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Using rare earth elements to trace wind-driven dispersion of sediments from a point source

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ABSTRACT

The entrainment and movement of aeolian sediments is determined by the direction and intensity of erosive winds. Although erosive winds may blow from all directions, in most regions there is a predominant direction. Dust emission causes the removal preferentially of soil nutrients and contaminants which may be transported tens to even thousands of kilometers from the source and deposited into other ecosystems. It would be beneficial to understand spatially and temporally how the soil source may be degraded and depositional zones enriched. A stable chemical tracer not found in the soil but applied to the surface of all particles in the surface soil would facilitate this endeavor. This study examined whether solution-applied rare earth elements (REEs) could be used to trace aeolian sediment movement from a point source through space and time at the field scale. We applied erbium nitrate solution to a 5 m^2 area in the center of a 100 m diameter field 7854 m^2 on the Southern High Plains of Texas. The solution application resulted in a soil-borne concentration three orders of magnitude greater than natively found in the field soil. We installed BSNE sampler masts in circular configurations and collected the trapped sediment weekly. We found that REE-tagged sediment was blown into every sampler mast during the course of the study but that there was a predominant direction of transport during the spring. This preliminary investigation suggests that the REEs provide a viable and incisive technique to study spatial and temporal variation of aeolian sediment movement from specific sources to identifiable locations of deposition or locations through which the sediments were transported as horizontal mass flux and the relative contribution of the specific source to the total mass flux.

1. Introduction

Wind eroded suspended sediment and fugitive dust move in the direction of the ambient wind and are capable of rapidly transporting sediments and associated contaminants great distances. Unlike water eroded sediment where the direction of transport is easily predicted, erosive winds may originate from any direction and so the transport pathway of the sediment is not easily predicted. However, post-event techniques such as wind-vector back tracing may be used to determine provenance.

Some naturally occurring biologic and mineralogic components in dust-source soils have allowed tracing of deposited dust to its provenance. Naturally occurring biologic tracers include microfossils and mineralogy (Alcantara-Carrio et al., 2010), fatty acid methyl esters (Kennedy, 1998), and living organisms on dust (Herbold et al., 2014). Mineralogical tracers employed to track dust deposits back to their source regions include ferromagnetic coatings (Hesse, 1997), uranium-lead dating of zircon grains (Gatehouse et al., 2001), and, more recently, oxygen vacancies and crystallization indices in silt-sized quartz grains (Ma et al., 2015; Toyoda et al., 2016). Perhaps the most commonly used tracers for fingerprinting the sources of dust deposits are elemental isotopic ratios (Grousset et al., 1998, 1992a,b; Aciego et al., 2015). Ferrat et al. (2011) and Liu et al. (2016) have used naturally occurring rare earth elements and other selected trace elements to determine the changing sources of sediments in aeolian deposits.

Physical and chemical tracers could potentially facilitate investigations into aeolian processes at smaller spatial scales if they could be selectively applied to discrete areas on the landscape. It would seem preferable, in the light of dangers to human and environmental health, to develop tracer materials for small spatial scales that are relatively non-toxic. They should ideally be coatings for the sediment particles that do not change the physical characteristics and wind entrainment of the particles. Fluorescent dyes and paints have been used to trace sediment movement in water-induced sediment movement (Yasso, 1966) and wind-induced sediment dispersal (Cabrera and Alonso, 2010). Ravi

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Fig. 1. Location of the study indicating the region of study at the southern end of the Southern High Plains of Texas and the location in the field at the BSFS in which the study was conducted.

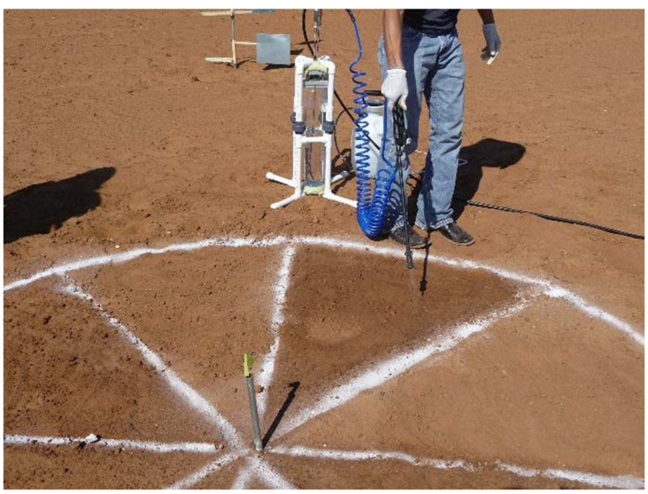

Fig. 2. Application of the erbium nitrate solution to an octant of the 5 m^2 source area.

et al. (2009) used a stable isotope of nitrogen (^{15}N) to investigate the post-fire redistribution of nutrients from nutrient islands in the northern Chihuahuan desert.

