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Variations in soil phosphorus biogeochemistry across six vegetation types along an altitudinal gradient in SW China

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ABSTRACT

The impacts and relative importance of temperature, precipitation, lithology, soil properties, vegetation type and microbial activity on soil P biogeochemistry along altitudinal gradients are poorly understood. Our aim is to reveal the variations and main driving factors governing soil P forms across six different vegetation types along an altitudinal gradient (2032–4235 m asl) on Mt. Gongga, southwest China. Soil P forms were measured using a sequential fractionation technique. The results showed that the spatial distributions of total P and organic P clearly exhibited altitudinal variations along the gradient. The total P stocks in the 3838–4235 m zones were significantly higher than those in the 2032–3614 m zones. This pattern is likely influenced by climate, soil erosion, total P content in the parent material and vegetation type. Unlike the total P stock, the concentrations and stocks of available P in the surface soils showed a parabolic pattern with altitude, with maximums at the 3060 m site and minimums at the lowest site. The Ca-Pi concentrations (extracted by 1 M HCl solutions) displayed a spatial pattern opposite to that of the available P. The NaOH-Pi concentrations changed little with altitude and accounted for a small part of the total P. The Ca-Pi represented the largest part of the total P at the 2032 m site and in the alpine zones, whereas the organic P contributed the largest portion of total P in the sub-alpine zones. A redundancy analysis showed that the general spatial pattern of all the P forms was mainly related to soil pH, vegetation and soil organic matter. In particular, the soil pH, which was mainly controlled by vegetation type and precipitation, significantly influenced the altitudinal pattern of Ca-Pi. The effect of soil pH, perhaps coupled with the amount of P returned by litter production, is a crucial factor in the parabolic pattern of available P between 2032 and 4235 m asl. Furthermore, in the 3060–4235 m zone, temperature becomes an additional important factor governing the pattern of available P due to its influence on litter decomposition rates. These results emphasize the central role of vegetation in regulating soil P biogeochemistry along the altitudinal gradient by affecting soil properties and litter production.

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1. Introduction

The understanding of soil phosphorus (P) processes is essential for maintaining sustainable development of mountain ecosystems (Wu et al., 2013a). While most studies on P regimes along altitudinal gradients consider the impact of P on vegetation, the opposite direction (e.g., influences of vegetation on soil P) is poorly understood (Lucas-Borja et al., 2012; Ushio et al., 2010). Soil P bioavailability in natural ecosystems is often simultaneously impacted by lithology (Mage and Porder, 2013), climate (Vincent et al., 2014), soil age (Zhou et al., 2013a), soil properties (Turner and Blackwell, 2013), and biological activity (Richardson et al., 2011). However, most previous studies have focused mainly on one single factor impacting P bioavailability. For example, chronosequences and climosequences have often been used to discuss the influences of soil age (Walker and Syers, 1976) and rainfall (Miller et al., 2001) on biogeochemical P cycling, respectively. Recently, some researchers have noted the need to investigate the interactions (Porder and Chadwick, 2009) and determine the relative importance (Mage and Porder, 2013) of these factors in order to understand P cycling in terrestrial ecosystems. Furthermore, to predict the P status of ecosystems regionally or even globally and to adequately represent P bioavailability in global biogeochemistry-climate models, the relative importance of the impact factors and their synergistic effects on P biogeochemistry should be explored comprehensively (Yang et al., 2013). The vertical vegetation and soil zones on high mountains provide an opportunity for determining the relative importance of the influences of lithology, climate, soil properties, vegetation, and their interactions on the biogeochemical P cycles in natural ecosystems.

There are two important theories that are suitable for explaining variations in soil P bioavailability along altitudinal gradients with similar bedrocks. The first theory is that the soil P bioavailability will decrease with increasing elevation because the decomposition rates of organic P will be reduced due to the decrease in temperature. For example, Vitousek et al. (1988) reported a decreasing trend in available P

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concentration with increasing elevation in a Hawaiian montane rainforest (760–1585 m asl). In a tropical montane forest in Ecuador, Soethe et al. (2008) also observed that the P availability in the organic horizon decreased with increasing elevation (1900–3000 m asl). Moreover, Vincent et al. (2014) found that the available P concentration decreased upslope in a subarctic tundra landscape (500–1000 m asl).

The second theory is the conceptual model of P evolution with pedogenesis proposed by Walker and Syers (1976). According to this model, the soil P bioavailability will decrease with increasing weathering intensity (and thus soil development) because large amounts of available P can be transformed into occluded P and organic P in more developed soils. Therefore, the available P in soils is speculated to decrease downslope as a result of increasing weathering intensity due to the increasing temperature and more developed vegetation.

