Review

Volcanic Ash, Insecurity for the People but Securing Fertile Soil for the Future

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Abstract: Volcanic eruptions affect land and humans globally. When a volcano erupts, tons of volcanic ash materials are ejected to the atmosphere and deposited on land. The hazard posed by volcanic ash is not limited to the area in proximity to the volcano, but can also affect a vast area. Ashes ejected from volcano's affect people's daily life and disrupts agricultural activities and damages crops. However, the positive outcome of this natural event is that it secures fertile soil for the future. This paper examines volcanic ash (tephra) from a soil security view-point, mainly its capability. This paper reviews the positive aspects of volcanic ash, which has a high capability to supply nutrients to plant, and can also sequester a large amount of carbon out of the atmosphere. We report some studies around the world, which evaluated soil organic carbon (SOC) accumulation since volcanic eruptions. The mechanisms of SOC protection in volcanic ash soil include organo-metallic complexes, chemical protection, and physical protection. Two case studies of volcanic ash from Mt. Talang and Sinabung in Sumatra, Indonesia showed the rapid accumulation of SOC through lichens and vascular plants. Volcanic ash plays an important role in the global carbon cycle and ensures soil security in volcanic regions of the world in terms of boosting its capability. However, there is also a human dimension, which does not go well with volcanic ash. Volcanic ash can severely destroy agricultural areas and farmers' livelihoods. Connectivity and codification needs to ensure farming in the area to take into account of risk and build appropriate adaptation and resilient strategy.

Keywords: Sinabung volcano; pyroclastic deposits; carbon sequestration; soil rejuvenation

1. Introduction

Volcanic activity has a significant impact on the world's ecosystem. Its eruption is catastrophic, spewing lava and ashes, posing a serious risk to humans and their livelihoods. Ashes ejected from the volcano can cause much nuisance to farmers, burying agricultural lands, and destroying crops. The ashes can also present harmful impacts on human health and animals, contaminating infrastructures, and disrupting aviation and land transport. The land area threatened by volcanic eruptions in Indonesia is around 16,670 km^2 and affects around 5,000,000 people.

However, the aftermath of volcanic eruptions leads to the world's most productive soils, volcanic soils. Soils derived from volcanic ash or tephra have the highest capacity to store carbon due to their poorly crystalline minerals that have large surface areas enabling complexation and physical protection. These soils also retain the most persistent soil organic carbon pools. It was estimated that, while volcanic ash soils (Andosols) cover only 0.84% of the earth's surface, they contain about 5% of global

soil carbon [1]. Soil organic carbon (SOC) stock for Andosols is estimated to be around 254 t C ha^{-1} in the upper 100 cm [2]. Soils derived from volcanic ash are also known to have a high human carrying capacity, as evidenced by the dense population in areas near volcanoes around the world [3]. Dutch soil scientist E.C.J. Mohr in 1938 [4] compared population densities of different districts near Mount Merapi, Central Java, Indonesia, and found higher population densities in areas with soils derived from volcanic ash. While SOC sequestration in volcanic ash soils (Andosols) have been widely discussed and reviewed, e.g., Reference [5], the carbon sequestration potential of tephra is less discussed. This soil material is particularly important in areas with volcanoes such as Indonesia, Philippines, Japan, New Zealand, Hawaii and Pacific Islands, the Caribbean islands, Iceland, and South America.

This paper aims to examine volcanic ash (tephra) from a soil security viewpoint, its main capability. Tephra rejuvenates soil and provides nutrients reserve, and has a large potential to sequester carbon over a relatively short period. This capacity ensures the security of our soils in active volcanic regions of the world. Its carbon sequestration potential can fulfill and even exceed global soil carbon initiatives, such as the 4 per mille soil carbon [6]. However, volcanic ash's condition for agriculture is poor as it is still unweather. This paper reviews the role of volcanic ash in sequestering SOC. It provides two case studies from recent volcanic eruptions from Indonesia. It further discusses how a soil security framework may be applied in areas suffering from constant volcanic eruptions.

2. Volcanic Materials and Their Chemical Composition

Materials ejected from volcanic eruptions are classified according to their form. Tephra describes all pyroclasts that leaves a volcanic vent by air, regardless of their type, size, and shape. It is also called volcanic ash, but sensu stricto tephra refers to ashes that are less than 2 mm in diameter. Pyroclasts have a broader meaning than tephra, which includes consolidated and unconsolidated materials [7].

The type and abundance of primary minerals in tephras depends on the volcano, but usually made up of volcanic glass (silica), quartz, plagioclase, pyroxenes, hornblende, biotite, olivine, etc. [8], examined tephra from the eruptions from Ruapehu volcano on 11 and 14 October 1995 in New Zealand. Tephra from the two eruptions contained 3.0 and 0.7% by mass of sulphur (S), significantly raised soil sulphate levels in the affected area. Also, its fine grain caused it to be oxidised rapidly, lowering the soil pH. Whereas, the composition of tephra from Mt. Talang in West Sumatra, Indonesia was dominated by labradorite (35%) and rock fragments (21%) [9–11]. The heavy mineral fraction consisted of hypersthene (11%), augite (3%), opaques (3%), and hornblende (traces). While the primary mineralogical composition of tephra from Merapi volcano (Central Java, Indonesia) consisted of more non-crystalline (53–60%) compared to crystalline components [12].

3. Volcanic Soils and Carbon Storage Capacity

When first deposited from volcanic eruptions, pristine tephra contained no organic carbon, but may contain some inorganic carbon. The inorganic carbon originated from volatile elements emitted during a volcanic blast in the form of carbon dioxide, carbon monoxide, methane, and carbonyl sulphide. In the absence of microorganisms during and after a volcanic eruption, this inorganic carbon flux immediately reacted with water molecule or calcium (Ca) to form carbonic acid or calcium carbonate [13]. However, as the volcanic ash weathered, it produced non-crystalline and poorly crystalline minerals and oxides [14]. The large specific surface area ($\sim$700 mg^{-1}) and great reactivity of these poorly crystalline minerals are mostly responsible in the complexation and stabilization of organic matter. Accumulation of organic carbon in the volcanic ash depends on the interaction among a series of biotic and abiotic factors.

