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Biogeochemistry of dust sources in Southern Africa

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ABSTRACT

In Southern Africa, the Makgadikgadi Pan in Botswana and the Etosha Pan in Namibia are two of the major dust sources in the Southern Hemisphere. Dust from Southern Africa could play an important role in sustaining the productivity of the surrounding terrestrial and marine ecosystems. However, very little is known about the biogeochemical properties of dust from this region. In this study, we analyze sediments from the Makgadikgadi and Etosha salt pans and the Kalahari dunes and compare the total nitrogen, total phosphorous, soluble iron and common anions between the soil fine fraction (<45 μm) and parent soil. Our results show that in the pans, the fine fractions are richer in total nitrogen and total phosphorous than the parent material whereas the parent material is richer in soluble iron than the fine fraction. In the Kalahari sands, the fine fraction is richer in total nitrogen whereas the parent material has higher total phosphorous and soluble iron than the fine fraction. This study quantifies the amount of biogeochemically important nutrients that can be emitted by Southern African sources which could be incorporated into models of dust emission and transport to assess the impact of dust in regional and marine ecosystems.

1. Introduction

Aeolian processes are intricately connected to Earth's climate, hydrological and biogeochemical cycles (e.g.; Goudie and Middleton, 2006; Ravi et al., 2011). Airborne dust absorbs and scatters solar radiation, affects rainfall, and transports nutrients from dust-emitting landscapes to deposition regions over the continents and oceans. Atmospheric transport of dust is a major supplier of phosphorous (P) (Mahowald et al., 2008) and iron (Fe) (Fung et al., 2000; Jickells et al., 2005) to open ocean surface waters and of P to land (Swap et al., 1992; Chadwick et al., 1999; Okin et al., 2004). Most major dust sources on Earth are found in the Northern Hemisphere (Prospero et al., 2002; Goudie and Middleton, 2006) and Northern Hemisphere sources account for more than 80% of global dust emissions (Ginoux et al., 2001). Remotely sensed data from the Total Ozone Mapping Spectrometer (TOMS) suggest that hyperarid areas (mean annual precipitation less than 100 mm), topographic lows and basins of internal drainage are the most common sources of dust (Prospero et al., 2002; Washington et al., 2003). There is very little large-scale dust activity in regions outside the 'dust belt', which comprises of the west coast of North Africa, Middle East, Central and South Asia (Prospero et al., 2002). The Southern Hemisphere exhibits low dust loading compared to the Northern Hemisphere and the currently active dust sources are the Lake Eyre Basin in Australia, the Makgadikgadi and Etosha salt-pans in Southern Africa, and the Salar de Uyuni in Bolivia and the Patagonian Desert in South America (Prospero et al., 2002; Goudie and Middleton, 2006).

Because of the low dust loading in the Southern Hemisphere, and the consequently low rates of Fe and P deposition, the productivity of Southern Ocean is overall low, when compared to the other oceans (Ridgwell, 2002). The existence of high nitrogen-low productivity areas in the Southern Ocean has been explained as the effect of Fe and P limitations (e.g., Okin et al., 2011). It has been argued that the enhanced delivery of dust during the drier epochs in the Earth history could have led to increased productivity of the Southern Ocean and this explains the lower atmospheric CO_2 concentration during glacial times (e.g., Martin, 1990). The low levels of pCO_2 in the atmosphere during the Last Glacial Maximum (LGM) which coincides with the increased dust loading can be attributed to additional nitrogen fixation (Falkowski, 1997) and the enhanced supply of Fe in dust to the Southern Ocean which further enhanced the ocean's "biological pump" (Martin, 1990), which is the vertical transport of carbon, nutrients and oxygen driven by the

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sinking of the organic matter from the surface to deeper water (Ridgwell, 2011). Sources in South America (especially Patagonia) is considered as the largest contributor of dust to the Southern Ocean during the LGM (Albani et al., 2012) whereas, results from a modeling study indicate that in current climate the dust in the Southern Hemisphere primarily originates from sources in Australia and South America (Li et al., 2008).

Recent studies have assessed the potential of the southern Kalahari to become an important dust source in the Southern Hemisphere (e.g., Bhattachan et al., 2012, 2013) and dust from these dunefields will commonly reach the Southern Ocean (Bhattachan et al., 2012). The remobilization of stabilized dunes in the southern Kalahari can result in dust emissions comparable to the currently active Makgadikgadi and Etosha pans (Bhattachan et al., 2012). There is some evidence that the southern Kalahari dunefields were active between 19,000 and 16,000 years B.P. (Lancaster, 1988). It is reported in some parts of the southern Kalahari, the dune crests have become active in areas of reduced vegetation cover, particularly during dry and windy periods (e.g., Lancaster, 1988; Wiggs et al., 1995). Overgrazing is considered a major driver for vegetation loss and dune mobilization in the region (Thomas and Twyman, 2004). It has been suggested that these dune and interdune areas will lose their vegetation cover and become active by 2070 (Thomas et al., 2005), however, this prediction has been challenged (e.g., Ashkenazy et al., 2011).

