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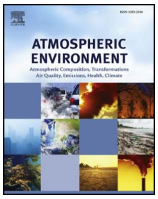

Short communication

Tank bromeliads capture Saharan dust in El Yunque National Forest, Puerto Rico

Dana L. Royer*, Kylen M. Moynihan, Carolyn Ariori, Gavin Bodkin, Gabriela Doria, Katherine Enright, Rémy Hatfield-Gardner, Emma Kravet, C. Miller Nuttle, Lisa Shepard, Timothy C.W. Ku, Suzanne O'Connell, Phillip G. Resor

Department of Earth and Environmental Sciences, Wesleyan University, Middletown, CT 06459, USA

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ABSTRACT

Dust from Saharan Africa commonly blows across the Atlantic Ocean and into the Caribbean. Most methods for measuring this dust either are expensive if collected directly from the atmosphere, or depend on very small concentrations that may be chemically altered if collected from soil. Tank bromeliads in the dwarf forest of El Yunque National Forest, Puerto Rico, have a structure of overlapping leaves used to capture rainwater and other atmospheric inputs. Therefore, it is likely that these bromeliads are collecting in their tanks Saharan dust along with local inputs. Here we analyze the elemental chemistry, including rare earth elements (REEs), of tank contents in order to match their chemical fingerprint to a provenance of the Earth's crust. We find that the tank contents differ from the local soils and bedrock and are more similar to published values of Saharan dust. Our study confirms the feasibility of using bromeliad tanks to trace Saharan dust in the Caribbean.

1. Introduction

Approximately 800 billion kilograms of dust each year is created in the Sahara and Sahel deserts of northwest Africa; a significant proportion of this dust is wind-transported across the Atlantic Ocean and into the Caribbean (Prospero et al., 1970; Huneeus et al., 2011; Prospero and Mayol-Bracero, 2013). Traces of this dust have been identified throughout the Caribbean region, including Puerto Rico (e.g., Reid et al., 2003; McClintock et al., 2015). This allochthonous input is likely critical for Caribbean ecosystems, especially with regards to limiting nutrients like phosphorus (Pett-Ridge, 2009), and has the potential to carry viable fungi and bacteria (Prospero et al., 2005).

The dwarf rainforest of the Luquillo Mountains in Puerto Rico's El Yunque National Forest (Fig. 1) is characterized by almost constant cloud cover and an average of 95–100% relative humidity throughout the year, which provides an abundance of cloudwater in addition to 30–60 cm per month of rainfall (Brown et al., 1983; Weaver, 1995; Daly et al., 2003; Murphy et al., 2017). The high humidity creates an environment that is excessively saturated, and soils are usually anoxic or suboxic (Weaver, 1995; Mount and Lynn, 2004).

Owing to the rain and cloudwater, the dwarf forest contains many epiphytes—plants that grow on other plants without bearing their roots in soil. The average epiphyte load on trees here is 555 g/m^2 (Weaver, 1972), with even higher loads on windward slopes (> 700 g/m^2; Brown et al., 1983). Tank bromeliads are epiphytes in the family Bromeliaceae that are characterized by a system of tightly overlapping leaves that forms a small "tank" in the middle of the plant's body; the most common tank bromeliad in the dwarf forest is *Vriesea sintensisii* (Baker) L.B. Sm. & Pittendr. (Fig. 2; Howard, 1968; Brown et al., 1983). The tank is used to capture rainwater, leaf litter, and other small particles or even organisms. This constitutes the plant's main source of nutrients (Nadkarni and Primack, 1989; Benzing, 2000). This hints at a possible dust contribution to epiphyte nutrition that could help these plants succeed in their harsh environment.

Two common ways to collect dust are by sampling the air directly with high-volume filtering systems mounted on towers (Prospero and Lamb, 2003; Kumar et al., 2014; Pourmand et al., 2014) or by analyzing the small traces deposited in soils (Muhs et al., 1990, 2007; Muhs and Budahn, 2009; McClintock et al., 2015). Sampling dust from the air directly can be cost prohibitive, requires time to set up equipment and wait for sufficient exposure, and doesn't fully capture the fraction deposited locally because some of the suspended dust may land elsewhere; identifying dust from soil can be difficult owing to its dilute (often $<$ 1%; McClintock et al., 2015) and sometimes pedogenically altered nature.

