water plays vital roles as the chemical solvent and transporting agent. Therefore water fluxes in watersheds are closely associated with the development and sustainability of vegetation in terms of nutrient dynamics and budgets (Sanchez, 1977). In North America and Europe, the watershed approach has been

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frequently used to evaluate the biogeochemistry of forests, including assessment of element cycling, nutrient losses and the effects of anthropogenic interferences on forests (Likens and Bormann, 1995; Moldan and Černŷ, 1994). In south-western China, including Guizhou Province, high acid deposition has been documented in several publications (Larssen et al., 1998; Xiao and Liu, 2004). Previous studies revealed that there was a wide range of soil pH (from 4.1 to 7.9) in the forested karst region in Guizhou Province (Tian et al., 2008). The observed variation in soil pH was attributed to the different mixing ratios of the weathering residues of carbonaceous rocks and sandy rocks or shale components in different soils, and also to the sensitivity of different soils to acid deposition (Tian et al., 2008).

In this study, watershed approach was employed to evaluate the role of various components of elemental cycles in element deposition and input–output budgets, and to investigate the effects of acid deposition on elemental fluxes in the karst region. Specific objectives were (1) to quantify hydrological processes and fluxes of elements through water cycling, and (2) to evaluate how elemental cycling was affected by acid deposition in a forested watershed after mountain closure in the karst region in Guizhou Province, in southwest China.

2. Materials and methods

2.1. Site description

The study was carried out at the Karst Forest Ecosystem Research Center (26°48′N, 106°45′E), located near Hefeng Village, Kaiyang County, which is about 55 km northeast of Guiyang City, the capital of Guizhou Province in southwest China (Fig. 1). The Center belongs to the Guizhou Academy of Forestry. The 148.3 ha watershed we studied was located in the lower part of the research center, with elevation ranging from 921 to 1385 m above sea level. The area is dominated by a subtropical mountainous monsoon climate with a mean annual air temperature of 12.8 °C. The dominant base rocks are dolomite and limestone, and the main soil type belongs to Mountainous Yellow Soil in the Chinese system of soil classification. The soil was generally shallow with average depth of less than 50 cm but varies markedly in depth in relation to the topography. Soil pH in the watershed ranged widely from 4.1 to 7.9, and soil exchangeable Ca^{2+} and Mg^{2+} decreased and exchangeable Al^{3+} increased exponentially with increasing soil acidity (Tian et al., 2008).

The original forest vegetation in this area belonged to subtropical mixed evergreen and deciduous broadleaf forests with dominant tree species belonging to the *Juglandaceae*, *Lauraceae*, *Fagaceae*, *Ulmaceae*, *Rutaceae*, and *Sapindaceae* families (Zhu and Wei, 1993). However, due to the intensive cultivation and excessive firewood gathering as a result of the rapid increase in population since the 1960s, the original vegetation cover had been seriously deteriorated and altered (Wang, 2002). The vegetation had largely been replaced by naturally-regenerated secondary forests since the enforcement of mountain closure, which prevented the forests from anthropogenic disturbance. The mountain closure was enforced by the government after the colossal 1998 flood in the Yangtze River watershed to prevent similar disaster from occurring. The dominant tree species in the naturally-regenerated secondary forests include *Quercus fabric*, *Liquidambar formosana*, *Pinus massoniana*, *Populus adenopoda*, *Ulmus pumila*, *Carpinus pubescens*, *Castanopsis fargesii*, *C. camphora*, and *Platycarya strobilacea*.

2.2. Monitoring and sampling

The soil water-holding capacity was investigated in five representative 20 × 20 m plots established in the watershed in August 2007 (Fig. 1). The plots were selected depending on the landform, position, and also the vegetation characteristics. The details of the 5 plots were described in Table 1. Three soil profiles at randomly selected locations in each plot were excavated and soil cores (100 cm^3 in volume) were taken from the 0–10, 10–20, and 20–30 cm soil layers. Soil water-holding capacity was determined using the centrifuge method (Klute, 1986; Reatto et al., 2008). The soil cores were first saturated for 24 h and then submitted to a high speed centrifuge (Kokusan Corp., Japan) to sequentially dewater to a water potential of −6.4 kPa (field capacity) and to −1500 kPa (permanent wilting point) under a constant temperature of 20 °C. The gravimetric water contents at −6.4 and −1500 kPa water potentials were determined and the soil water-holding capacity was calculated as the difference.

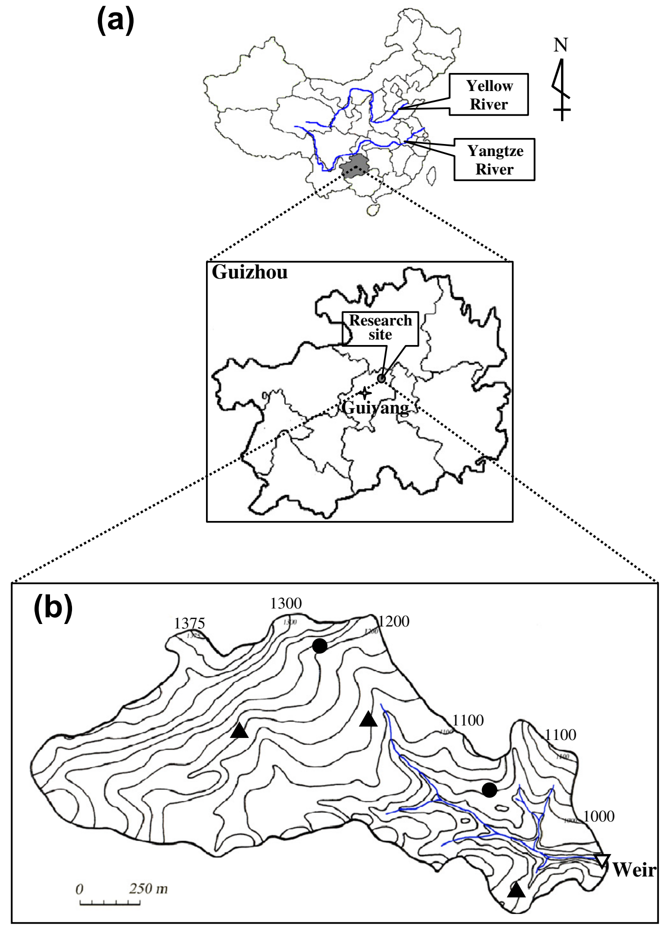

Fig. 1. (a) An illustration of the location of the study site in Guizhou Province, China; and (b) the watershed and the illustration of the study plots. The *solid circles* are the plots for hydrology and nutrients fluxes study, and both the *solid circles* and *triangles* are the plots for soil water-holding capacity measurement. The *open triangle* is the location of the weir.

The measurement and sampling of bulk precipitation, throughfall, and stemflow were carried out weekly between July 2007 and August 2008 in two of the five plots representative of the forest type, based on the vegetation composition (Fig. 1). Triplicate throughfall and stemflow collectors were set up in each of the two plots. Double replications of bulk precipitation samples for each of the two plots were collected in the open area, without any cover from above or surrounding, about 200 m away from the forests. Polyethylene funnels (30 cm in diameter) placed 1 m above the ground were used to collect the bulk precipitation and throughfall samples. A nylon mesh was placed in each funnel to prevent debris from falling into the water sample collector. Water