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Dust, climate, and soil biogeochemistry on volcanic islands

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Abstract

Dust input to the landscape plays an important ecological role on a global scale. Work by others on the Hawaiian Islands has demonstrated that dust provides nutrients for ecosystem development and maintenance in volcanic terrains. We review the bedrock geochemistry of volcanic islands (Galápagos, Azores, Canaries, South Shetlands) from different climatic regions with a variety of aeolian dust fluxes. We estimate fluvial chemical weathering fluxes; with published dust fluxes, we examine the role of dust input into soil and ecosystem development. Mean annual temperature from the South Shetlands and Canary Islands are used to predict Σcations from chemical weathering and atmospheric fluxes of P. Published chemical weathering fluxes are computed using the first 100 ka loss rates for the Hawaiian Islands; values for other locations were determined by comparing mean annual rainfall to Hawaiian mean annual rainfall. Furthermore, to assess the process of rock transformation into soil, we compare elemental losses or gains and the role of dust in ecosystem maintenance with estimates for Hawaii. Our calculated atmospheric total phosphorus fluxes range from 0–1 mg P m^{-2} a^{-1} for South Shetland and the Galápagos Islands and up to 30 mg P m^{-2} a^{-1} for the Canary Islands. The Galápagos Islands have a low calculated P weathering flux (6 mg P m^{-2} a^{-1}). That estimate, along with the published observation that most dust reaching the Galápagos originates from high nitrate soils of the Atacama Desert suggests the Galápagos ecosystem may be extremely phosphorus limited.

Keywords: Galápagos Islands; basalt; chemical weathering; phosphorus.

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1. Introduction

Ecosystems developed on volcanic islands often depend on rock weathering as a source of nutrients, particularly for phosphorus, but also for calcium, potassium, and silicon. This weathering dependence occurs, in particular, early during ecosystem development. Hawaii has been well studied as a model ecosystem in this regard. However, other volcanic islands have been less well or unstudied for the their sources of nutrients and the importance of atmospherically delivered P. In particular, the Galápagos Islands of Ecuador are important ecological sites valued for their role in the development of Charles Darwin's ideas about evolution, and for the home of the giant tortoises (*Chelonoidis spp.*) which are currently characterized as vulnerable by the International Union for the Conservation of Nature.

During ecosystem development, plants use up the rock-derived nutrients (Ca, K, Na, Mg, Si, and P) (Chadwick et al., 1999) while atmospherically-derived nutrients, primarily N, are accumulating. As a result of the changing sources of nutrients to an ecosystem, young ecosystems are typically nitrogen limited and old ecosystems are typically phosphorus limited. This model, originally proposed by Walker & Syers (1976) cited the low rate of total phosphorus (TP) input atmospherically and thus the requirement for weathering of soil parent material to provide P for plant development during the first 20,000 years of soil development. As a result, early during soil or ecosystem development, nitrogen-fixing plants dominate until soils have accumulated sufficient amounts of organic N to supply ecosystem requirements. Once all rock sources of P had been depleted, non-nitrogen fixing organisms can then compete successfully for the organic sources of both N and P (Walker & Adams 1958; 1959). Apatite is probably the primary source of P in most parent rock (Williams et al, 1969) and serves as the primary source of P to ecosystems until depleted, whereupon organic P release is the primary source of P. In addition to rock type, landscape age has been shown to be an important control on weathering rates and ecosystem development (Carey et al, 2005).

Experiments conducted on ecosystems developed on a chronosequence of six basaltic lava fields in Hawaii quantified the rapid weathering and nearly complete loss of base cations there, based on profiles measured in soil developed on lavas of ages of 300–20,000 years and a slower release of Al, P, and Si on soils developed on basaltic lava flows up to 4.1 million years in age (Vitousek et al., 1997; Chadwick et al., 1999; Crews et al., 1995). Elemental additions as part of those experiments confirmed the Walker and Syers model of N limitation early in ecosystem development and P limitation at the 4.1 Ma site.

