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The flux of Saharan dust to Panama and its influence on soil geochemistry

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Abstract

The long-range transport of Saharan dust to South America, the Caribbean Basin, and even the southern United States has been demonstrated by both remotely sensed satellite data and direct measurements. In this work, we use Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) data and deposition models developed by Yu et al. (2015) and African dust geochemical data (Muhs et al., 2010; Moreno et al., 2006) to calculate the elemental influx to the landscape in Panama. These deposition values are compared to our own soil geochemical data collected from soil pits and rock data from the Upper Rio Chagres watershed of central Panama. The CALIOP-based estimate of Saharan dust deposition to Panama is 50 kg ha^{-1} yr^{-1} and the flux of phosphorus is 35-122 g P ha^{-1} yr^{-1}. Dust-derived Ca can add as much as ~4% to total topsoil Ca concentrations. Lower dust contributions were calculated for other key elements, such as K (~0.35%) and P (0.03%). Contributions of dust to soil depend on bedrock type, and vary seasonally, though spatial variation is likely to exist as well.

Keywords: Panama; African dust; Atmospheric deposition; Phosporous; Nutrient cycling

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1. Introduction

Tropical forests depend on phosphorus in soils to maintain plant growth and development. In the Vitousek Landscape Model, landscapes in humid environments become depleted in crucial elements, such as calcium, magnesium, potassium, and phosphorus, from weathering over time, which drives a shift in soil composition from rock-derived to atmospherically-derived nutrients (Vitousek et al., 1997). Atmospheric inputs of nitrogen are continuous to the landscape, resulting in phosphorus depletion and nitrogen enrichment in older systems.

On strong seasonal winds, material from Northern Africa traverses the Atlantic Ocean and is deposited on tropical landscapes in Central and South America. Each July, the Intertropical Convergence Zone (ITCZ) moves northwards, shifting the trans-Atlantic dust plume over Panama. Recent estimates suggest nutrient inputs to terrestrial ecosystems from this dust plume are high, with a June-July flux equivalent to between 10 and 29% of P in nearby monthly litter fall (Gross et al., 2016). Deposition of Saharan dust has been shown to alter soil geochemistry in other areas, such as the Canary Islands (Muhs, et al., 2010), Caribbean (McClintock et al., 2015; Pett-Ridge, 2009; Muhs & Budahn 2007), the southern United States (Zamora et al., 2013), and the Amazon Rainforest (Yu et al., 2015; Bristow et al., 2010; Okin et al., 2004; Talbot et al., 1986), yet the elemental effects on Panamanian soils remain poorly characterized.

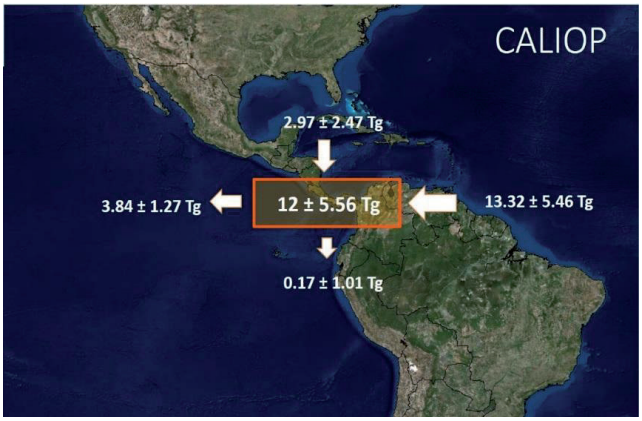

Fig. 1. Flux of Saharan dust into Panama with zonal and meridional transport from Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP). The flux box is defined between 4°N and 12°N in latitude and between 75°W and 95°W in longitude. The total deposition of dust is 12 ± 5.56 Tg over an 8-year average

2. Methods

Soil samples were collected from the Upper Rio Chagres watershed, in central Panama. Three soil profiles from different rock lithologies (gabbro, hydrothermally altered basalt (a.k.a. “greenstone”), and granite) were analyzed for major and trace elements at The Ohio State University using X-ray fluorescence (XRF). Soil trace elemental concentrations were compared to published source rock (Harmon et al., 2016; 2009) and dust flux information (Moreno et al., 2006; Muhs et al., 2010) to determine the influence of dust on soil chemistry.

Deposition rates were calculated using the Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP)model, developed in Yu et al. (2015). The area of Panama was defined as a region between 4°N and 12°N in latitude and between 75°W and 95°W in longitude. The model, which defines geographic areas more realistically and accounts for zonal and meridional transport of dust, separates dust from non-dust aerosols through depolarization ratio measurements. A multi-year data set spanning eight years from 2007 to 2014 was used to determine seasonal, annual, and average depositional values (Fig. 1). The eight-year average annual deposition value of 12 ± 5.56 Tg was used with published literature values on the geochemistry of Saharan dust (Gross et al., 2016; Muhs et al., 2010; Moreno et al., 2006) to calculate P deposition to the Panamanian landscape and percent contribution of oxides in dust to topsoil.