Zehetner [15] examined if organic C accumulation in volcanic soils can offset CO_2 emissions from volcanic activities. He compiled data from studies conducted on Holocene volcanic deposits in different parts of the world to assess the SOC accumulation potential of volcanic soils (Figure 1). He found that SOC accumulation rates decreased with increasing soil age, with the largest rate 0.5 t C/ha/year in the first 50 years and decreases to less than 0.1 t C/ha/year after 1000 years. While soil

carbon content can be quite high in the surface horizons (up to 10%), the accumulation of organic matter was most rapid in the first 100 years. He further suggested that there is an upper limit of volcanic soils C sequestration at approximately 20 Tg/year, which is relatively insignificant in the global terrestrial C cycle. Nevertheless, we still believe that there is a potential to use volcanic ash as a terrestrial carbon sequester.
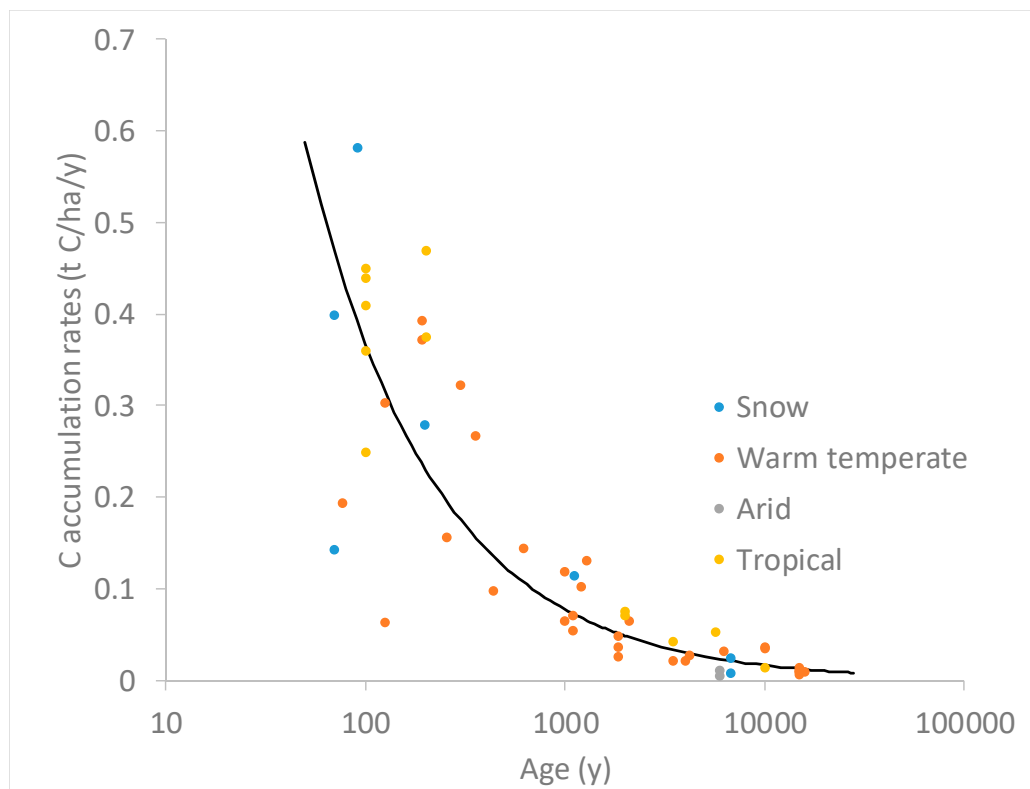

Figure 1. SOC accumulation rates in volcanic soils (data from Reference [15]).

A study from a chronosequence in the Etna region in Italy [16], where the soils were developed from lava, showed that a 125-year period of pedogenesis resulted in a SOC accumulation rate of 0.3 t C/ha/year. The rate of SOC accumulation in the 91-year-old tephra deposit of Mt. Bandai (Japan) is between 0.10 and 0.58 t C/ha/year, with a rapid accumulation rate during the early stage of soil development [17]. However, another study on volcanic soils from Sierra del Chichinautzin Volcanic Field in Mexico indicated that, after 10,000 years, the C accumulation rates are only in the order of 0.02 to 0.07 t C/ha/year [18].

Here we report studies that evaluated SOC accumulation since volcanic eruptions.

3.1. Krakatau, Indonesia

Mount Krakatau erupted on 27 August 1883 and formed a remnant Rakata Island, which was covered by ashes. The tropical island with high rainfall (2500–3000 mm/year) led to a rapid recolonization of vegetation and now a well-developed forest. Analysis of soils of Rakata, 110 years after the eruption showed that the SOC content ranges from 49 t C/ha at 720 m elevation to 140 t C ha at 480 m elevation [19]. This is equivalent to rates of accumulation between 0.44 to 1.3 t C/ha/year.

Within the Krakatau complex, there are four islands: Sertung, Panjang, Rakata, and Anak Krakatau. Mt. Anak Krakatau meaning Child of Krakatau emerged from the caldera in the 1930s and is composed of lava and pyroclastic deposits from the late Mt. Krakatau. Since its emergence from the sea, Anak Krakatau has progressively grown and considered as one of the fastest growing volcano in Indonesia. Anak Krakatau erupted on 22nd December 2018, ejecting tons of ashes and caused a collapse of

South-West slope of the island. When the authors visited Mount Anak Krakatau in 2015 (Figure 2), the organic C content of the soil range from 1.3 to 1.7%, or approximately 49 t C/ha in the top 25 cm, or an average accumulation rate of 0.34 t C/ha/year.

Figure 2. Soils developed in Mt. Anak Krakatau and primary vegetation. (Photos taken 15 April 2015 by authors).

3.2. Mount Pinatubo, Philippines

Mt Pinatubo erupted on June 1991 ejected a large volume of ashes and lahars covering large agricultural areas in Central Luzon. The ash contains a high amount of volcanic ash and about 1.7 g/kg of P_2O_5. It appears that lahar mixed with soils promote regrowth of vegetation, mainly grasses, and

leguminous plants. Seven years after the eruption, the lahar deposit has an OC content of 0.8% and nitrogen content of 0.066% [20].

