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Applying volcanic ash to croplands – The untapped natural solution

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ABSTRACT

A nature-based soil security solution is proposed. In countries with active volcanoes, such as Indonesia, volcanic ash could be used to supply nutrients and reduce CO_2 from the atmosphere. The weathering can draw CO_2 from the atmosphere; in addition, volcanic ash with 0% carbon can turn into soils with around 10% organic carbon. In Indonesia, soils of volcanic origin cover about 31.7 million ha or 17% of its land area. Frequent volcanic eruptions made volcanic ash or tephra readily available. However, tephra is not widely used and has not been adequately investigated as a soil amendment to sequester carbon. This paper calculates the magnitude and opportunity of CO_2 drawdown potential from volcanic materials produced annually in Indonesia. In years with significant volcanic eruptions, the subsequent withdrawal will be 100–200 Mt CO_2 or 20–40% of the country's fossil fuel emission. The CO_2 captured when volcanic materials weather is part of the global carbon cycle and is influenced by land-use decisions. Currently, volcanic ash is often eroded and rapidly transferred to aquatic systems. In relevant landscapes, actively managing this untapped resource is more feasible than external basalt applications as volcanic ashes do not need to be ground, can soak up significant amounts of carbon from the atmosphere, and build fertile soils that supply an abundance of nutrients to achieve food and soil security. Volcanic ash needs to be included in carbon accounting and its management could be part of emission reduction strategies.

The sunrise seemed smothered: a deep red glow that refused to brighten. By ten in the morning, I was certain night had been returned to us. I felt something brush against my skin, with the softness of snow. Snow? I touched my finger to it, incredulous, until I saw that it smudged. Ash. Within an hour, the sky, from horizon to the heavens, was filled with it. It fell in heavy showers with a soft patter, coating the deck then forming a thick layer.

Guinevere Glasfurd, 2020, The Year Without Summer.

1. Introduction

Volcanic rock dust has been long advocated as a soil amendment on croplands for soil rejuvenation and adds nutrients to ancient weathered soils (d'Hotman de Villiers, 1961). Enhanced rock weathering—spreading rock dust, particularly basalt, on farmland to reduce atmospheric CO_2—is now widely promoted (Beerling et al., 2020, 2018; Moosdorf et al., 2014). The weathering of silicate minerals takes up CO_2 from the atmosphere and can serve as a negative emission technology to mitigate climate change. In addition, the nutrients released during weathering can contribute to food and soil security (McBratney et al., 2014).

The feasibility and scalability of enhanced rock weathering are debated (Smith et al., 2020). Rock dust has very low solubility and low availability to plants that could lead to the low efficiency of soil improvement (Van Straaten, 2006). A recent study by Beerling et al. (2020) proposed that an application of 40 tons of crushed basalt per hectare per year on global croplands would remove 0.5–2 Gt CO_2 yr^{-1}. Such high annual rock dust applications (equivalent to ≈2.6 mm of materials) are greater than the average soil erosion rate in agricultural fields (1 mm yr^{-1}) (Montgomery, 2007). With agricultural soil erosion already an issue, adding enormous amounts of rock dust, if not well managed, could lead to increased erosion rates, with subsequent consequences for waterway health.

In countries with active volcanoes, volcanic ash (tephra) is a more feasible, nature-based solution for soil improvement and CO_2 reduction. Because tephra can capture and store carbon, tephra-derived soils—Andisols (or Andosols)—are some of the most fertile and carbon-rich mineral soils in the world. Andisols cover only 1% of the earth's surface, yet they contain about 5% of global soil carbon stocks (Dahlgren et al., 2004). Our analysis of topsoil volcanic soil in West Sumatra shows a mean organic carbon content of 4%, and in some cases, the carbon content can reach up to 15% (Fiantis et al., 2017). Being fer-

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tile, Andisols often support dense human populations and are critical in ensuring food security (Arnalds, 2013).