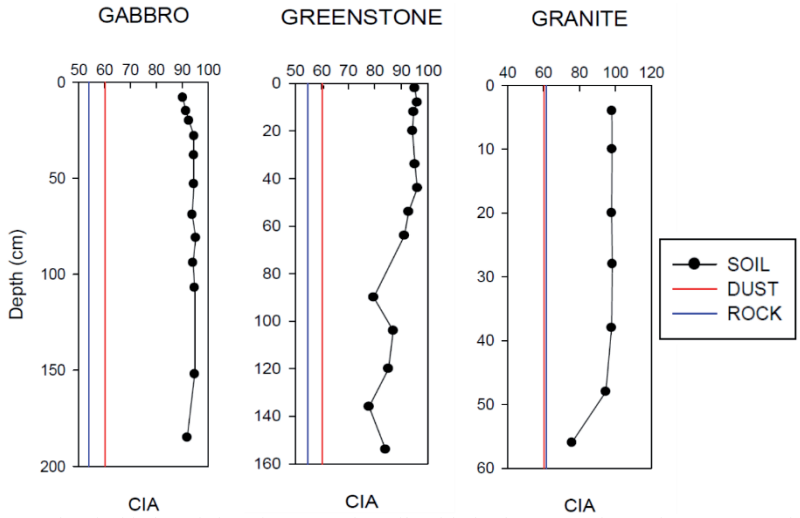

Fig. 2. Chemical index of alteration (CIA) for soils with depth compared to rock (Harmon et al., 2016; 2009) and dust values (Moreno et al., 2006)

3. Results

The highest dust deposition to Panama occurs annually in June and July during the wet season, with fluxes traversing from East to West and North to South, as previously noted in Gross et al. (2016). Chemical index of alteration (CIA) values were calculated for the soil profiles and compared to dust (Moreno et al., 2006) and source rock values (Harmon et al., 2016; 2009). All three soils had high CIA values (>80%), typical of highly weathered soils in the humid tropics. In highly weathered soil environments such as this, rock-derived elements are usually depleted with respect to source rocks and atmospheric dust, which is demonstrated in the depth profiles (Fig. 2).

The CALIOP-based estimate of Saharan dust deposition to Panama is 50 kg ha^{-1} yr^{-1} including dust import and export in the zonal and meridional directions (Fig. 1). There is strong seasonal variability in deposition, with much of the inputs occurring in the spring months and the start of the wet season (Fig. 3). Concentrations of specific elements were not extrapolated from this model output. Instead, P concentrations from published literature values of Saharan dust of 740 ppm (Moreno et al., 2006) and 700 ppm (Muhs et al., 2010) near the Bodélé Depression, and 2440 ppm (Gross et al., 2016) near Panama were used to estimate the total African dust flux of P to Panama, resulting in a range of 35-122 g P ha^{-1}

yr^{-1}. Dust-derived Ca makes up ~4% of topsoil Ca concentration. Other key elements, such as K and P, showed lower contributions (~0.35% and ~0.03% respectively), but continual inputs of these elements could support long-term ecosystem productivity.

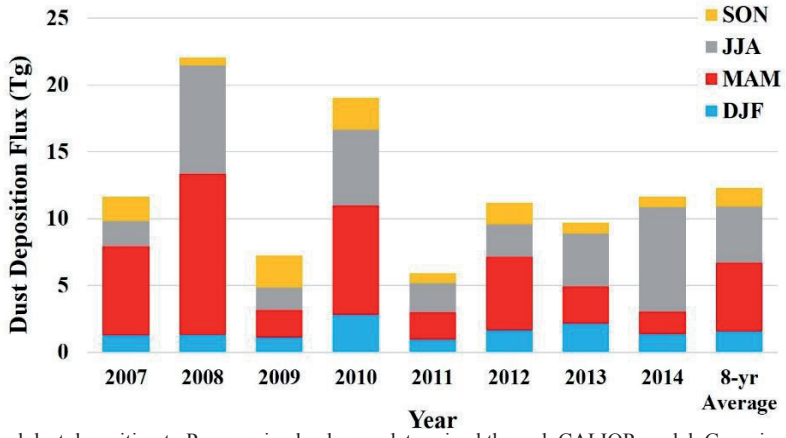

Fig. 3. Annual dust deposition to Panamanian landscape determined through CALIOP model. Grouping of months based on trans-Atlantic transport of dust in northeasterly trade winds beginning in boreal winter (DJF) and continuing through spring (MAM)

4. Discussion

Evidence of Saharan dust deposition has been found in many parts of the Americas. A key component of this dust is P, which in highly weathered environments in the humid tropics, such as Panama, helps sustain primary productivity. Our P deposition estimate of 35-122 g P ha^{-1} yr^{-1}, as shown in Table 1,is comparable within one order of magnitude to the estimates for the Amazon basin (Yu et al., 2015; Bristow et al., 2010; Talbot et al., 1986) and Puerto Rico (Pett-Ridge, 2009). Using the P concentration in dust of 780 ppm (Bristow et al., 2010) cited in Yu et al. (2015), our area normalized annual P deposition (~39 g P ha^{-1} yr^{-1}) is similar to that of the Amazon Basin (23 g P ha^{-1} yr^{-1}). Both deposition rates were calculated using the CALIOP model and distinguished Saharan dust from other sources using depolarization ratio measurements.