3.3. Mount St. Helens, USA

Twenty-five years after the eruption of Mt. St. Helens, the concentration of total soil C and N has increased to 4 and 0.4 g kg^{-1}, respectively [21]. Two species of perennial lupine (*Lupinus Lepidus* and *Lupinus latifolius*) were the first plant colonized the volcanic ash deposits. These two legumes are an important factor in ecosystem development and plant succession following volcanic disturbance. They were able to colonize and persist on volcanic deposits because of their ability to fix atmospheric N$_2$ via symbiosis with *Rhizobium,* and subsequently, accumulate organic matter. Total C increased at an average annual rate of about 46 mg kg^{-1} (29 ± 7 kg ha^{-1}) under bare soil, 128 mg kg^{-1} (70 ± 17 kg ha^{-1}) under live lupines and 161 mg kg^{-1} (88 ± 17 kg ha^{-1}) under dead lupines. The carbon content after 25 years of eruption is still quite small (4000 mg kg^{-1}) with small SOC accumulation rates. They hypothesised that the organic matter inputs are in balance with outputs [21].

3.4. Iceland

Iceland has a high concentration of active volcanoes, and its soil is mainly Andosols derived from tephra and aeolian sediments of volcanic glass [22]. SOC sequestration rate in a sandy desert following a seven-year restoration process was evaluated [21]. The desert's parent material is volcanic glass with a low carbon concentration, and they found an annual carbon accumulation of 0.4–0.63 t C/ha. Meanwhile, sequestration rates of 0.23 t C/ha/year following tree plantation in a degraded heathland was reported [23]. Another study reported a long-term carbon accumulation rates of 0.17–0.3 t C/ha/year in Southwest Iceland [24].

Another study [25] reported SOC accumulation in a 50-year-old volcanic island Surtsey. Seagull colony on the island provided nutrient enriched areas, and thus SOC concentration has been increasing from 0.08% (taking the 1986 value as baseline SOC concentration, the first year of permanent seabird colonization) to 0.9 ± 0.3% on deep tephra sand and 4.6 ± 0.4% on shallow tephra sand. The accumulation rate is between 0.1-0.4 t C/ha/year.

3.5. Kasotchi Island, Alaska

Kasatochi volcano erupted in August 2008 and buried a small island in pyroclastic deposits and fine ash. Subsequently, microbes, plants, and birds begun to re-colonize the initially sterile surface. Five years post-eruption, SOC content is still relatively small (<0.2% C). However, microbial activities in pyroclastic materials with organic matter (OM) inputs were one or two order magnitude larger than in materials without OM input [26].

3.6. Hawaii

Soil development's effect on SOC stock along chronosequences in Hawaii was evaluated [27]. The study found that SOC content followed a similar trend as the soil development where volcanic parent materials weathered to non-crystalline minerals during the first 150,000 years, followed by a decline in the amount of non-crystalline minerals and an increase in stable crystalline mineral accumulation. Similarly, SOC accumulated to a maximum after 150,000 years and then decreased by 50% over the next four million years. They explained this through a change in SOC-mineral stability mechanisms during soil formation [28]. As these increase over time, the minerals lose the capacity to stabilize carbon or the soil becomes saturated.

Reference [29] evaluated a chronosequence of 10, 52, and 142-year-old lava flows on Mauna Loa, Hawaii. They found aboveground biomass accumulated rapidly in the first decade of primary succession. However, SOC accumulation lagged behind biomass, with negligible SOC at the 10-year site. SOC accumulation rates at 0.13 and 0.27 t C/ha/year were found at the 52- and 142-year sites.

They concluded that weathering rates of lava, in part, regulate rates of nitrogen fixation in these young ecosystems.

4. The Weathering of Volcanic Ash

Most studies on the primary succession of volcanic islands focused primarily on flora and fauna community changes and hardly look into the development of soil carbon. In early stage of weathering, cations were leached from volcanic ash when they were in contact with water and significantly increased the concentration of plant nutrients in soils. As such, re-vegetation or plant recovery prevailed immediately. Volcanic ash weathered rapidly to form short-range order alumino-silicate mineral (allophane, imogolite). These non-crystalline clay minerals have a high capacity to protect SOC in volcanic soils.

The establishment of plants and biomass led to the accumulation of SOC. Simultaneously, as pools of carbon developed, the volcanic ashes underwent weathering or decomposition processes. Nitrogen supply to pioneer plants was hypothesised as a key to the re-vegetation of volcanic ash affected areas [20]. It is continuous feedback that the increase in SOC will enhance release of nutrients and increase in cation exchange capacity and water holding capacity. These have positive effects on plant growth. Once the soil has increased its fertility, secondary colonizers will establish, which in turn further enhance SOC accumulation.

The decomposition of volcanic ash is likely to be proportional to the quantity of inputs N particular from not highly lignified plant biomass of lupines [30]. Net migration of plant nutrients from volcanic ash leads to progressive stages of plant succession from assembly to interaction [31]. The quantity and quality of substrates released from volcanic ash during decomposition influence the rate and pattern of plant succession through physical and biological amelioration of bare sites and subsequent interaction among colonists [31,32]. They also affect the succession below ground as the numbers, diversity, and activity of microbial are increased and interaction between lupines and fungi.

Soil carbon storage on volcanic soils across a high-elevation climate gradient on Mauna Kea, Hawaii showed that, after 20 ky, pedogenic processes have altered the nature and composition of the volcanic ash such that it is capable of retaining SOC [33]. The sites have a cold climate and low rainfall (~250–500 mm). Under such dry condition, the rate of carbon supply to the soil was driven by coupling of rainfall above ground plant production.

Tephra deposited on top of soil also provides a unique weathering pathway. It was hypothesised that buried organic-rich soil pumps protons upward to the tephra layer, which acts as an alkaline trap for CO_2 [34]. Pioneer plant (blue-green algae or cyanobacteria) used the CO_2 to initiate environment recovery. Black and brown patches were observed on tephra layer as the growth of cyanobacteria progress. Then, the algae mat provides suitable habitats to support mosses and higher plants life [35].

5. SOC Stabilisation Mechanisms

The ability of Andosols to store a large amount of C is mainly due to the dominance of short-range-ordered clay minerals (allophane, imogolite, and ferrihydrite) and metal-humus complexes (Al/Fe–humus complexes) in their colloidal fraction. However, there are also non-allophanic Andosols, where Al-humus complexes are dominant. The mineralogical properties of these non-crystalline materials present a high reactive surface area and are regarded as the major agent of C stabilisation.

