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Characteristics of pristine volcanic materials: Beneficial and harmful effects and their management for restoration of agroecosystem

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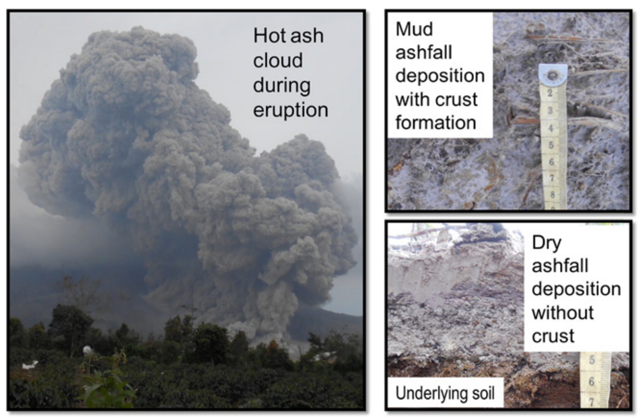
HIGHLIGHT

- Volcanic ashfall damages agroecosystem but potentially enriches soil nutrients
- Pristine ashfall decreases soil pH and cation exchange capacity, and increases Al
- Mud-ashfall generates encrustation on the soil surfaces but not for dry-ashfall
- Gypsum acts as a cementing agent of hard surface crust
- Agroecosystem restoration should apply lime and disrupt surface encrustation

GRAPHICAL ABSTRACT



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ABSTRACT

Eruption of Sinabung volcano in Indonesia began again in 2010 after resting for 1200 years. The volcano is daily emitting ash and pyroclastic materials since September 2013 to the present, damaging agroecosystems and costing for management restoration. The objective of the study was to assess properties and impacts of pristine volcanic material depositions on soil properties and to provide management options for restoring the affected agroecosytem. Land satellite imagery was used for field studies to observe the distribution, thickness and properties of ashfall deposition. The pristine ashfall deposits and the underlying soils were sampled for mineralogical, soluble salt, chemical, physical and toxic compound analyses. Results showed that uneven distribution of rainfall at the time of violent eruption caused the areas receiving mud ashfall developed surface encrustation, which was not occur in areas receiving dry ashfall. Ashfall damaged the agroecosytem by burning vegetation, forming surface crusts, and creating soil acidity and toxicity. X-ray diffraction (XRD) and scanning electron microscope (SEM) analyses of encrustated layer indicated the presence of gypsum and jarosite minerals. Gypsum likely acted as a cementing agent in the formation of the encrustation layer with extremely low pH (2.9) and extremely high concentrations of Al, Ca and S. Encrustation is responsible for limited water infiltration and root penetration, while the extremely high concentration of Al is responsible for crop toxicity. Mud ashfall and dry ashfall deposits also greatly changed the underlying soil properties by decreasing soil pH and cation exchange capacity and by increasing exchangeable Ca, Al, and S availability. Despite damaging vegetation in the short-term, the volcanic ashfall enriched the soil in the longer term by adding nutrients like Ca, Mg, K, Na, P, Si and S. Suggested

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management practices to help restore the agroecosystem after volcanic eruptions include: (i) the application of lime to increase soil pH, increase cation exchange capacity and decrease Al and S toxicities, (ii) the selection of crops which are tolerant to low pH and high concentrations of soluble Al and S, (iii) physically disrupting the hard surface crusts that form on some soils (if <2 cm thick) to allow water infiltration and root penetration, (iv) application of N and K fertilizers, and (v) incorporation of dry ashfall into the soil (if <5 cm thick) to exploit the newly deposited nutrients.

1. Introduction

Sinabung volcano in Indonesia has erupted intermittently since July 2010 to July 2013. However, the eruption increased intensity by daily emitting ash and pyroclastic materials since September 2013 to the present and is unpredictable when it will cease. This is the longest eruption period recorded for any of the 127 active volcanoes in Indonesia. The ^{14}C dating of charcoal in pyroclastic flow deposits indicated that the Sinabung volcano had been dormant for 1200 BP years prior to this eruption (Sutawidjaja et al., 2013). The height of the ash column during Sinabung eruption varied between 500 and 3000 m (mostly 500–2000 m) to the atmosphere. The ash deposits contained silicon dioxide (SiO_2), magnetite, anorthite, pyrite, and illite which are typical of hydrothermally altered minerals (Sutawidjaja et al., 2013). Serious negative impacts occurred across highly productive farm in the surrounding areas especially on the middle and lower slopes and volcanic plains that continuously received ashfall. Changes to the chemical and physical properties of the soil affected agricultural activities (crop production) and ecology (water infiltration and biodiversity).