2. Methods

We used published data for world-wide dust fluxes (Jickells et al., 2005) and modeling results for world-wide TP fluxes (Mahowold et al., 2008) to determine aerosol TP input to several volcanic island locations. We determined chemical weathering fluxes at each location studied by using the rate of P mobilization rates from 10 ka basalt flow for Hawaii (Chadwick et al., 1999) and ratio of mean annual rainfall at each location to the Hawaiian 250 cm rainfall.

The range of P fluxes we calculated based on rock weathering and rainfall in these same locations (Table 1) varies only by a factor of approximately three, a considerably smaller range than the aerosol TP fluxes.

Table 1. Estimated phosphorus input to ecosystems on volcanic islands. Atmospheric fluxes were determined using modelled inputs from Mahowald et al. (2008). Chemical weathering fluxes were calculated using rates for Hawaii from Chadwick et al. (1999) and the ratio of the mean annual rainfall to that of Hawaii for 250 cm rainfall and P mobilization rates from the 20 ka basalt flow on the Big Island of Hawaii.

Island location	Latitude	Mean annual rainfall (mm)	Atmospheric dust total P flux (mg m^{-2} a^{-1})	Rock weathering P flux (mg m^{-2} a^{-1})
Galápagos	0°	417	<0.5–1	6
Canary Islands	28° N	170	5–30	5
Azores	39° N	1046	2	18
South Shetlands	63° S	700–1000	0.5–1	9

3. Results

The Galápagos Islands provide a chronosequence of sites over a somewhat smaller range of time, of approximately 1000 years to 1.4 Ma years. Based on a synthesis of three models (Ginoux et al., 2001; Duce et al., 1991; Mahowold & Luo, 2003) and one satellite observational study (Kaufman et al., 2005), Jickells et al. (2005) showed that the Galápagos Islands, at approximately 0° latitude and 1000 km west of Ecuador, receive a low total dust aerosol flux of <0.5 g m^{-2} $year^{-1}$. The mineral fraction of the dust is the most important source of total phosphorus globally and averages 700 pm total phosphorus (Taylor and McClennan, 1995). In the Galápagos Islands, the total phosphorus (TP) input via dust is as little as 0.5 mg P m^{-2} a^{-1} (Mahowold et al., 2008). Total atmospheric phosphorus flux to other volcanic islands geographically widely distributed from 39° N to 63° S suggest an atmospheric TP flux of 0.5–1 mg P m^{-2} a^{-1} to the South Shetland Islands at 63° S, 2 mg TP m^{-2} a^{-1} to the Azores Islands, and 5–30 mg TP m^{-2} a^{-1} to the Canary Islands (Table 1) based on modeling results published by Mahowold et al. (2008). The range of P fluxes we calculated based on rock weathering and rainfall in these same locations (Table 1) varies only by a factor of approximately three, a considerably smaller range than the aerosol TP fluxes.

4. Discussion

Our calculations are based on a series of assumptions, including that the mafic volcanic rocks that serve as the protoliths for the soils on volcanic islands will weather faster than the continental-like dust that is the likely composition of the mineral fraction of the aerosol input. The basalts composing the different volcanic islands have different amounts of phosphorus and vary fivefold. On the Galápagos, a set of age-dated basalts showed an average P of 1.52 mg g^{-1} and a range of 0.8–3.7 mg g^{-1}

Santa Cruz, one of the oldest and tallest of the Galápagos Islands has an age of 1.4 Ma. Its height creates a rain shadow so all the ecological zones are present on Santa Cruz. In the Hawaiian chronosequence the Molokai sites are the most similar in age to Santa Cruz. In Molokai, at the 1.5 Ma age site in Hawaii, the P weathering rate has decreased by approximately one hundredfold. By analogy then, Santa Cruz island may now have an order of magnitude greater TP input from dust than from rock weathering (~1 mg m^{-2} a^{-1} vs. 0.06 mg m^{-2} a^{-1}).

Table 2. Ages of rock and total phosphorus content of basalts on volcanic islands where soil has developed.