A study on volcanic soils from Chile and found that SOM has the largest correlation with Al, rather than with clay content and climatic conditions [5]. They concluded that Al is the principal factor for immobilization of SOC in acid volcanic soils.

Soil organic matter (SOM) density fractionation study [36] on a soil horizon derived from tephra from the last eruptive phases of the Piton des Neiges in the Reunion Island, showed that the largest proportion (82.6%) of organic matter was associated with minerals in organo-mineral complexes. Imogolite-type materials bound 6-fold more OM than anorthoclase, and 3.5-fold more OM than iron oxides. Buried horizons, which were dominated by crystalline minerals (feldspars, gibbsite), have

the least capacity to store organic matter and the fastest carbon turnover. In contrast, buried horizons dominated by poorly crystalline clay minerals (proto-imogolite and proto-imogolite allophane) store large amounts of organic matter with low carbon turnover.

Allophane spherules tend to form nanoaggregates up to about 100 nm in diameter [37,38]. The nano pores both within and between nanoaggregates provide physical protection to SOC, where they cannot be accessed by microbes [39]. The organo-mineral complexes of volcanic soils can also protect soil carbon from disturbances caused by forest management, thus preventing potential carbon loss [40].

Mechanisms for chemical and physical stabilization of SOC in volcanic ash soils can be summarised as Reference [41]:

- direct stabilization of SOC in organo-metallic (Al-humus) complexes,
- indirect chemical protection of SOC (notably aliphatic compounds) through low soil pH and toxic levels of Al, and
- physical protection of SOC by the very large micro- or nanopores.

6. Case Study—Indonesia

The following case study from two areas in Indonesia showed how tephra from a fresh eruption could accumulate a high amount of carbon in a relatively short period [35].

6.1. Pot Experiment, Mount Talang

Mount Talang in West Sumatra, Indonesia erupted in April 2005 (Figure 3), and ashes from the eruption were collected [40]. The texture was a sandy loam, with coarse (2.0–0.05 mm), medium (0.05–0.002 mm) and fine (<0.002 mm) particles of 13, 68 and 19%, respectively. Based on the silica (SiO2) content of 57%, the tephra of Mt. Talang is considered as a basalto-andesitic ash. Cation exchange capacity (CEC) was low with a value of 5.50 $cmol_c$ kg^{-1}.

Figure 3. The eruption of Mt. Talang in April 2005. Photo by Authors.

A pot experiment was carried out to study C accumulation on the tephra. The experiment was conducted in wired-house. There were 2 main treatments: (1) A single tephra layer or without soil, (2) a tephra layer was placed above existing soil surface (15 cm of A horizon and 15 cm of B horizon). The thicknesses of the tephra layer were 0, 2.5, and 5.0 cm simulating tephra deposition. The experiment is a randomized design with tree replicates on each treatment. Five mm of filtered water was added

daily to each pot throughout four years of experiment. The water added was approximately equal to 14 years of precipitation in the Mt. Talang area.

The first noticeable change on the tephra layers was transformation of tephra color. The moist color of the surface tephra layer changed from light gray to very pale brown after 24 months and becoming pale brown after 46 months (Figure 4). This color transformation can be attributed to oxidation and liberation of Fe from tephra grains as well as accumulation of OC [40].

| Surface of volcanic ash at initial condition | Surface of volcanic ash after 3 months | Surface of volcanic ash after 5 months |
| Surface of volcanic ash after 8 months | Surface of volcanic ash after 15 months | Surface of volcanic ash after 30 months |

Figure 4. Changes in the surface volcanic ash layer during a pot experiment. Photo by Authors.

After two months, blue-green algae (cyanobacteria) started to colonize the bare tephra layer formed an algae mat. After 16 months, the surface was transformed into a green film of lichen. Vascular plants (grasses and shrubs) started to establish after two years (Figure 4). Inorganic carbon was detected by a SEM-EDX (Figure 5).

The initial total C content of the tephra is 0.19%, and after 46 months, the C content of the 2.5 cm tephra layer on top of the soil increased to 1.75%, and the C content of the 5 cm tephra layer on top of the soil increased to 0.9%. Meanwhile, tephra by itself accumulates less carbon with a concentration of 0.6%. Sequestration rates of 0.2 to 0.5% C per year or 0.5–0.7 t C/ha/year were observed for volcanic ashes, which were added on top of soils (Figure 6).

After 46 months root hyphae were observed with a SEM. The hyphae were attached to volcanic ash grains (Figures 7 and 8) and may help in weathering of the materials and helped sequester more C in soil. The ashes contain light minerals include labradorite (35%) and rock fragments (21%), whereas the heavy mineral fractions consist of hypersthene (11%), augite (3%), opaques (3%) and hornblende (traces) (Figure 9).

This study indicated that volcanic ash could sequester carbon rapidly and in large quantities. However, plants and microbial activities are required to enhance the C sequestration potential for pristine volcanic ashes.