Here we seek to test if we can detect Saharan dust within the tanks

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[*] Corresponding author. Department of Earth and Environmental Sciences, 265 Church St., Middletown, CT 06459, USA.
E-mail address: droyer@wesleyan.edu (D.L. Royer).

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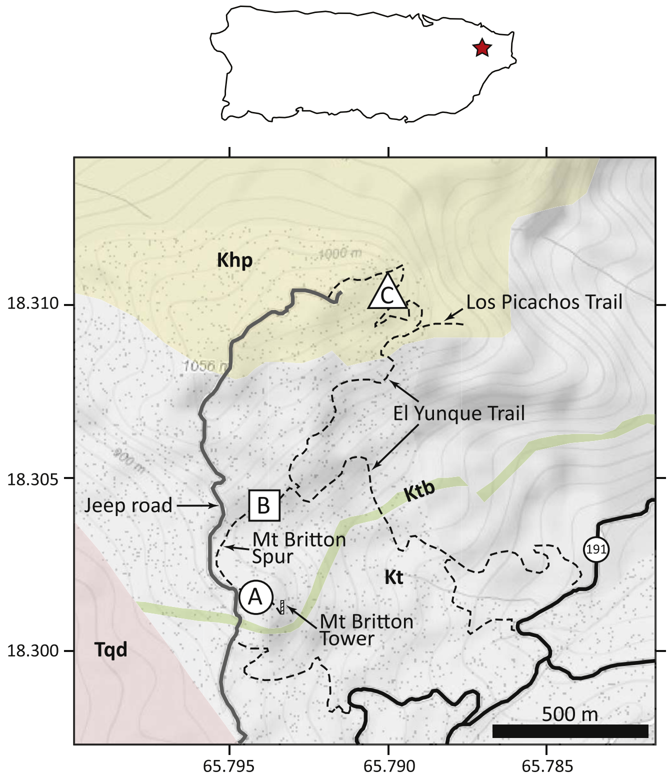

Fig. 1. Map of Puerto Rico with general field area marked with red star (top) and detailed map of field area (bottom). Field sites are marked "A", "B", and "C". Khp = Hato Puerco Formation; Kt = Tabonuco Formation (Ktb = breccia-conglomerate member); Tqd = Río Blanco stock. Geology comes from Seiders (1971); topographic base map comes from Esri's world topographic map. Tick marks show latitude (°N) and longitude (°W). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Fig. 2. Field photo showing the technique of sampling a tank of the bromeliad *Vriesea sintensisii*.

of bromeliads growing in the El Yunque dwarf forest. We use standard chemical fingerprinting techniques for detecting provenance, including the relative ratios of trace metals (e.g., Sc, Th) and rare earth elements (REEs; e.g., Eu, La, Sm, Yb) (e.g., Muhs et al., 2007). Our more general goal is to test how well tank bromeliads serve as a natural vessel for distinguishing the regional sources of atmospheric deposition. If successful, the approach could be a simpler and lower-cost alternative to existing approaches.

2. Material and methods

We sampled bromeliad tanks of *Vriesea sintensisii*, soil, and bedrock at three sites in the El Yunque dwarf forest over the course of three field campaigns (January 2009, 2015, and 2017; different tanks were sampled each year). Site A is along the trail between the junction of the Mt. Britton Spur and paved jeep road (18.302°N, 65.795°W; 900 m a.s.l.) and the Mt. Britton tower; site B is along the Mt. Britton Spur between its junction with the El Yunque Trail (18.305°N, 65.793°W; 875 m a.s.l.) and jeep road; and site C is alongside the El Yunque trail, several hundred meters north of its junction with the Los Picachos Trail (18.311°N, 65.790°W; 1000 m a.s.l.) (Fig. 1). At each site, we sampled the upper 15 cm of six soils with a plastic trowel. Soils were put in sealed plastic bags, then later dried at 50 °C and passed through a 75 μm sieve, removing most sand-sized (and coarser) particles; nearly all African dust in the Caribbean basin is finer than 75 μm (Prospero and Mayol-Bracero, 2013).