Island location	**Rock age, ka**	**Total P ($mg\ g^{-1}$)**	**Data source**
Fernandina, Galápagos	<0.8	0.0988	Kurz and Geist (1999)
Fernandina, Galápagos	<0.4	0.0960	Kurz and Geist (1999)
Cerro Azul, Isabela, Galápagos	69	0.0977	Kurz and Geist (1999)
Floreana, Galápagos	80	0.1005	White et al. (1993)
Floreana, Galápagos	1520	0.2261	White et al. (1993)
Floreana, Galápagos	103	0.0528	Kurz and Geist (1999)
Floreana, Galápagos	26	0.0611	Kurz and Geist (1999)
Floreana, Galápagos	272	0.0622	Kurz and Geist (1999)
Genovesa, Galápagos	0	0.053	White et al. (1993)
El Hierro, Canary Islands	—	0.1758	Day et al. (2010)
El Hierro, Canary Islands	—	0.1312	Day et al. (2010)
El Hierro, Canary Islands	—	0.254	Day et al. (2010)
El Hierro, Canary Islands	—	0.2317	Day et al. (2010)
San Miguel, Azores	—	0.1758	White et al. (1979)
Graciosa, Azores	—	0.1340	White et al. (1979)
Pico, Azores	—	0.0977	White et al. (1979)
Pico, Azores	—	0.1340	White et al. (1979)
South Shetlands	—	0.0949	Lyons et al. (2013)
South Shetlands	—	0.0977	Lyons et al. (2013)
South Shetlands	—	0.1089	Lyons et al. (2013)
South Shetlands	—	0.0977	Lyons et al. (2013)

Few age dates are available from the basalts of the Galapagos Islands. A range of ages from 400 years to 1500 ka has been determined for rocks from the islands of Fernandina and Santa Cruz of the Galápagos (Table 2) for a chronosequence analogous to those used by Chadwick et al (1999) on the Big Island of Hawaii to Molokai. Over that chronosequence, the P weathering rates have declined by 100×. Mass losses in Hawaii at lower rainfalls (50–100 cm a^{-1}) increased by over a factor of two from 10 ka to 350 ka (Porder et al., 2007). By analogy with the Hawaiian chronosequence, Santa Cruz island should have much more P from dust than from rock weathering, approximately 1 mg P $m^{-2}\ a^{-1}$ for dust compared to as little as 0.06 mg P $m^{-2}\ a^{-1}$ from rock weathering.

Based on the notion that rock weathering depends not only upon ambient temperature but also on the amount of rainfall, a conceptual model for the changing ecosystem dependence upon rock weathering or dust input for TP can be proposed (Fig. 1). On volcanic islands, initially the ecosystem dependence upon dust for P is of low importance. Over time dust becomes more important as a source of TP to the ecosystem but the importance of dust as a source of TP depends upon the amount of rainfall to the system. Particularly on islands with high rainfall, depletion of the rock sources of P, most commonly the mineral apatite, occurs quickly, and after about 100–200 ka dust is a major source of P to the ecosystem. By about 1 Ma, there is very little P left in primary minerals to serve as a nutrient to the plant ecosystem and dust is the primary source of mineral P.