When tephra weathers, the chemical breakdown of calcium and magnesium takes CO_2 from the atmosphere. Weathered base cations and precipitated bicarbonate in soils are stored as inorganic carbon or leached out (Taylor et al., 2016). Climate and vegetation mediate the rate of weathering, but they are also influenced by soil solution, pH, and redox conditions (Dahlgren et al., 1999; Harley and Gilkes, 2000; Renforth, 2012). In addition, newly deposited tephra has 0% organic carbon and can rapidly accumulate carbon (Zehetner, 2010). Weathered ash has poorly crystalline minerals with a large surface area that enables carbon complexation. Once captured, organic carbon persists in these soils for a long time (Crow et al., 2015) and is protected from mineralization by organometallic complexes, forming physical and chemical barriers that prevent it from being released back to the atmosphere. One experiment demonstrated that newly deposited tephra could accumulate soil organic carbon at a rate of 1.8–2.5 t CO_2 per ha per year through the establishment of lichens and vascular plants (Fiantis et al., 2016). This rate is much higher than any soil carbon management system (Minasny et al., 2017).

Good land management is critical to achieving and maintaining high levels of soil carbon as freshly deposited ash is easily eroded and transported to aquatic environments where it becomes a burden on the environment, and cannot weather and capture carbon. However, part of it may be dredged from rivers and used as coarse sand in cemented buildings. We do not have estimates of the quantity involved.

Indonesia has half of the known deadly volcanic eruptions in the world (Kusky, 2008), and smaller volcanic eruptions happen, on average, once per month. Because of repeated eruptions, soils in volcanic landscapes usually have successive layers of ash. Soils like this can be found near the 127 active and inactive volcanoes spread over the islands of Sumatra, Java, Bali, Lesser Sunda Islands, the northern part of Sulawesi, and the Moluccas. The ash is often considered a nuisance, is not widely used as a soil amendment in croplands, and has not been adequately investigated as an alternative to crushed basalt. However, with the right land management practices, it could be a resource to improve soil and capture atmospheric CO_2. The aim of this paper is to highlight the opportunity of CO_2 drawdown potential from volcanic materials. We calculated volcanic materials that are produced annually in Indonesia and estimated its CO_2 capture potential. We then discuss some soil and landscape processes that are affected by the application of tephra.

2. Volcanic materials and their CO_2 capture potential

This paper estimates the amount of volcanic materials produced annually in Indonesia since 1970 and its potential to capture atmospheric CO_2. Volcanic eruption data were retrieved from the Global Volcanism Program https://volcano.si.edu/. Reported Volcanic Explosivity Index (VEI) was converted to the volume of volcanic materials based on the geometric mean of the estimated volume of the VEI index. The volume of materials (V) was then converted to mass based on the bulk density (ρ) of observed on volcanic materials in Sinabung (Fiantis et al., 2019) 1.3 ± 0.4 Mg m^{-3}.

There are two mechanisms of carbon capture: (1) though weathering, and (2) through accumulation of organic matter.

The potential CO_2 capture via weathering (R, as a fraction of the mass of rock) was estimated following the equation of Renforth (2012):

$$R = \frac{M\mathrm{CO}_2}{100}\left(\frac{\%\mathrm{CaO}}{M\ \mathrm{CaO}} + \frac{\%\mathrm{MgO}}{M\ \mathrm{MgO}}\right)\omega\ \gamma$$

where M refers to molecular weight and % refers to percentage mass of the elements, ω represents additional drawdown of cations = 1.7, γ is the factor affecting the reaction due to the temperature calculated based on the Arrhenius equation.

There is a range of volcanic materials from basic basalt to highly acidic rhyolite (Fig. 1). Basalt with a higher amount of Ca and Mg would have a higher CO_2 consumption during weathering than rhyolite (Tobar, 2019). R values for various volcanic materials were calculated from the geochemical concentration of volcanic materials in Indonesia along the Sunda-Banda Arc (Fig. 1) (Mucek et al., 2017) with a mean value of $R = 0.2 \pm 0.06$.

A soil organic carbon concentration potential (SOCp) for the volcanic materials was calculated based on observed SOC values from West Sumatra (Fiantis et al., 2017) (mean 4.2±0.10 g 100 g^{-1}). Finally, the Monte Carlo simulation with 1000 iterations was used to simulate the distribution of soil mass and CO_2 withdrawal potential each year as the sum of all reported volcano eruptions:

$\sum V * \rho * R + V * \rho *$ SOCp $*44/12$.