At sites B and C, we sampled rock in the form of loose rock (intact bedrock is rare in this deeply weathered landscape). The ridgelines are within a few hundred meters at both sites, and these upper hillslopes are underlain by the same bedrock as at our sites (Fig. 1); we therefore consider the sampled rock representative of the parent material for our soils. We used a rock hammer to trim weathered regions; the remaining rock was then homogenized in a shatterbox.

The bromeliad tanks usually contain a mixture of water, organic matter, and small inorganic particles. We extracted these contents with a 60 ml plastic syringe attached to ~20 cm of Tygon tubing (Fig. 2). For some tanks, we used a plastic spoon or deionized water to loosen the particles adhered to walls. All tank contents were then transferred to plastic centrifuge tubes. We combined the contents of ten tanks per tube in 2009, and five tanks per tube in 2015 and 2017. All plastic equipment was cleaned with dilute trace-metal grade HNO_3, rinsed in doubly-deionized water, and dried. Clean syringes, tubing, and spoons were used for each set of five tanks (or ten for the 2009 sampling). We sampled 35 tanks at site A and 60 tanks each at sites B and C, resulting

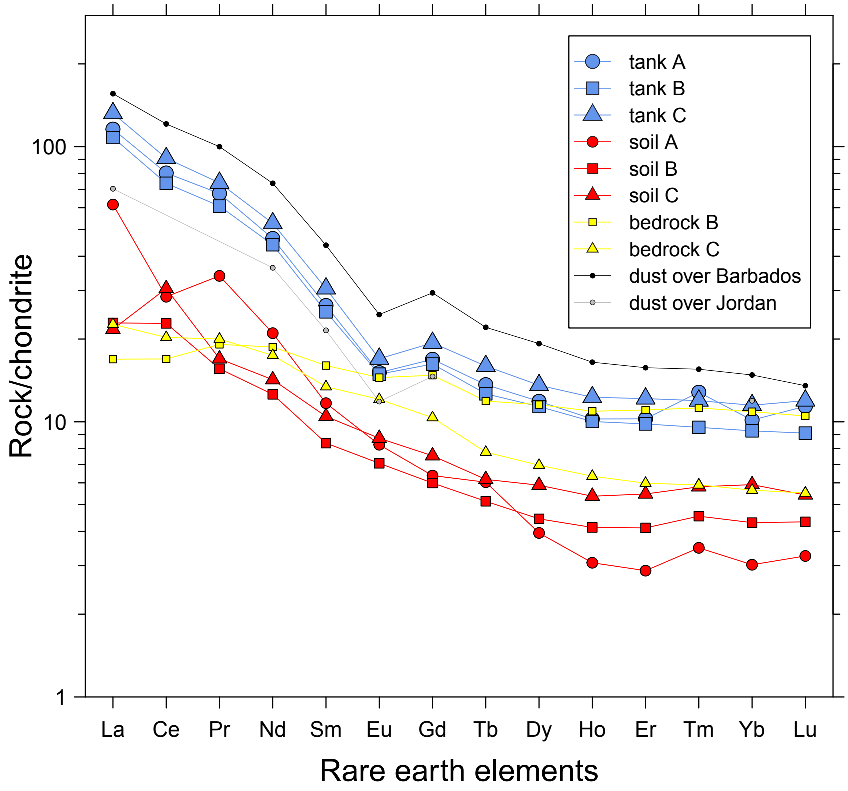

Fig. 3. Concentrations of rare earth elements normalized to chondritic composition. Each series is the mean of the associated data. Barbados data come from Pourmand et al. (2014) and Jordan data from Abed et al. (2009).

in 6, 11, and 11 discrete samples, respectively.

The tank contents were either centrifuged or allowed to settle for a few days, and then the majority of the water was removed by syringe and the residue dried at 50 °C. Our target minimum mass for inorganic solids was 0.1 g. To better gauge if our samples met this target, we combusted the organic matter in borosilicate glass vials at 500 °C for 4 h. All samples from 2009 and 2015 exceeded the minimum target (range = 0.2–0.6 g), but none from 2017 did (range = < 0.01–0.05 g). To achieve the minimum mass for the 2017 samples, we combined ten samples into two from site B, and ten into one from site C. Thus, our final sample count for tank contents was 6 for site A, 3 for site B, and 2 for site C.