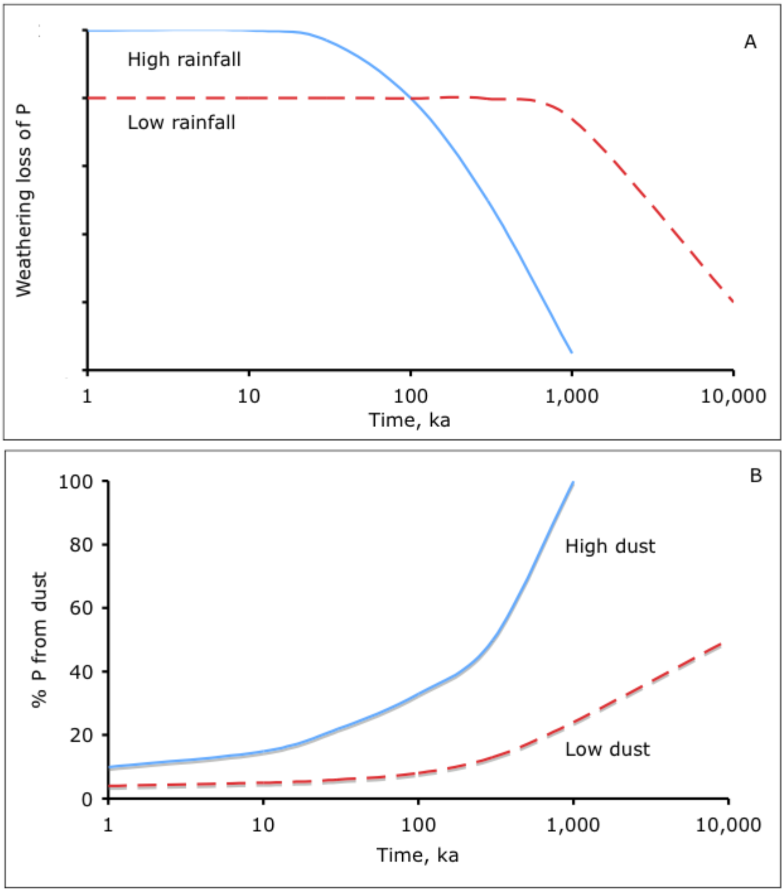

Fig. 1. Model of phosphorus sources to volcanic islands over time. A. Rock weathering loss of P on islands with high rainfall and low rainfall. B. Dust input of P to islands with high dust inputs and low dust inputs.

Organic P is being recycled by this time. Similar processes occur on volcanic islands with low rainfall, but dust may be a significant contributor of TP at early ages of ecosystem development on island with low rainfall due to the slow weathering of rock in systems with little rainfall. The rock source of TP may last longer, but on islands with low rainfall, dust becomes even more important later in time on low rainfall islands.

The importance of dust as a source of TP to volcanic islands may change over geologic time. Changing sources of dust to the Galápagos Islands during the Holocene may have provided a variable source of P and other plant nutrients and also act as a legacy source of nutrients today. An analysis of sediment cores from El Junco Crater lake show increased grain sizes compared to present at 800 years BP and also at 4200 yr BP, 3200 years BP and 200 years BP (Conroy et al., 2008). They interpreted the grain size increases as due to increased rainfall and perhaps increased dust removal at those times.

The dust legacy to the Galápagos Islands may also be recorded in South American ice core records. Ice core data from Peru showed increased dust between approximately 4500 and 4000 years BP, fluxes that are as great as 15× background (Thompson et al., 1995). Ice cores from farther south, from Bolivia, document a different dust record, with multiple times of higher dust loads between 6000 and 2000 years BP, fluxes that are about 8× higher in the Holocene than during the last glacial maximum (Thompson et al., 1998). These unusual and high dust fluxes may reflect drought on the Altiplano and higher snow lines or they may reflect a regional source of dust. In the Galápagos Islands, there may remain a legacy source of dust accumulated during these times in the past when much higher dust fluxes played a very important role in ecosystem health and the soils there may still retain some legacy of those higher dust fluxes.

5. Conclusions

Seminal work by Vitousek, Chadwick, Derry, Porder and their colleagues has demonstrated that dust is an extremely important source of plant nutrients. In their work in Hawaii they showed that this is especially important for Hawaiian soils greater than 170 ka. The dust reaching Hawaii comes from Central Asia and its TP content is 0.17–0.35 mg m^{-2} a^{1}.

As chemical weathering rates decline in time and the mineral nutrient sources become depleted in the rocks, the importance of dust as a source of plant nutrients becomes more significant for all volcanic island chains or where volcanism has become dormant. Most dust reaching the Galápagos Islands comes from the Atacama desert with very high N concentrations. The Galápagos Islands ecosystems are likely to be extremely P-limited, even early in ecosystem development.

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