3. Volcanic materials as a carbon sink

Based on volcanic eruption data since 1970, on average, 47 Mt of volcanic materials were ejected in Indonesia each year. In certain years, for example, between 2013 and 2019, several large eruptions such as Merapi, Kelud, Sinabung, and Anak Krakatau produced around 500–600 Mt of materials per year. The geochemical composition of the volcanic materials varied from basalt to rhyolite (Fig. 1). We calculated the potential carbon withdrawal via weathering of these materials (Renforth, 2012) and also estimated the potential soil organic carbon accumulation in the materials (Fiantis et al., 2016).

Fig. 2 shows the mean and statistical distribution of potential of CO_2 drawdown is around 12 Mt CO_2 per year. In years with significant eruptions, the ash could withdraw 100–200 Mt $CO_{2\ eq}$, which is 20–40% of Indonesia's annual fossil CO_2 emissions (530 Mt $CO_{2\ eq}$ in 2016, Worldometer, 2020). Our results are comparable with the analysis of Beerling et al. (2020), which estimated that Indonesia would need to apply 91 Mt of silicate materials to remove 17 Mt $CO_{2\ eq}$ and 380 Mt of silicates to remove 67 Mt $CO_{2\ eq}$, annually (Table 1 of Beerling et al., 2020). Note that the latter estimate is based on a 1-D reactive transport model parameterized for basalts. However, the energy to crush basalts is large in addition to the logistical cost for sourcing and spreading (Moosdorf et al., 2014).

Ashes in areas near volcanoes can be sourced relatively easily and applied locally (at a rate of 20–80 t/ha). When large eruptions occurred, volcanic materials could be road and river transported to areas of weathered soils such as Oxisols and Ultisols for soil rejuvenation (Anda, 2016). We note that these numbers (Fig. 2) are potential values assuming all volcanic materials can be utilized. Factors such as erosion could diminish weathering efficiency. There are, of course, caveats that CO_2 and other volatiles are emitted by volcanoes and enhanced during eruptions. Values of CO_2 emission for major subaerial volcanoes in Indonesia, according to Fischer et al. (2019), is around 7.55 Mt CO_2/year. Nevertheless, these are natural emissions that cannot be avoided.

Finally, weathering of tephra can be an inspiration for citizen science and school projects to bring awareness of soil weathering and its role in the global carbon cycle. Kwasniewska et al. (2020) demonstrated that monitoring buried tephra bags for primary school children in Ireland is a way to evaluate perceptions of climate change and the carbon cycle.

4. Effect on soil and landscape

The effect of volcanic ash is determined by its quantity and composition (Tobar, 2019). Tephra could be acid to alkaline (Fig. 1), but they contain lots of soluble elements. Gases and volatile elements released during volcanic eruption could be adsorbed by tephra (Witham et al., 2005). The type of magma influences the composition of volcanic ash. The general ions adsorbed are Cl, Ca, Na, SO_4^{2-}, Mg, and F, which are highly soluble and immediately leached into the soil and the environment.

Dahlgren and Ugolini (1989) examined the addition of tephra from Mt. St. Helens on soil processes in Spodosols in the Cascade Range, Washington, U.S.A. They found that basic cations (Ca^{2+} = N^{a+} > Mg^{2+}

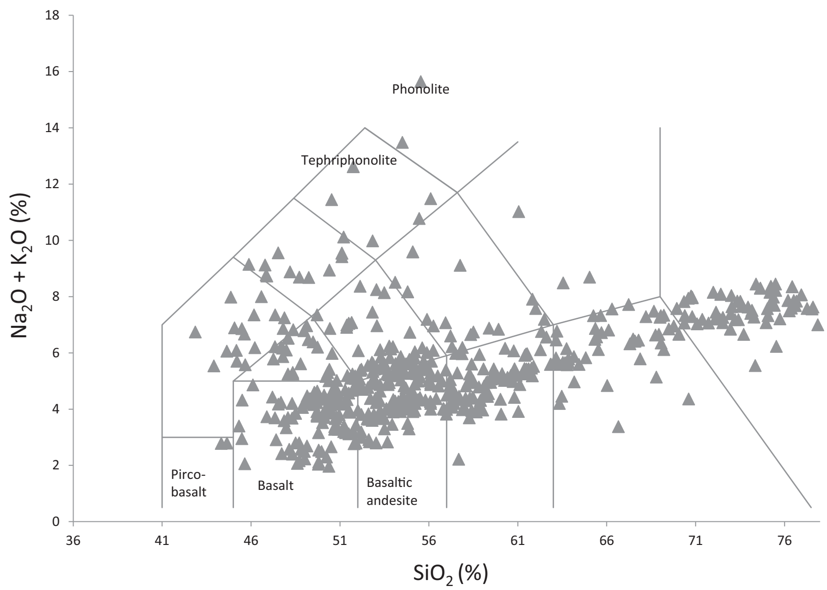

Fig. 1. Geochemistry of volcanic materials of volcanic centers along the Sunda-Banda Arc, as compiled from the GeoRock database (Mucek et al., 2017).