Cyanobacteria have the ability to utilize both CO_2 and bicarbonate (HCO_3) as an inorganic carbon source to produce biomass. The growth of blue-green algae on the soil surface can significantly increase SOC.
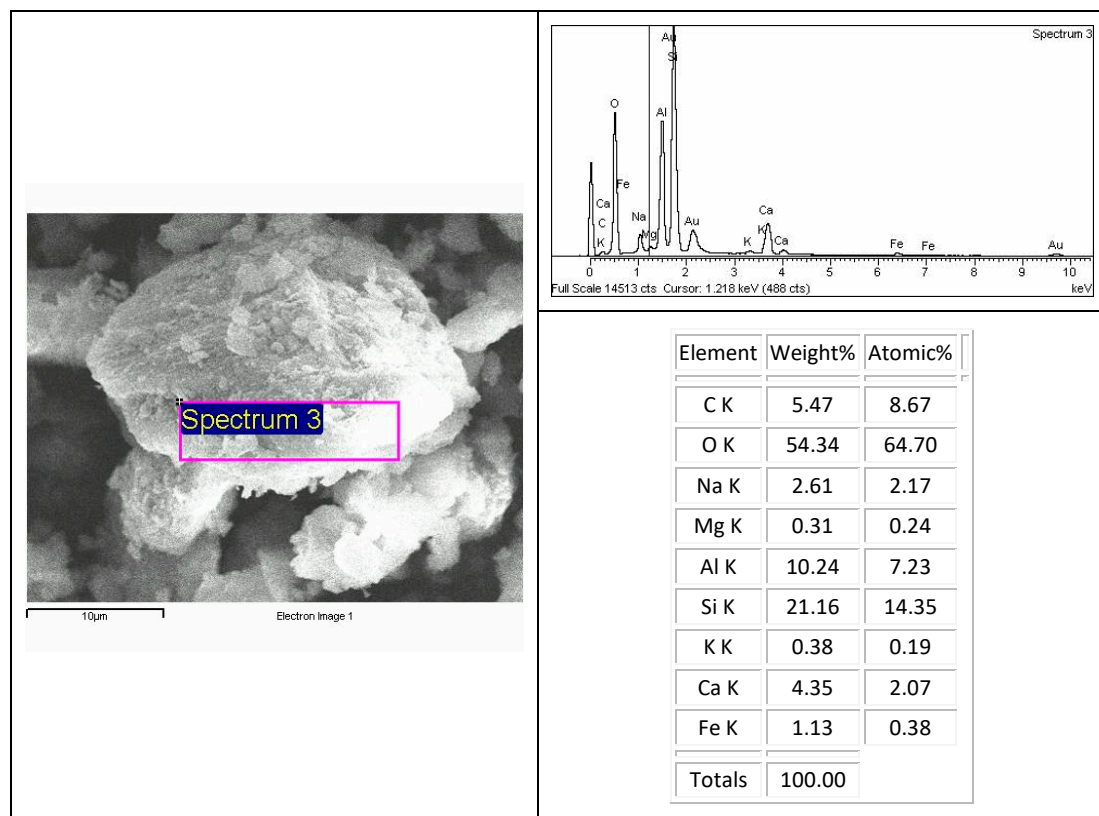
Figure 5. Surface characteristics of a volcanic ash grain with its elemental composition. Photo by Authors.
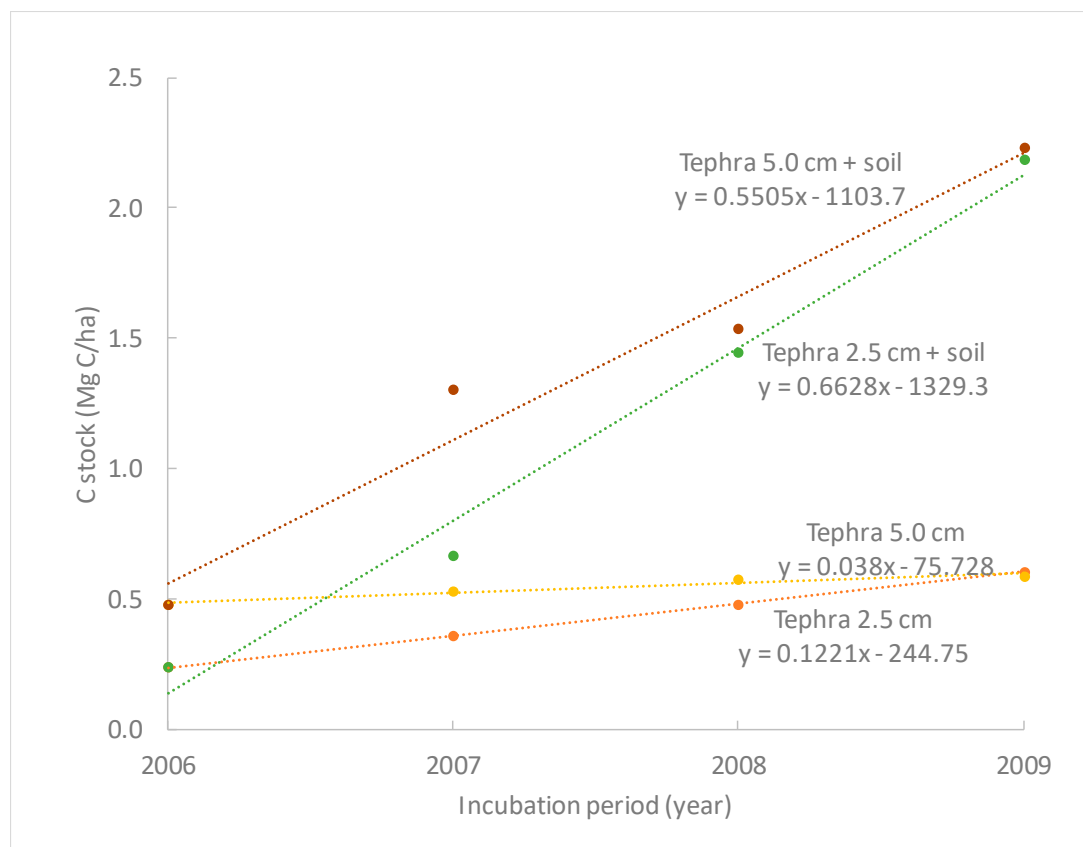

Figure 6. Soil C stock of volcanic ash (tephra) after four years of incubation [40].