The Indonesian government has implemented the prohibited areas or red zones within a 5 km radius from the volcanic vent, which was regarded as a hot ashfall hazard. Areas beyond the red zone were allowed to be cultivated but still faced problems for crop growth due to ashfall. Detailed studies on the mineralogical, physical and chemical properties and the elemental compositions of the pristine ashfall and its effects on the underlying soils and crop growth are needed to develop management strategies for restoring the agroecosystems.

Volcanic gases and airborne materials (tephra) were destructive to agroecosystems during and after eruptions because they affect crop yields, vegetation growth, water infiltration, dust pollution, and change the microclimate. The composition of gases emitted from a fumaroric field of Merapi volcano (Indonesia) was in order of dominance H_2O, CO_2, SO_2, H_2, H_2S, HCl, CO, HF and S_2 (Voight et al., 2000). Similarly, Greenland (1984) reported that volcanic gases in Hawaii were dominated by H_2O, CO_2, SO_2, H_2, H_2S, HCl, CO, HF and S_2. These emissions showed the potential of gas pollution to the environment and induce acidic aerosols and acidic precipitation (Dahlgren et al., 2004). Condensation of acidic aerosols on ashfall results in high sulfate containing minerals which can decrease soil pH. Johnson and Parnell (1986) reported volcanic plumes from the Masaya Caldera in Nicaragua which damaged vegetation due to very acidic rain (pH 2.5) composed of HCl and H_2SO_4. Ayris et al. (2015) in their review of Mount St. Helens tephra leachate stated that each tephra particle carries a unique assemblage of salts due to a physically and chemically evolving eruption plume and volcanic cloud. In addition, Ayris and Delmelle (2012) in their review of immediate environmental effects of tephra emission concluded that Ca, Cl, Na and S are usually the most abundant soluble elements released when the freshly erupted tephra material interacts with water.

Stoiber and Rose (1974) reported the formation of sulfate minerals in volcanic fumarole encrustations in Central America. Africano and Bernard (2000) showed various sulfate minerals in the fumarolic environment of Usu volcano in Japan. Zimbelman et al. (2000) described sulfate minerals, natroalunite and minamiite, around fumaroles of Mount Rainier in Washington. All these reports imply there is a potential toxicity of sulfate minerals to crops and vegetations following an eruption. The objective of the study was to assess properties and impacts of pristine volcanic deposits on soil properties and to develop management strategies for agroecosytem restoration. Restoration strategies are needed as a baseline for other areas where no information is available on the properties of the pristine volcanic materials.

2. Materials and methods

Prior to eruption, the areas around the lower slopes and volcanic plain of Sinabung volcano were cultivated by local farmers to produce various high quality vegetables (e.g., cabbage, chilly, and carrot), fruits (citrus and avocadoes) and perennial crops (coffee). After the eruption field visual observations showed dried trunks of the citrus, avocado and coffee trees which were damaged or killed by hot ashfall deposition. Land satellite imagery (Thematic Mapper, acquisition November 15, 2014) was used for field studies to observe distribution, thickness and properties of ashfall deposition.

Fresh ashfall deposition (SNF) was collected at a distance of about 5 km (the boundary of the implemented red zone) from the eruption center (Fig. 1). It was collected within an hour after eruption (allowing the materials time to cool) to avoid any loss of soluble salts which are readily released new nutrients once contacted with water. This fresh ashfall was collected from clean concrete areas used to dry rice milling. For relatively older ashfall depositions (cumulative depositions from July 2010 to January 2014), five sampling sites were selected. Sampling sites were designed to cover different environmental conditions including elevations, land uses, landforms, ashfall deposition thicknesses, and distances from the eruption centre. All sampling sites and their associated environmental conditions are shown in Table 1 and Fig. 1. Soil mini pits (SN1, SN2 and SN3) and profile pits (SN5, SN6 and SN7) were made, and both the ashfall deposits and the underlying soil horizons were sampled for mineralogical, chemical and physical analyses. Samples of ashfall and soils of about 1 kg each were collected from each layer of ashfall deposits and from soil mini pits and profile pit layers, respectively. A mini pit SN1 has a cumulative thickness of ashfall deposition varying between 5 and 12 cm, depending on micro-relief architectures resulted from management practices, viz. raised bed system showed thicker deposition in the furrows than on the raised beds.

Mini-pits SN2 and SN3 occurred at similar locations and received a similar thickness of ashfall but have different cultivation practices. Mini pit SN2 represented areas without cultivation, while mini pit SN3 represented areas cultivated for vegetables where the ashfall deposits were incorporated into the underlying soil layer. Profile SN5 represented land use for crop rotations (rice, vegetable, maize) with irrigation facilities. Profile SN6 represented land use for citrus and avocadoes. Profile SN7 represented areas where the soil was not affected by volcanic ashfall or the effects were minimal (ashfall was observed only on crop leaves but not on soil surfaces). This profile was used as a baseline to observe the effect of ashfall on underlying soil properties. Currently, the