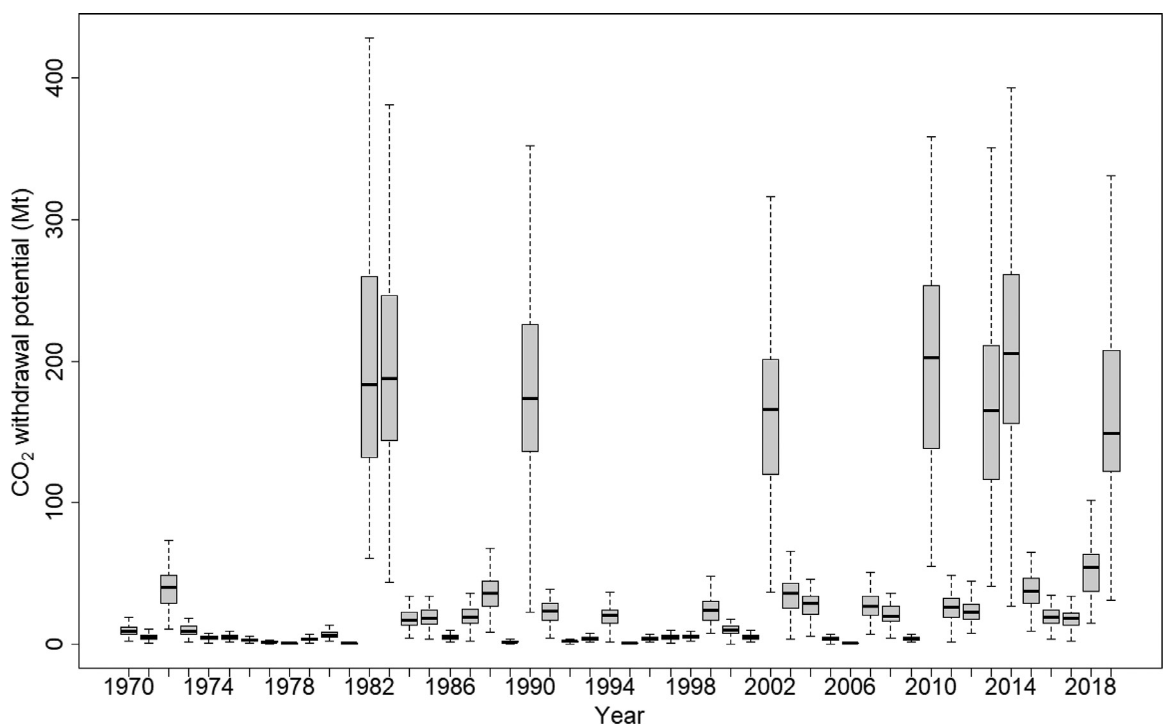

Fig. 2. Annual CO_2 withdrawal potential (Mt $CO_{2\ eq}$) from volcanic materials in Indonesia. The boxes and whiskers represent the distribution of the estimate.

> K^+) and SO_4^{2-}, were easily leached from the tephra. These cations displaced H^+ and Al^{3+} from the exchange sites in the upper horizons. The soluble salts and Al^{3+} moved through the soil profile where they were adsorbed by soil minerals. Calcium, K^+, Al^{3+}, and SO_4^{2-} were strongly retained in the B horizons, whereas Na^+, Mg^{2+} and Cl^- showed little affinity to the solid phase. The initial weathering was a mainly incongruent dissolution of the solid. Base cations and silicon released by weathering were leached from the tephra, while aluminum and iron were immobile and accumulated in the tephra (Dahlgren et al., 1999).