All samples (tank contents, soil, rock) were analyzed for their elemental chemistry by sodium peroxide fusion methods followed by ICP-AES and ICP-MS analyses (the "GE ICM90A" package from SGS laboratories, Burnaby, British Columbia, Canada). Complete results are available in Appendix A.

In 2015, we also sampled bromeliad leaves with the goal of identifying a Saharan component in the tissues themselves. Our four discrete samples ranged from 21-28 g leaf dry mass, corresponding to 0.9–2.0 g ash weight. Unfortunately, all samples were below detection for the relevant metals. These data are not discussed further.

We adopted previous strategies that were successful in distinguishing the chemistry of Saharan dust from Caribbean bedrock (e.g., Muhs and Budahn, 2009; McClintock et al., 2015). These strategies largely focus on the relative ratios of REEs, especially europium (Eu), lanthanum (La), samarium (Sm), and ytterbium (Yb), which vary considerably in the earth's crust (McLennan, 1989). Following convention, we first normalized the REE concentrations to that in chondrites (Taylor and McLennan, 1985; McLennan, 1989); these normalized values are denoted with the subscript "N". For europium, we computed its anomaly relative to its neighbors samarium and gadolinium (McLennan, 1989):

$$Eu/Eu^* = Eu_N / (Sm_N \times Gd_N)^{0.5}.$$

Muhs and Budahn (2009) also found differences between Saharan dust and Caribbean bedrock in elemental ratios involving thorium (Th), scandium (Sc), lanthanum (La), zirconium (Zr), chromium (Cr), neodymium (Nd), and tantalum (Ta), an approach that we also adopt.

We compared our results to that from dust collected over Jordan (Abed et al., 2009) and Barbados (Pourmand et al., 2014), both of which are partly comprised of Saharan dust.

3. Results

The tank contents are chemically distinct from their adjacent soil and bedrock (blue vs. red and yellow symbols in Fig. 3). The chondrite-normalized REE concentrations of the tank contents are considerably higher (upwards of 5-fold), especially for the light REEs. The REE pattern in the tanks is much more similar to that from dust collected over Jordan and Barbados (gray and black symbols in Fig. 3; Abed et al., 2009; Pourmand et al., 2014). The europium anomaly (Eu/Eu*) is also much larger in the tank contents and Jordan and Barbados dust than in the adjacent soil and bedrock.

Crossplots of REE ratios further show a close chemical similarity of the tank contents to Saharan-derived dust (Fig. 4a–b). In both plots, the tank content data occupy a chemical region closer to the Barbados dust field than to the Jordan dust field, but all three are distinct from the soil and bedrock field. In the La_N/Sm_N vs. Eu/Eu* crossplot (Fig. 4b), the soils are mostly in a region between the bedrock and tank + dust region. In general, the soil from site A is more scattered and plots closer to the tank + dust field than the other soils (Fig. 4a–b).

Other crossplots of metal ratios (Fig. 4c) and ternary plots of metal percentages (Fig. 5) also show the chemical distinction of tank contents from their adjacent soils and bedrock. Some of the soils from site A are intermediate between the other soils and tank contents (Fig. 4c and Fig. 5a), and the soils at all sites are commonly intermediate between the bedrock and tank contents (Fig. 5a–b; but compare with Fig. 5c). Dust data are sparse for these elements, but the data that do exist support a strong Saharan provenance for the tank contents (gray dots in

Fig. 5c).

