Catena 172 (2019) 1–10

Contents lists available at ScienceDirect

Catena

journal homepage: www.elsevier.com/locate/catena

Temperature effects on the first three years of soil ecosystem development on volcanic ash

Ryunosuke Tateno[a,*], Chikae Tatsumi[b], Masataka Nakayama[b], Koichi Takahashi[c,d], Dorsaf Kerfahi[e], Jonathan Adams[e,f,**]

[a] Field Science Education and Research Center, Kyoto University, Kyoto, Japan
[b] Graduate School of Agriculture, Kyoto University, Kyoto, Japan
[c] Department of Biology, Faculty of Science, Shinshu University, Matsumoto, Japan
[d] Institute of Mountain Science, Shinshu University, Matsumoto, Japan
[e] Department of Biological Sciences, Seoul National University, Seoul, Republic of Korea
[f] Cranfield Soil and Agrifood Institute, Cranfield University, Cranfield, UK

ARTICLE INFO

Keywords:
Carbon accumulation
Nitrification
Primary succession
Temperature gradient
Weathering
Volcanic ash

ABSTRACT

Little is known of the earliest stages of soil ecosystem development on volcanic ash, and how this process is affected by temperature. We studied the first three years of soil development in a field-based mesocosm experiment, situated in different climates across Japan. Newly fallen, sterilized volcanic ash from the Sakurajima volcano (Kyushu, Japan) was placed into pots and positioned at six locations with mean annual temperatures ranging from - 1.6 °C to 18.6 °C. At 24 months into the experiment, C and N accumulation showed only a weak linear correlation with temperature, but by 36 months there was a clear exponential relationship. This applied only to the top 2 cm of the developing soil, and was not apparent in the lower part of the ash. We suggest that this acceleration in warmer climates relates to a positive feedback involving bryophyte cover, which had become much denser by the third year in the warmer sites. Surprisingly, the abundance of 16S rRNA gene copies of bacteria, fungi, archaea - as well as ammonia oxidizers – did not increase from 12 months to 36 months, and did not show any relationship to temperature, suggesting that input from plants is the major factor in increasing C and N buildup in the soil. Overall it appears that temperature effects on bryophyte cover buildup may be important in controlling the temperature relationship in soil development on volcanic ash.

1. Introduction

The process of soil development in primary successional environments has long been a major theme in ecology and geology (Clements, 1916; Huggett, 1998). As well as studies on soil development in debris flows (Turk et al., 2008; Turk and Graham, 2009), sand dunes (Lichter, 1998), and glacier forelands (Kaye et al., 2003; Mavris et al., 2010), there has been a considerable amount of work on volcanic primary succession – including both lava flows and volcanic ash deposits (Vitousek et al., 1993; Vitousek and Farrington, 1997; Kato et al., 2005). There have been studies on soil development in ash deposits that at the start of the study were already several years old (Fujimura et al., 2012, 2016), or older (Ohta et al., 2003; Ibekwe et al., 2007; Zeglin et al., 2016), but there has been little work on the very earliest stages of soil ecosystem development. The first three years or so of soil ecosystem development have barely been studied, perhaps due to the difficulties in gaining access to recent volcanic eruption sites.

It is unclear to what extent the major living components of a soil system – bacteria, archaea and fungi, including important functional groups for biogeochemical processes such as ammonia oxidizers – are present in these earliest stages. Studies on volcanic ash deposits that were already several years old have suggested that early stages in volcanic ash soil development are carried out by chemoautotrophs (King, 2003; Fujimura et al., 2012, 2016). For example, Fujimura et al. (2012, 2016) reported the importance of Fe(II)- and H_2-oxidizing chemolithotrophs in a 3.5–6.6 years old ash deposit in Miyake Island, Japan, in initiating the accumulation of organic carbon (C) and then contributing to the development of subsequent microbial communities. Furthermore, Freeman et al. (2009) pointed out the importance of photoautotrophic bacteria (cyanobacteria) in high-elevation barren

* Correspondence to: R. Tateno, Field Science Education and Research Center, Kyoto University, Kyoto 6068502, Japan.
** Correspondence to: J. Adams, Soil and Agrifood Institute, Cranfield University, College Rd, Cranfield MK43 0AL, Bedfordshire, UK.
E-mail addresses: rtateno@kais.kyoto-u.ac.jp (R. Tateno), j.m.adams@cranfield.ac.uk (J. Adams).

https://doi.org/10.1016/j.catena.2018.08.009
Received 1 June 2018; Received in revised form 9 August 2018; Accepted 10 August 2018

soils. Only later were larger organisms such as bryophytes seen as having a major role (O'Toole and Synnott, 1971).

It is also unclear what relationship, if any, the process of soil ecosystem development shows to climate - especially temperature. Temperature is seen as a major controlling factor in ecosystem establishment or recovery (Pastor and Post, 1986; Vitousek and Farrington, 1997) as well as pedogenesis (Tsai et al., 2010), but it is unclear how early in the process it becomes important. In this study we were interested in experimentally comparing the effect of temperature on soil ecosystem development from volcanic ash, over the first three years of primary succession. This study was a follow-on from Kerfahi et al. (2017), which discussed the first two years of experimental soil ecosystem development. As we will report here, a pattern was obtained when Year 3 was added to the dataset, with implications for understanding the processes of ecosystem establishment on volcanic ash.

Furthermore, we report here on the inorganic nitrogen (N) dynamics at very early stage of soil development. Nitrogen is not normally present in parent materials such as rock, lava and volcanic ash in certain kinds of metasedimentary and metavolcanic rocks (Holloway et al., 1998). N deposition from the atmosphere is thought to be the primary source in the earliest stages of microbial community development on volcanic ash, while microbial N fixation eventually becomes more important.