In New Zealand, tephra from eruptions from the Ruapehu Volcano in 1995, contained a high amount of sulfur (3000–10,000 mg/kg) and was acid (pH 4–4.5). The water soluble elements of S, K, Mg and Se modified soil exchangeable cation pools and immediately available to plants (Cronin et al., 1997). The elemental S in the tephra could be oxidized rapidly and lowered soil pH. In some heavily affected areas, liming may be necessary.

Anda and Sarwani (2012) collected water samples from the river immediately after the eruption of Mt Merapi in Central Java in 2010 and found high concentrations of base cations and anions. Similarly, Fiantis et al. (2010) conducted a leaching experiment on recent tephra from Mt Talang in West Sumatra and found the large release of basic cations and phosphorous.

However, one of the most common physical problems is that the ash can be hydrophobic. Thick layers of ash could cause an increase in surface runoff and erosion. Rainfall following tephra deposit can easily remove tephra with reported erosion rates exceeding

100,000 t km^{-2} year^{-1} (Arnalds, 2013). Wind erosion of tephra affects ecosystems, agriculture, and health but can provide beneficial dust inputs afar. This will negatively affect downstream water quality. Tephra is commonly considered as pollutants of water, increased turbidity, acidity, fluoride, and some cations Al, Mn, Fe (Ayris and Delmelle, 2012; Stewart et al., 2006).

Vegetation regrowth can be a challenge as the tephra composition, when added in large amounts, can be unfavorable to plants. Thus tephra needs to be incorporated into the soil and efforts for vegetation regrowth using local vegetation adapted to volcanic ash soils (Ishaq et al., 2020a).

Finally, we also would like to point out if the ashes were not used in agricultural fields, they could be washed down in the rivers or oceans. In that case, the ability to withdraw CO_2 still can occur (Longman et al., 2019) but would be at a reduced rate and not benefitting soil quality.

5. Conclusions

Atmospheric carbon dioxide (CO_2) removal by applying rock dust to croplands as a negative emission technology has a nature-based counterpart. In tropical ecosystems with frequent volcanic eruptions, tephra is an attractive alternative to crushed basalt as a CO_2 mitigation strategy. Tephra is readily available, does not need to be crushed, and offers better soil improvements and higher CO_2 capturing capabilities at potentially lower application rates. In summary,

1. Tephra is a starting point for C sequestration as nature-based solution.

Tephra weathering consumes CO_2, and as it weathers, it takes up organic carbon, which is physically and chemically protected in the soil. The increase in soil carbon in tephra will further enhance weathering and release of nutrients which have positive feedback on plant growth.

2. With land cover change, ash is more prone to erosion, reducing C sequestration as it ends up in aquatic environments.

Ash-deposits are initially a problem for people, livestock, and crops (Anda, 2016; Fiantis et al., 2019; Ishaq et al., 2020b). In urban and open-field agriculture, much of the ash currently ends up in streams, rivers, lakes, or the sea—with uncertain consequences for its carbon capturing potential.

3. Incorporating ash in the soil over croplands is technically more feasible than crushed rock, which will increase soil C sequestration and be part of climate mitigation response.

As with rock dust, land management is critical for turning what is currently viewed as a nuisance into a resource and ensuring it does not run off. In forested and agroforestry landscapes, much of the ash stays on the soil surface or is incorporated into the topsoil by farm management. How farming practices affect the ash's carbon-capturing potential needs to be assessed further (Anda, 2016).

The current evidence for conclusion number 1 is strong, fair for number 2, and exploratory for 3. The potential CO_2 withdrawal from volcanic ash also needs further study. The mechanisms of geochemical processes of volcanic mineral weathering and dissolution in soils need to be better understood so that the ash application rate and method can be optimized. There is a need for a careful and complete life-cycle assessment of applying these volcanic materials (energy requirement and greenhouse gas production). In addition, the economic feasibility and socio-economic impacts of the process need investigating. Because of its potential CO_2 capturing capabilities, tephra should be included in carbon accounting, and its management can be part of emission reduction strategies. This untapped natural solution is highly relevant to countries with active volcanoes such as Iceland, Japan, the Philippines, Chile, and Papua New Guinea.

Using volcanic materials eliminates the question of the effectiveness of rock application in tropical systems (Edwards et al., 2017). Actively managing this resource can ensure soil and food security.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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