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Soil sulfur content and its spatial distribution in a small catchment covered by volcanic soil in the montane zone of central Japan

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ABSTRACT

High concentrations of organic C and Al/Fe oxides, and low bulk density are responsible for the accumulation of large amounts of S compounds in volcanic soils. The purpose of our study was to clarify the spatial distribution of S compounds and determine the factors governing that distribution within the Katsura Headwater Catchment, a small drainage basin covered by volcanic soil in a mountainous area of the North Kanto district, central Japan. Geostatistical analysis revealed a strong spatial dependence of total S concentration throughout the catchment area. Total S concentrations were higher on upper slopes than on lower slopes, and higher in deeper soils (20–50 cm depth) than in surface soils (0–20 cm depth). Our analyses also revealed similar spatial variations of the characteristic pedogenic volcanic minerals properties (i.e., concentrations of oxalate extractable Al, Fe, and Si), total C concentrations, and bulk density. The strong relationships of total S with the pedogenic mineral properties indicate that the accumulation of S in the soils is governed predominantly by the abundance of those pedogenic minerals, and that the influence of volcanic ash as a parent material is reflected more strongly in residual soils than in colluvial soils. Because the total S concentrations of the residual and colluvial soils differ, so too do the S pools in the uppermost 50 cm of these soils: residual soils retain larger amounts of S (2030 ± 590 kg S ha^{-1} on average) than colluvial soils (1400 ± 590 kg S ha^{-1} on average). Our results indicate that volcanic ash that remains in situ on the upper slopes of the small Katsura Headwater Catchment contributes strongly to the accumulation and spatial variation of S. Total C inputs from plant communities might also influence S accumulation, particularly in surface soils.
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1. Introduction

Volcanic soils are found in many Asian countries, particularly within the circum-Pacific volcanic belt. Their unique chemical and physical properties (i.e., high concentrations of organic C, Al/Fe oxides, and short-range ordered minerals and low bulk density) (Shoji et al., 1993) have been reported to contribute to S retention. Strong correlations between sulfate adsorption capacity and Al/Fe oxides, allophane, and imogolite in soils have been observed in many studies (e.g., Kimsey et al., 2011; Strahm and Harrison, 2007). The retention of large amounts of occluded sulfates in volcanic soils (Andisols) near an active volcano has been associated with the presence of ferrihydrite (Delfosse et al., 2005a; Delmelle et al., 2003). Furthermore, the presence of large quantities of Al/Fe-humus complexes in humic horizons in volcanic soils in Japan has resulted in the highest accumulations of organic C among mineral soils worldwide (Nanzyo et al., 1993). According to Tanikawa et al. (2009), large amounts of organic S have accumulated in volcanic soils in Japan, and 40% of that S is in an Al-associated form. Therefore, volcanic soils have a high capacity for retention of S in both inorganic and organic forms.

In hilly and mountainous areas of volcanic regions, volcanic ash deposited on flat terrains (e.g., mountain ridges) and on the upper parts of gentle slopes commonly remains in situ, whereas less volcanic ash is retained on the lower slopes, particularly where slopes are steep (Matsui et al., 1990). Thus, the unique chemical and physical properties of volcanic soils are more prominent in areas where deposits of volcanic ash remain, and the distribution of such soils and their accumulated S is dependent on topography.

Traditionally, the influence of topography on soil properties is described by the catena concept (Bushnell, 1942; Ellis, 1932). Several catenary sequences of soils have been studied to assess the effect of a narrow environmental gradient of climate, vegetation, and landscape position on spatial variations of soil S components (Huang

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and Schoenau, 1996; Roberts and Bettany, 1985). Recently, a geostatistical approach was used to describe the variability of particular soil properties and to analyze their spatial distributions (e.g., Goovaerts, 1999; Heuvelink and Webster, 2001). At the catchment scale, this approach is effective because soil properties can change continuously in response to multiple and successional environmental influences within a catchment (Yamashita et al., 2011). A quantitative description of soil S distribution at the catchment scale may be useful for clarifying S dynamics in a forested catchment and for evaluation of the part played by S accumulation in mitigation of soil acidification. To date, no published studies have used a geostatistical approach to determine the spatial distribution of soil S components within a forested catchment.

The aim of our study was to examine the spatial variations of total S concentration in the Katsura Headwater Catchment (KHC), a small drainage basin in the North Kanto district of central Japan, and to determine the factors that control the accumulation of S within the catchment. For our study, we considered $Al_o + 1/2Fe_o$, total C concentration, and bulk density as the key representative properties of volcanic soils. The reasons why we chose these properties are that $Al_o + 1/2Fe_o$ concentration and bulk density are used to identify andic soils (Soil Survey Staff, 2010), and that volcanic soils contain the highest level of organic C content in the world (Batjes, 1996). On the basis of past research, we hypothesize that the spatial variation of total S concentration in the KHC is controlled by these properties of volcanic soils, both in surface soils and deeper soils; that topographic position influences the amount of volcanic ash incorporated in the soils; and that the influence of the input of organic C from fresh litter on the variations of total S concentration is greater for surface soils than for deeper soils.