The study [40] found that soil OC accumulated approximately linearly with time (Figure 5). The OC content of tephra layer increased significantly after 8 months and was nine times higher after 46 months as more vegetation emerged. The rate of OC accumulation on tephra on existing soil layer was 5–15 times faster than just only tephra. Rate on 2.5 cm tephra layer (with soil) was larger than 5.0 cm, highlighting the importance of life on existing soil. Sources of OC accumulated in the tephra layer during the first year was cyanobacteria, the second year was from cyanobacteria and lichens, and the third to fourth year was from shrubs or grasses.
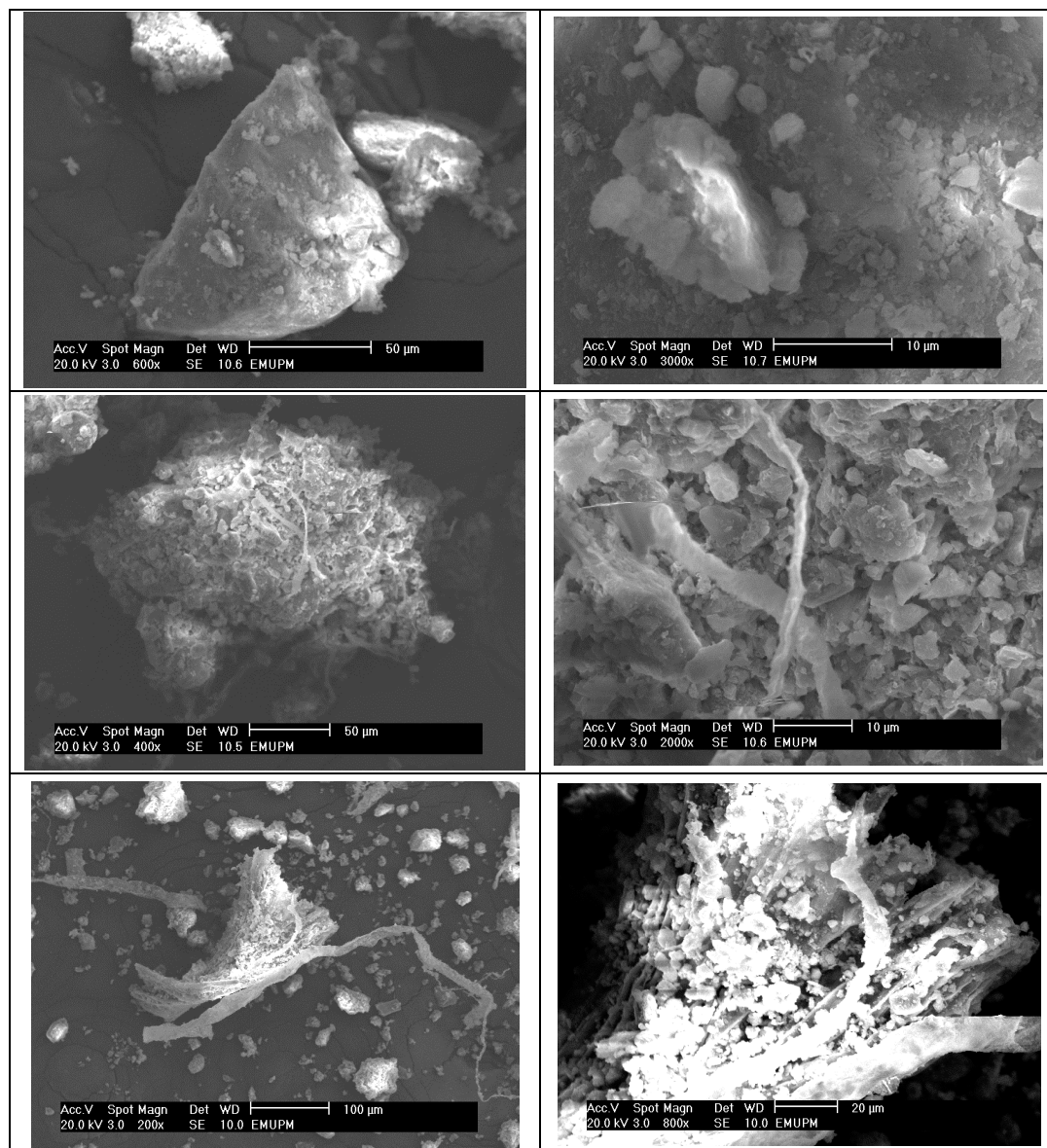
Figure 7. Scanning electron microscopy of volcanic ash from Mt Talang after 46 months of incubation.
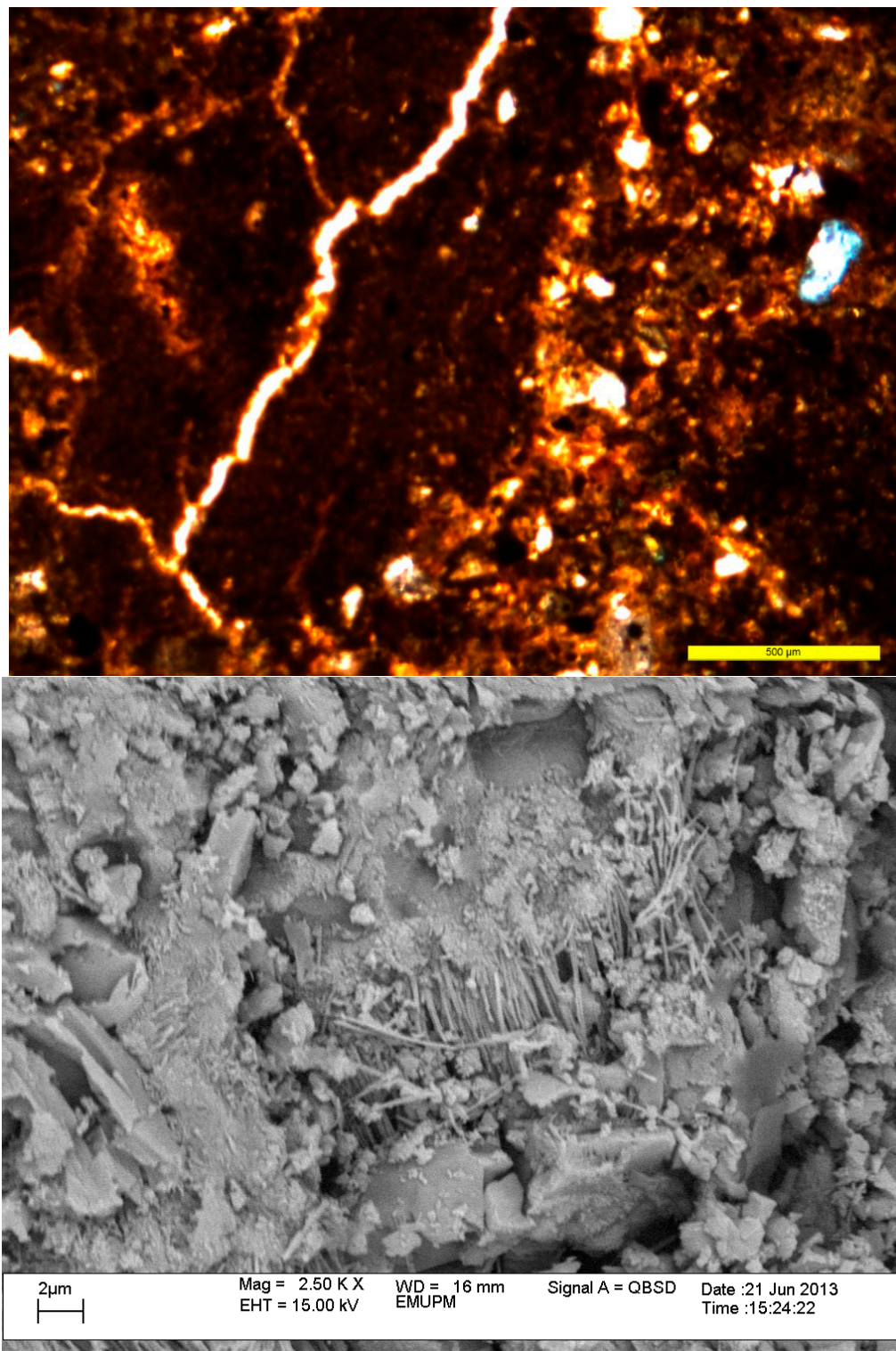
Figure 8. Root hyphae captured on a microscope (above) and micrograph of root hyphae attached to volcanic ash grains after 46 months of experiment. Photo by Authors.
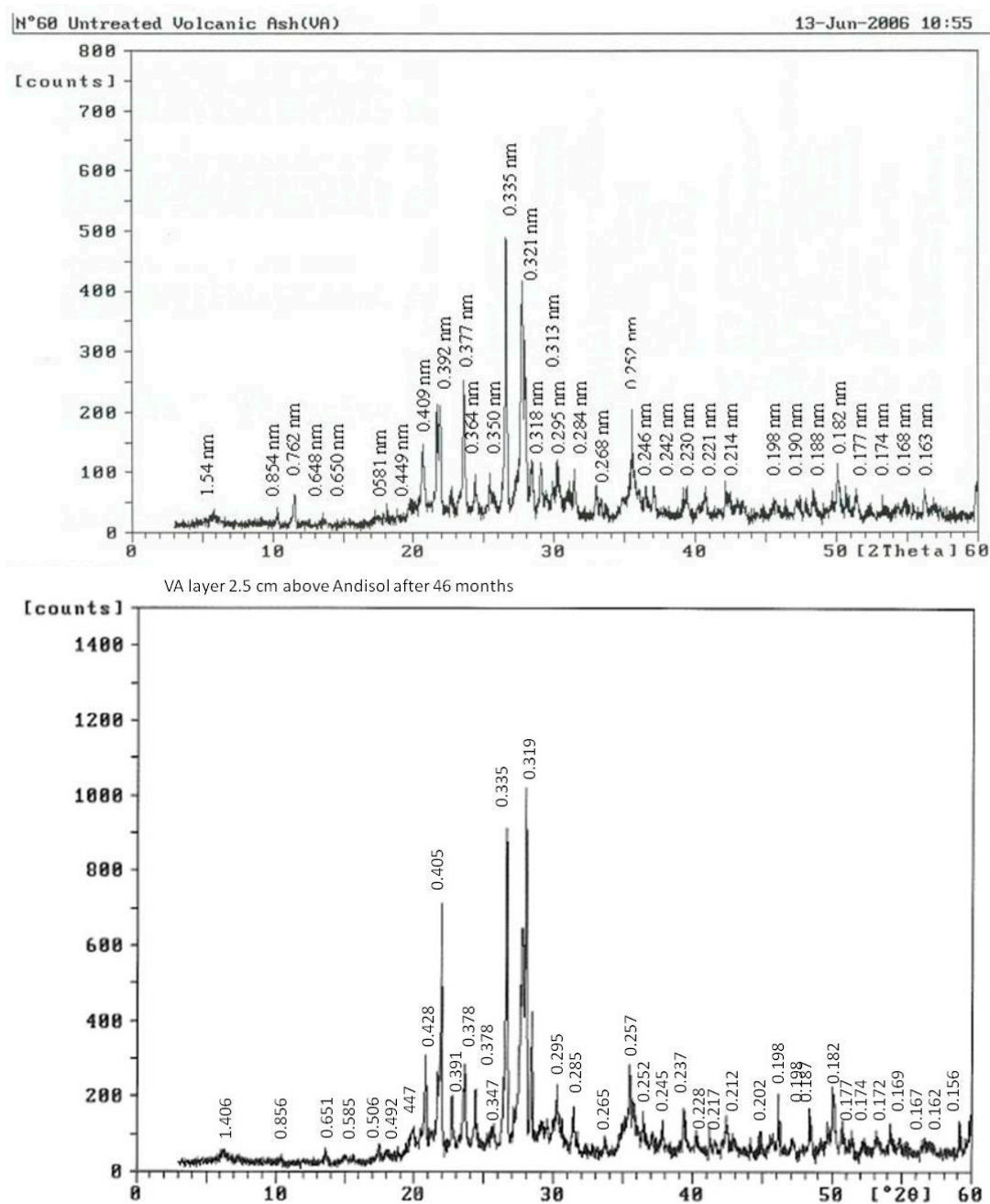
Figure 9. XRD traces of volcanic ash and volcanic ash changes after 46 months.