Mt. Gongga in southwestern China provides an ideal place for examining P biogeochemical cycles across different climates and vegetation types. On the eastern slope of Mt. Gongga, there is an altitudinal difference of 6600 m and, thus, a large temperature and precipitation gradient (Zhong et al., 1999). Seven vegetation zones are distributed between the alpine frigid meadow to the evergreen broad-leaved forest on the slope (Liu and Qiu, 1986). The soil P bioavailability on Mt. Gongga will decrease with altitude according to the first theory but increase with altitude according to the second one. If the effects of vegetation types are considered, the spatial pattern of the P bioavailability along this slope is likely more difficult to predict. For example, a recent study suggested that changes in temperature significantly influenced PO_4^{3-}–P concentrations in a subarctic region, but the effects of temperature depended strongly on the dominant vegetation type (Sundqvist et al., 2014).

Here, in combination with the relevant geochemical and biological factors, the forms and stocks of soil P were investigated using a modified Hedley fractionation technique (Tiessen and Moir, 1993) on Mt. Gongga. In particular, the aims of the study are the following:

(1) Revealing the spatial distribution of the soil P bioavailability and forms along the altitudinal zones on Mt. Gongga.
(2) Because the variations in soil P biogeochemistry along the altitudinal slope are likely influenced by temperature, precipitation, soil properties, vegetation type and microbial activities, the second goal is to identify the main driving factors among these potential factors.

2. Materials and methods

2.1. Study area

Mt. Gongga is located in southwestern China at the southeastern edge of the Tibetan Plateau and has an elevation of 7556 m (Fig. S1). The area within 29 km of Mt. Gongga has a total topographic relief of 6600 m because it is located in the transition zone between the Tibetan Plateau and the Sichuan Basin. Due to this huge altitudinal difference and its distance from cities, there are seven pristine altitudinal vegetation zones on the eastern slope of Mt. Gongga (Fig. 1). The climate of the eastern slope of Mt. Gongga is controlled by the Eastern Asian Monsoon. The parent rocks in the study area are mostly derived from glacial deposits and are mainly composed of granitoids (Yu, 1984). The soil types at different altitudes were classified according to the China soil classification system (Yu, 1984), as shown in Fig. 1.

Two observation stations (at 3000 and 1600 m asl) were established by the Institute of Mountain Hazards and Environment, Chinese Academy of Sciences on the eastern slope of Mt. Gongga in 1988 and 1992, respectively (Fig. S1).

2.2. Sampling

Seven altitudes (low altitude: 2032 (S1) and 2362 (S2) m asl, subalpine zone: 2772 (S3), 3060 (S4) and 3614 (S5) m asl, alpine zone: 3838 (S6) and 4235 (S7) m asl) were selected for sampling (Fig. S1, 1, Table 1). Five pits with a distance of >50 m from each other were dug at each altitude in July 2011 (Fig. S1, Table 1). The locations of these pits were on gentle slopes and under canopies of the dominant plants. Samples were collected from the walls of the approximately 0.5 m wide soil pits dug with a hand spade to the depth to which it was manually possible. These soil profiles were divided into the four horizons O, A, B and C (Table 1). One- to two-kilogram soil samples were collected hierarchically from the C to the O horizon. Soil samples from the A horizon were individually collected to measure the C, N and P of the microbial biomass (Mb-C, Mb-N and Mb-P). At each altitude, one profile was selected to collect samples for bulk density measurements. The soil bulk density of the O and A horizons was measured by excavating pits with a certain volume. The volume of the excavated soil could be measured by backfilling with a known volume of water (Maynard and Curran, 2006). The bulk density of the B and C horizons was measured using the cylin-

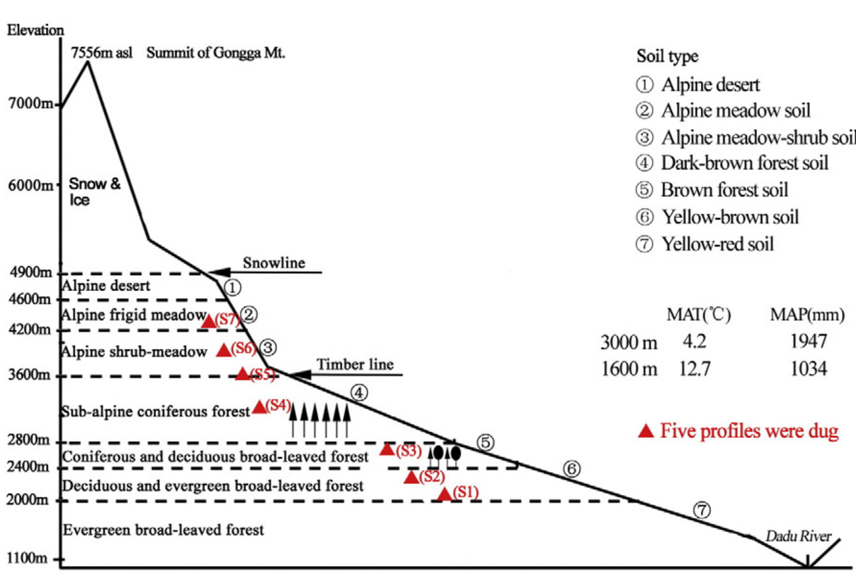

Fig. 1. Altitudinal zonation of vegetation type, soil type, temperature and precipitation with altitude on the eastern slope of Mt. Gongga, SW China (modified from Zhong et al., 1999).

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