The range of dust-derived P deposition rates listed for Panama in Table 1 arelikely due to the methods used to classify the origin of the dust, as Gross et al. (2016) used oxygen isotopes in PO_4^{3-} to delineate sources, and to seasonal variability in dust flux rates. P deposition values for the heavy dust transport months of June and July were used to estimate a flux of 88 g P ha^{-1} $month^{-1}$by Gross et al. (2016). The wet season in Panama runs from May through December, during which dust fluxes are the highest. The CALIOP model estimates that as much, if not more, dust deposition occurs during the early spring months (March, April, May) than during the height of the wet season (June, July, August) (Fig. 3). This seasonal increase in rainfall can readily solubilize P and other dust elements with precipitation events during the wet season and increase the uptake rate in topsoil through primary productivity (Zamora et al., 2013; Chadwick et al., 1999). Our work shows that P deposition to Panama is strongly seasonal, therefore the very large annual flux calculated for the wet season and extrapolated annually by Gross et al. (2016) in Table 1 is very likely an over estimate.

Table 1. Estimated phosphorus deposition of Saharan dust to ecosystems in the Americas. Deposition values were calculated using modelled inputs from CALIOP and concentration values from Moreno et al. (2006), Muhs et al. (2010), and Gross et al. (2016). The results are compared to publish values

Location	P Deposition (g P ha^{-1} yr^{-1})	Study
Puerto Rico	230 ± 80	Pett-Ridge, 2009
Amazon	23 (7-39)	Yu et al., 2015
Amazon	141-483	Bristow et al., 201
Amazon	11-47	Talbot et al., 1986
Panama	616 ± 216	Gross et al., 2016
Panama	35-122	Our Study

The percent contribution of several elemental oxides in dust to soil was investigated for the three soil pits with different lithologies. Panamanian soils are highly weathered (Fig. 2), with the granite-derived soils highly depleted in Ca. The percent contributions vary widely among chemical species, and also among the different soil pits (Fig. 4). For Ca, the difference between contributions in the gabbro lithology and granite lithology is greater than a factor of 10, and for P, the difference between the gabbro lithology and greenstone lithology is greater by about a factor of 2. Though continual inputs of Ca, K, and P could aid in rainforest productivity (Porder et al., 2005; Chadwick et al., 1999), there is a clear variation among contributions of dust to soil that is related to bedrock type and hence initial elemental concentrations and weather ability. In particular, the spatial distribution in geology suggests that dust deposition is more important in granite terrain, which has lost Ca over time. We used a uniform deposition rate of 50 kg ha^{-1} yr^{-1} for Saharan dust across the surface of Panama, but spatial variability of deposition as evidenced in Puerto Rico (McClintock et al., 2015), could affect dust contribution to soil percentages to a different degree.

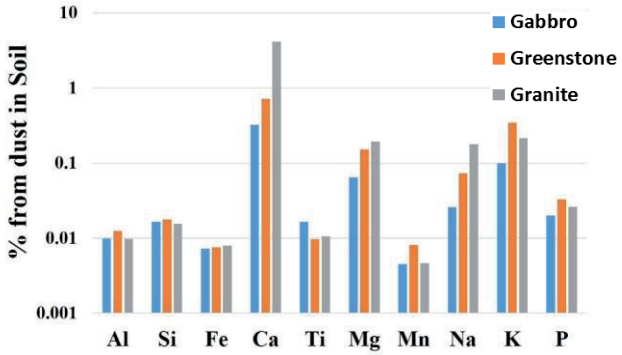

Fig. 4. Percent contributions of Saharan dust to three soil pits with different lithologies in Panama. Dust concentrations from Moreno et al. (2006) were used for the calculations

5. Conclusions

Nutrients from rock-derived minerals are important for ecosystem development, but humid tropical environments such as that of Panama, are heavily depleted in these nutrients. The trans-Atlantic dust plume carries material from the Sahara region and deposits much of these depleted elements, including phosphorous, onto the landscape surface. In Panama, P deposition ranges from 35 to 122 g P ha^{-1} yr^{-1} based on P concentrations from the literature,

with the highest deposition occurring in the spring and early summer months. Dust deposition is not uniform seasonally and the relative contributions of dust to the soil depend on the rock type from which they are derived. We predict aspatial variation in dust flux, as seen in Puerto Rico (McClintock et al., 2015),to exist in Panama as well. Though much of the dust-deposited P is likely rapidly taken up and recycled by the vegetation, continual inputs of Ca, Mg, and K could also significantly aid in long term rainforest productivity.

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