Our main working hypothesis here was that there would be a temperature effect on the rate of soil ecosystem development (organic C, organic N, inorganic N, abundance of each of the major microbial groups) would become apparent by Year 3 (36 months) of the experiment. Given the large range of climates studied in this experiment, it was surprising to us that no strong temperature effect on C, N or microbial biomass emerged in the first two years to 24 months (Kerfahi et al., 2017). We anticipated that as the soil ecosystem developed, including development of a bryophyte cover, this effect would eventually show itself more clearly because of the temperature sensitivity of plant growth and metabolism in producing exudates, dead organic material, etc. that would enrich the soil in C and N. So far, there has been little evaluation of the effect of temperature on the earliest stages of ecosystem development on volcanic substrates, under standardized conditions. While a strong temperature effect would certainly be expected on basic biological and ecological principles, it is important to test such assumptions if ecology is to be rigorously based.

2. Materials and methods

2.1. Source of the volcanic ash

Mt. Sakurajima (31°35′N, 132°39′E, height 1117 m) is an active volcano located in southern Kyushu Island, Japan. Mt. Sakurajima is situated in the Aira caldera created by catastrophic eruption of around 29,000 years BP (Kobayashi et al., 2013). Large eruptions have periodically occurred since then, interspersed with less active phases. In the last thousand years, three large eruptions occurred in the Bunmei era (1471–1476), An-ei era (1779–1782), and Taisho era (1914–1915) (Biass et al., 2017) – mainly involving lava flowing from upper parts of the volcano and covering parts of the lower slopes. Since 2006, a new phase and different type of volcanic activity started, involving small explosions and ash deposition over the surrounding slopes over the volcano. These have become more active over time (Iguchi et al., 2013), and presently thousands of small eruptions occur annually (Miwa et al., 2013). The volcanic ash of Mt. Sakurajima is characterized as slightly acidic, of relatively low redox potential, and enriched in ions such as Si, Na, Cl, and SO_4 (Kawano and Tomita, 2001). Detail of mineral composition of volcanic ash was summarized in Hillman et al. (2012) and Miwa et al. (2013).

Table 1
Mean annual temperature (MAT), mean annual precipitation (MAP), elevation, latitude and longitude of each site.

Site name	MAT (°C)	MAP (mm)	Elevation (m)	N	E
NK_2800 m	−1.6	Unknown	2800	36°07′	137°33′
NK_1450 m	7.0	1991	1450	36°07′	137°37′
NK_650 m	12.1	1045	650	36°15′	137°57′
KY	14.6	1584	140	35°04′	135°46′
TK	14.0	3410	660	31°31′	130°46′
SJ	18.6	2266	3	31°35′	130°35′

2.2. Experimental sites

Six experimental sites were used to position pots of volcanic ash in trays. Six locations across Japan whose mean annual temperature ranged from −2.6 to 18.6 °C (Table 1). We used recently deposited ash from Mt. Sakurajima for the experimental pot microcosms, as described below.

i) The Sakurajima site (SJ) is in the warm temperate zone of southern Japan, with a mean annual temperature of 18.6 °C (1981–2010) and a mean annual precipitation of 2265.7 mm (1981–2010) according to Kagoshima Meteorological Station, Japan (31°33′N, 130°33′E, 4.0 m a.s.l.). The areas sampled were on the lower slopes of the volcano, around 25–50 m above sea level. The site was situated in an open area in the native pine scrub.
ii) The Takakuma site (TK) is in a warm temperate forest site in the surrounding hills near the Sakurajima Volcano, in the Takakuma Experimental Forest of Kagoshima University, southern Kyushu, Japan (31°31′N, 132°46′E, 538 m a.s.l.). The site is about 10 km from the crater of Sakurajima with mean annual precipitation is 3410 mm and a mean annual temperature of 14.0 °C (1999–2004). The site was situated in an open area by a forest road.
iii) The Kyoto site (KY) is in a warm temperate forest site about 600 km northeast of Sakurajima at Kamigamo Experimental Station, Kyoto University near Kyoto City, Japan (35°04′N, 135°46′E, 140 m a.s.l.). Mean annual temperature is 14.6 °C and annual precipitation is 1538.6 mm (Kamigamo Experimental Station in 1981–2010). The samples were positioned on an open lawn next to the site weather station.
iv, v, vi) Three sites were set at different elevations on Mt. Norikura (summit 3026 m a.s.l.) in central Japan, located 800 km northeast of Sakurajima. The elevations of the three experimental sites on Norikura were 650 m, 1450 m and 2800 m a.s.l. (described here as NK-650 m, NK-1450 m, and NK-2800 m). There were no nearby meteorological stations of each site for Norikura, but we calculated MAT based on the nearest meteorological stations on the lower slopes and near summit of Mt. Norikura. Assuming a mean lapse rate is 0.6 °C/100 m, MAT of NK-650 m 1450 m and 2800 m can be calculated 12.1 °C, 7 °C and −1.6 °C, respectively (Kerfahi et al., 2017).

For comparison of C and N contents of mature developed soils in Japan with the volcanic ash in the experimental pots at weight basis ($g\,kg^{-1}$), we used the published data set from 39 sites of well-developed vegetated soils throughout the Japanese archipelago covering 44°20′N to 26°50′N (Urakawa et al., 2015).

2.3. Setting up in-situ incubation experiment

We collected newly fallen volcanic ash on plastic sheeting in an open space (an unused parking lot) near the Sakurajima volcano, over a period of several weeks on March 2012. The freshly accumulated ash was removed and stored every week. The freshly accumulated ash samples were sieved at 2 mm mesh screen to remove large particles before use. The ash was sterilized by heating in portions to 200 °C in a