In Southern Africa, large values of aerosol optical thickness are observed over the Makgadikgadi and Etosha pans (Prospero et al., 2002; Washington et al., 2003), with highest dust activity between August–October (Prospero et al., 2002). The Paleo-Makgadikgadi was one of the largest paleo-lake systems in Africa (Ringrose et al., 2005; Eckardt et al., 2008) and covered over 120,000 km^2 (Washington et al., 2003). The Makgadikgadi Pan today comprises of the Ntwetwe Pan in the west and the Sua Pan in the east and has a combined surface area of approximately 6000 km^2 (Prospero et al., 2002). Even though annual evapotranspiration exceeds annual precipitation (400 mm/yr) (Ringrose et al., 2005), Ntwetwe Pan is occasionally flooded by water from the Boteti River during periods of high precipitation in the Okavango Basin (Thomas and Shaw, 1991; Prospero et al., 2002). Similarly, Sua Pan receives surface water from Nata River and other ephemeral streams located along its eastern and northeastern shores (White and Eckardt, 2006). The Etosha Pan at 1080 m above sea level (Bryant, 2003; Miller et al., 2010) covers an area of 4800 km^2 (Prospero et al., 2002) and is the endorheic drainage of a watershed in Northern Namibia and Southern Angola above the Great Escarpment (Buch and Rose, 1996).

Coupled dust emission-atmospheric circulation models (e.g., Mahowald et al., 2005, 2008) are often used to investigate the contribution and impacts of bioactive nutrients transported in dust to depositional areas (Bergametti et al., 1992; Zhu et al., 1997; Baker et al., 2010; Okin et al., 2011). Thus, the biogeochemical properties of dust measured at the source region are different from those of the dust that is deposited. Nevertheless, the analysis of dust samples from the source areas remains a crucial step in understanding the relative importance of different dust sources. Thus, for dust from Southern African sources to play an important role in the productivity of ocean and terrestrial ecosystems it should contain sufficient amounts of nutrients and micronutrients. It is therefore crucial to investigate the chemistry of sediments from dust emitting landscapes. In this study we assess the concentrations of N, P, soluble ferrous iron (Fe (II)) and common anions in the fine fraction and parent material of sediments both from currently active (e.g., pans) and potential (e.g., stable dune sands) dust sources in Southern Africa. Although it is often accepted that finer particles (<2.5 μm) travel long distances, several studies in fact have shown that larger particles (greater than 10–20 μm) can also travel long distances before deposition (e.g., McTainsh et al., 1997; Middleton et al., 2001; Lawrence et al., 2010); therefore here we focus on a fine fraction defined as particles less than 45 μm. To this end, in this study we concentrate on the case of Southern Africa and investigate the biogeochemical properties of soil fine fraction that could be emitted by existing and potential dust sources in the region and compare it to the parent material.

2. Methods

2.1. Soil sampling and particle size analysis

Samples were collected from the top 5 cm of the surface of the Makgadikgadi (n = 14 samples), and Etosha pans (n = 4 samples) (Fig. 1). The Kalahari sand samples were collected from a well-managed farm's interdune at Bokspits and a recovering interdune at Struizendam (with three replicates at each site) (Fig. 2). Samples from vegetated and bare dunes in the southern Kalahari did not yield sufficient dust fraction needed for the analyses, therefore only interdune samples were analyzed in this study. The location of study sites and characteristics are included in Table 1. A subset of the sample was run through a particle size analyzer (LS 13,320, Beckman Coulter®) for grain size analysis. The grain size distributions of the samples from the Makgadikgadi and Etosha pans and Kalahari interdunes are included in Table 2. The fine sized fractions analyzed in this study were obtained by sieving soil samples from the dust source regions, consistent with other studies (e.g., Guieu et al., 2002; Lafon et al., 2004; Shi et al., 2011). All samples were sieved through a 45-μm sieve to separate the fine fraction present in the soil from the parent soil on the assumption that particles smaller than 45 μm will be transported mainly by suspension. In this study, the 45 μm cutoff was used because dry-sieving soil with finer meshes is often impeded and biased by electrostatic forces. The samples (about 25 g for the pan samples and about 300 g for samples from the interdune) were placed on a Ro-tap sieve shaker and shaken for an hour. The sieved fraction was weighed and the percent yield (sieved fraction/parent soil) is reported in Table 3. To evaluate the contribution of fine particles to the soil N, P, and Fe (II) content, biogeochemical analyses were performed both on the fine soil fraction (<45 μm) and on unsieved parent material. The parent material was ground using a Pica-Mill Soil grinder for biogeochemical analyses (Cianflone Scientific; Pittsburg, PA, USA).

2.2. Laboratory analyses

Ferrous iron (Fe (II)) is soluble in water and is therefore the most bioavailable form of iron (Mahowald et al., 2005). Samples were analyzed for Fe (II) iron using a method outlined in Zhu et al. (1997) and Bhattachan et al. (2012). For both parent soil and the dust fraction, 0.25 g of dust/soil was soaked in 10 ml of 0.5 M HCl and then shaken for an hour. The solution was centrifuged, filtered and the pH of the aliquot was increased to 5.5 by adding a highly concentrated ammonium acetate buffer solution. Fe (II) was then measured spectrophotometrically using a Shimadzu® 1800 UV photospectrometer at 562 nm after 0.1 M ferrozine was added to the solution (Zhu et al., 1997). Iron ammonium sulfate was used as a standard and the range of detection for the photospectrometer was between −4 and 4 Abs.

Total nitrogen content of the dust fraction and parent material was measured using a Carlo Erba Elemental Analyzer (Model NA 2500; Carlo Erba, Milan, Italy) with a 1020 °C combustion tube and 650 °C reduction tube and helium as a carrier gas. Atropine was used for standard and the detection limit for the machine is 0.005%. Total phosphorous was determined using a modified Kjeldahl