2. Materials and method

2.1. Study site and soil sampling

The KHC lies about 120 km northeast of Tokyo (lat 36°32′N, long 140°18′E; elevation 210–270 m). Data from the nearest weather station (AMeDAS Kasama station, Japan Meteorological Agency) indicate a mean annual temperature of 13.1 °C and mean annual precipitation of 1330 mm. The catchment covers an area of 2.3 ha within which a thick volcanic ash soil overlies consolidated Mesozoic shale and sandstone. Regional and widespread tephra have been deposited as a result of cataclysmic volcanic eruptions during the late Pleistocene and Holocene (Table 1). The catchment is a steep-walled (>30°) valley with gentler upper slopes (Fig. 1). The lowermost 1.0 ha of the KHC is covered by 40-year-old *Cryptomeria japonica* D. Don forest. The middle and upper slopes are covered by deciduous broad-leaved forest dominated by species of the Betulaceae (birch) and Fagaceae (beech) families. The soil has been classified as a Brown Forest Soil (Forest Soil Division, 1976) and as a Cambisol (FAO-UNESCO, 1990).

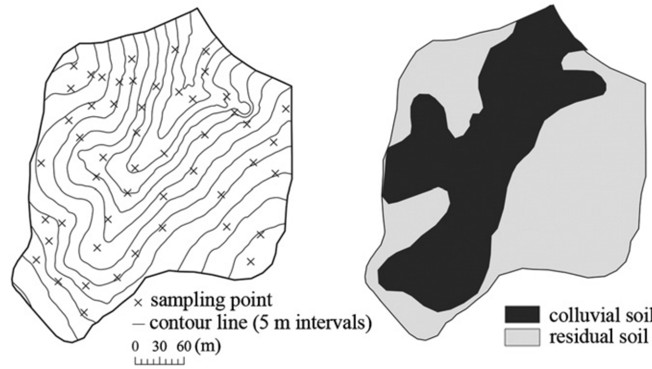

Fig. 1. Topographic map of the KHC showing sampling points (a) and distribution of soil types (b; modified from Ohnuki, 2003).

We used a 4.7-cm-diameter liner sampler (Daiki, DIK-110B, Tokyo, Japan) to collect 51 soil cores, each to a depth of 50 cm. We refer here to the upper 20 cm of the cores as “surface soils” and to the lower 30 cm as “deeper soils.” Core locations were chosen to sample representative microtopographic units.

Soils above the convex break of slope (the upper slopes) are 0.5–6 m thick, with the thickness varying with topography; these soils showed low resistance during penetration tests, indicating that they contain no gravel and are derived from volcanic ash without mixing with weathered shale and sandstone (Y. Ohnuki, personal communication, 2012) (Fig. 2). At some locations on the upper slopes, a 20-cm-thick layer of orange pumice (Nt-S, 14–15 ka, Table 1) has been identified at depths of 1–2 m during previous soil investigations (Y. Ohnuki, personal communication, 2012), indicating that the volcanic ash soil above this layer was formed after 14–15 ka. We did not sample the shale and sandstone underlying the volcanic ash soils on the upper slopes.

In contrast, soils on the steeper, lower slopes (below the convex slope break) were deposited mostly by gravity and overland flow. They comprise thoroughly mixed soils derived from both volcanic ash and the underlying shale and sandstone (Fig. 2). The thickness of these soils (0.1–6 m) varies with topography. The uppermost 50 cm of the soils on the lower slopes contains much gravel, which generated high resistance during penetration tests (Y. Ohnuki, personal communication, 2012). A few samples of deeper soils on the lower slopes contained a layer of well-weathered shale and sandstone representing a C horizon, which was not encountered in the deeper soils of the upper slopes.

We defined the soils on the upper slopes as residual soil and those on the lower slopes as colluvial soil and applied these definitions to both the surface soils (0–20 cm) and the deeper soils (20–50 cm).

For determination of fine soil bulk density, samples were oven dried (105 °C) and sieved (2-mm mesh) to exclude gravel and

Table 1
Tephras of late Pleistocene to Holocene age in the North Kanto district (Machida and Arai, 2003).

Tephra ID	Thickness (cm)	Cataclysmic eruption (ka)	Volcano	Tephra category (regional/widespread)	Geological age
Hr-FA	>0	1.5	Mt. Haruna	Regional	Holocene
K-Ah	>0	7.3	Kikai caldera	Widespread[a]	Holocene
Nt-S[b]	20	14–15	Mt. Nantai	Regional	Late Pleistocene
AT	10–20	26–29	Aira caldera	Widespread[a]	Late Pleistocene
Ag-KP	40–100	>45	Mt. Akagi	Regional	Late Pleistocene
DKP	0–5	55	Mt. Daisen	Widespread[a]	Late Pleistocene
Ag-Mz1	5–10	55–60	Mt. Akagi	Regional	Late Pleistocene
Aso-4	>15	85–90	Aso caldera	Widespread[a]	Late Pleistocene
K-Tz	2–5	95	Kikai caldera	Widespread[a]	Late Pleistocene
On-Pm1	>0	100	Mt. Ontake	Widespread[a]	Late Pleistocene

[a] Widespread means deposited over almost all of Japan.
[b] Nt-S layer (~20 cm thick) was observed at 1.0–2.0 m depth at some sampling points.

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