The lanthanides, also known as Rare Earth Elements (REE) are very attractive as environmental tracers. They are generally present in very low concentrations in most soils, are trivalent cations that are strongly adsorbed to the soil's exchange complex, and are available as 15 different elements with the same valence and behavior in the soil. In addition, they have small detection limits, are inexpensive to use, have standard analytical methods, small environmental risk, and do not affect particle behavior (Mahler et al., 1998).

For more than two decades, investigators studying water erosion and subsequent sedimentation have used REE tracers. The seminal work by Knaus and Van Gent (1989) used REE tracers to study rates of accretion in depositional aquatic environments. Since then, REE tracers have been applied to locations on the landscape to investigate spatial patterns of soil redistribution by water (Matisoff et al., 2001; Zhang et al., 2001, 2003; Liu et al., 2004; Kimoto et al., 2006; Polyakov et al., 2009). Laboratory leaching of the tagged sediments with a MgCl solution (Matisoff et al., 2001) and water (Zhang et al., 2001) indicated that the tracers were tightly adsorbed to the soil matrix.

In spite of the successes reported using REE tracers to study water-induced soil redistribution, the literature is devoid of aeolian investigations utilizing these tracers. REE oxides are insoluble in water and aggregates as used in many water erosion studies are sufficiently large that they are not wind erodible (Bagnold, 1941). Fortunately, almost all the REEs are soluble in nitric acid and then easily diluted for surface application. We hypothesized that surface applied REE solutions would result in particle adsorption of the trivalent REE ion so that the treated soil could be traced through space and time on an active aeolian landscape. To investigate the utility of the REE tracer for aeolian process investigations we tagged soil from a small area to represent a point source and sampled the redistribution over a 3 month wind erosion season.

2. Methods

The field study was conducted on the western edge of field 8 at the United States Department of Agriculture Agricultural Research Service (USDA-ARS) Big Spring Field Station (BSFS) near Big Spring, Texas, USA (Fig. 1), a semi-arid dryland farming region that has a history of aeolian activity (Van Pelt et al., 2007). The soil in this field is an Amarillo fine sandy loam (fine-loamy, mixed, thermic, superactive, Aridic Paleustalf) that has a long history of cultivation and tillage. In February 2011, a 100 m diameter circle centered at 32° 16′ 13″ north latitude by 101° 29′ 17″ west longitude was surveyed in the field, tilled to incorporate any surface plant residues, and rolled with a cylindrical implement to create a flat, bare surface.

At the center of the field, an approximate 2.5 m diameter circle was surveyed and divided into eight octants. The REE Erbium was chosen for this experiment due to its low toxicity and very low native concentration in the soil of 0.38 mg kg^{-1}. We decided to increase the concentration of Erbium in the soil by three orders of magnitude increase in erbium concentration in each octant. To achieve this dosage 8.245 g of erbium oxide (Er_2O_3) was dissolved in 75 ml of 2 N HNO_3 until totally dissolved, diluted with 1.8 L of distilled water and applied evenly to the soil surface of each octant using a precision sprayer (Fig. 2). This approach resulted in a total of 57.67 g of elemental erbium being applied to the 5 m^2 area for a mean erbium concentration in the upper 2 cm of 380 mg kg^{-1}.

Big Spring Number Eight (BSNE) sediment trap masts (Fryrear, 1986) were installed in circles centered on the REE application site at 2 m, 25 m, and 50 m radii. Samplers were positioned on the masts to have openings centered on 5, 10, 20, 50, and 100 cm above the ground surface. On the 2 m radius circle, sampler masts were located at 0, 60, 120, 180, 240, and 300° from magnetic north for a total of six sampler masts. On the 20 m and 50 m radius circles, sampler masts were located at 0, 30, 60, 90, 120, 150, 180, 210, 240, 270, 300, and 330° from magnetic north for 12 sampler masts on each circle and a grand total of 30 BSNE sampler masts in the field.

Meteorological data including wind speed, wind direction, air temperature, relative humidity, and precipitation were collected in an adjacent field. The BSNE samplers on the masts were collected weekly early in the morning, the sediment from each of the 150 individual BSNE samplers was carefully emptied into labelled, weighed soil cans, and the BSNE samplers were placed back on their respective masts