6.2. A Natural Experiment, Mt Sinabung

Mt Sinabung in North Sumatra was dormant for more than 400 years and came active again in 2010 (Figure 10). Eruptions were recorded in 2010, 2013, 2014, and 2016. On 28th January 2014, Sinabung erupted spewing pyroclastic flow and ash. Volcanic ash carried by rain-covered areas of the Sigarang Garang village, which is located Northeast of the foot of the volcano (Figure 11). After deemed safe, the local people returned to the village and cleaned up the substantial amount of ash and bagged them.

Figure 10. Volcanic eruption of Mt Sinabung and ashes covered Sigarang Garang Village in January 2014. Photo by authors.

Figure 11. Volcanic ashes from Mt. Sinabung covering local villages in January 2014. Photo by authors.

We visited the village in January 2017 and found ashes that were exposed to rainfall were already colonised by lichens, and some has established grasses. Ashes that were stored and not exposed to rainfall were in a dry condition without any plants (Figure 12). Tables 1 and 2 show some chemical analysis of these samples.

Figure 12. (**A**) Tephra deposit with initial carbon sequestration under atmospheric (**B**) Tephra in dry condition under a roof, 3 years after being deposited locally. Photo by authors.

Table 1. Carbon content and soil chemical properties of volcanic ash from Sinabung, which erupted in 2014, and measured in 2017.

Samples	pH (H_2O)	Total C (%)	Total N (%)	C/N
Ash with lichens (1 cm)	6.56	4.240	0.007	618.72
Ash with lichens (5 cm)	7.41	4.135	0.010	415.70
Ash with grasses	7.48	1.597	0.041	38.92
Ash without plants	4.80	0.184	0.002	107.41
Fresh Ash erupted 31 December 2016	5.90	0.099	0.000	

Table 2. CEC, Silica and alumina content of volcanic ash materials of Sinabung.

Samples	CEC ($cmol_c$ kg^{-1})	SiO_2 (mg kg^{-1})	Al_2O_3 (mg kg^{-1})	SiO_2/Al_2O_3
Ash with lichens (1 cm)	6.45	63.15	12.32	5.12
Ash with lichens (5 cm)	11.94	42.61	5.83	7.36
Ash with grasses	10.03	43.49	6.14	7.07
Ash without plants	8.60	49.23	11.27	5.00
Fresh Ash erupted 31 December 2016	1.91	63.68	15.16	4.20

The ash has an inorganic C between 0.1–0.2%. After three years of lichens colonisation, the C content increased to 4.1% (Table 1). Additionally, in materials covered with grass, the C content increased to 1.6%. This limited data demonstrated the high capacity to accumulate C over a short period.

6.3. Volcanic Ash, the Role of Soil Security

Here we would like to link volcanic ash in the framework of soil security [41] in the case study of Sinabung based on the framework outlined in Bouma [42].

Farmers in the area near Sinabung suffered because of repeated volcanic eruptions since 2010 and ashes constantly being deposited on their farming land. While the volcanic materials are valuable in terms of ecosystem services and boosting soil's capability, the ashes caused farmers lost their income. An estimated 53,000 hectares of farmland was destroyed by volcanic ash in 2014. Local farmers adaptation includes reducing cultivation area, regularly hosing off the ashes from plants, and planting quick maturing vegetables [43]. Some farmers were resettled to new area by the local government in

Siosar area, Karo regency, with each family getting a 500 m^2 plot for farming. In the new area, social, cultural, and economic life have flourished.

To ensure soil security for farmers in the future, the volcanic ash possess high capability for supplying nutrients and absorbing carbon, however, it's weathering took time (2–4 years). The current condition is an economical threat for farmers and if eruption continued it will be dangerous to live in the area. The role of connectivity is to inform farmers on the danger of volcanic threats and educating them about the risks. Farmers' perception of risk of volcanic hazards is a complex interaction between cultural beliefs and socio-economic constraints [44]. They also need to be informed on the valuable ashes that will keep their soil fertile for centuries. Farmers need to be trained to have a diverse range of cash crops as buffer. Or temporary shift to other types of occupation [45]. Policy from the local government need to make sure farmers are well-equipped to handle the disaster.

An example from Kinali village in Siau Island, part of the archipelagic district of Sitaro, North Sulawesi Province, Indonesia demonstrated that people have adapted to volcanic eruptions from Mount Karangetang [46]. This volcano is classified as both category 2 (high risk of lava, lahars, dense volcanic ash, and the possibility of pyroclastic flows) and category 3 (frequently affected by pyroclastic flows, lava, lahars, dense volcanic ash) by the Indonesian Government. However, the villagers realized that the volcano eruption bring fertility to the soil and in turn produce high-quality nutmeg that generates good income. The keys to such adaptation is social cohesion, strength knowledge and skills to face hazards, availability of good infrastructure, availability of food and water to cope with shortages, enough saving, and appropriate political support [46].

7. Ecosystem Recovery after Volcanic Eruption

Tephra, which initially does not contain organic carbon and life form, has a high capacity to capture CO_2 from the atmosphere through plants. The fine-size tephra, when exposed to the natural atmospheric environment, can store moisture, which enabled blue-green algae to colonise the bare surface layer forming an algae mat. This succession is followed by the development of layers of lichen, and then colonisation of vascular plants.

Ecosystem recovery after volcanic ash deposition depends on the thickness of the deposit. Re-vegetation was faster on shallow ash layer (2.5 cm) compared to thicker tephra layer, with a pedogenic time between 6 to 12 months [36]. The thin volcanic ash layer has positive nutrient responses to vegetation. The area around Mount St. Helens in Washington State USA with 10–20 cm thick tephra after the eruption in 1980 started to recover after ten years. Meanwhile, in Krakatau islands in Indonesia with >100 cm thick of ash layer, plant recovery and new soil development only commenced after 100 years [47]. While both areas are quite different in terms of climate and parent materials, it shows the importance of the thickness of the ashes.

Survival of vegetation underneath of tephra layer plays an important role on the reestablishment of ecosystem. Response capability of the buried plants is related to rhizome, shoots, and seeds, which survived after the eruption. Annual plants recovered faster than perennial plants [48]. Initially, plants suffered nutrient deficiency such as N and P to growth [20] and the presence of nitrogen-fixing pioneer plants can accelerate plant recovery or applying nitrogen fertilizer [49].. Organic matter in these volcanic soils tends to be stabile as they formed stabile organomineral complexes and physically protected.

8. Conclusions

Tephra deposited to the soil surface renew the soil and sustain its productivity. Also, tephra has a large capacity to sequester atmospheric carbon. As the ash weathers to secondary minerals more organic carbon can be preserved and protected in the soil. The protective mechanisms of SOC in these soils include organo-metallic complexes, chemical protection through low soil pH and toxic levels of Al, and physical protection by the micro- or nanopores.

Most studies on plant succession of volcanic ash regions focused on flora and fauna community changes and rarely look into the development of soil carbon. Accumulation of SOC in these

newly-deposited tephra plays an important role in the development of plants. The increase in SOC in tephra will enhance weathering and release nutrients that have positive effects on plant growth. Research on C dynamics and sequestration potential on newly deposited tephra is still rare. Beside its large C sequestration potential, it may provide clues on the initial pedogenesis.

Volcanic ash plays an important role in the global carbon cycle and ensures soil security in volcanic regions of the world. However, farmers living in the volcano area also need to be considered. Volcanic ash will severely affect agricultural area and farmers' livelihood. As the value of tephra as new soil fertile materials is yet to be quantified, it is underappreciated and becomes a nuisance for local farmers. Connectivity and codification needs to ensure farming in the area to take into account risk and build appropriate adaptation strategies and resilience.

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