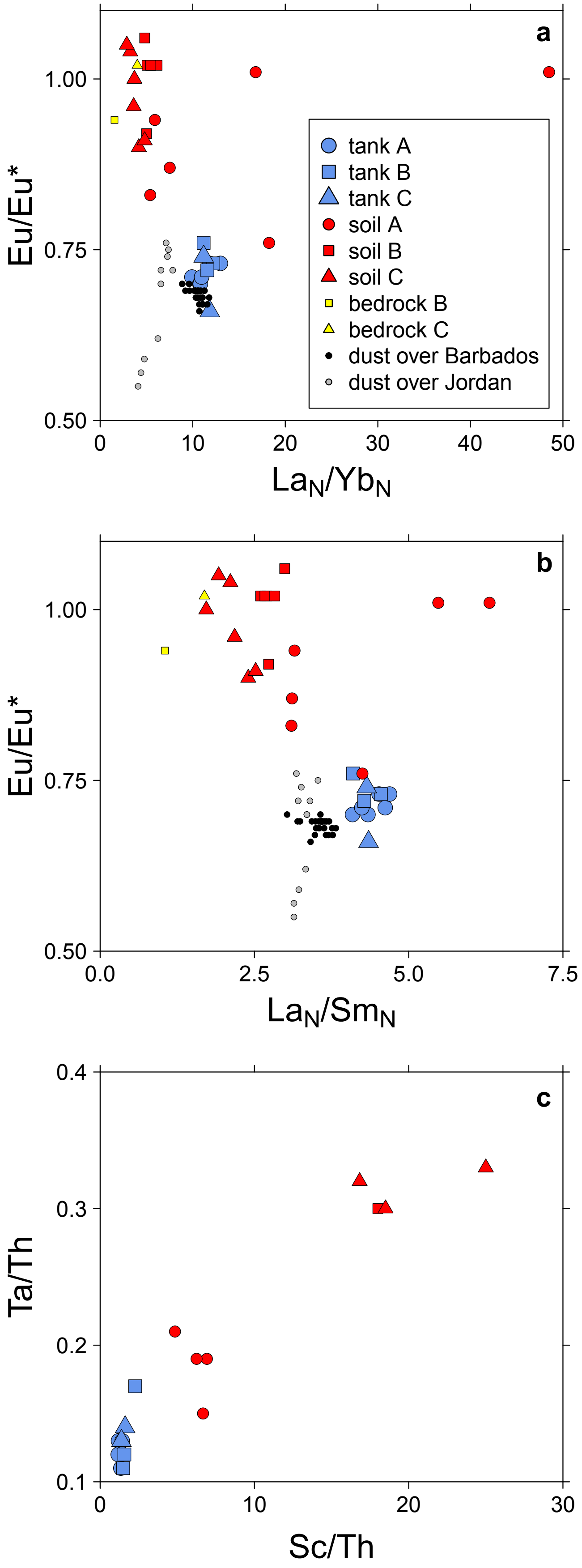

Fig. 4. Crossplots of metal ratios. Individual samples are plotted (not site means). Barbados data come from Pourmand et al. (2014) and Jordan data from Abed et al. (2009).

4. Discussion

Our primary goal was to test if we could identify a Saharan origin from bromeliad tank contents. Using trace metal chemistry as a means to identify crustal provenance, it is clear that the tank contents are distinct from their adjacent soil and bedrock, and very similar to the reported chemistry of dust collected over Jordan and Barbados (Figs. 3–5). We therefore consider the test successful: bromeliad tanks can be analyzed to identify the provenance of atmospheric dust inputs.

Some of the chemical plots show the soil intermediate between bedrock and dust (Fig. 4b and Fig. 5a–b), especially for site A, suggesting substantial dust input to the soils (see also Muhs et al., 1990, 2007; Muhs and Budahn, 2009; McClintock et al., 2015), but other plots do not (Fig. 5c). At site A, some soil measurements are more scattered than that at other sites (Fig. 4a–b), as are the tank contents, albeit less commonly (Fig. 5b). One explanation for this scatter is the bedrock. Sites A and B are underlain by the Tabonuco Formation (“Kt” in Fig. 1), and site C by the Hato Puerco Formation (“Khp” in Fig. 1). Both formations are comprised of marine-deposited volcaniclastic rocks from the Cretaceous, principally of andesitic to basaltic composition (Seiders, 1971). Because the bedrock and soils from sites B and C are so chemically similar (yellow and red squares and triangles in Figs. 4–5), we do not think the formational difference is the cause of the dissimilarity observed at site A. During the early Paleogene, a granodiorite intruded into the Luquillo region, forming the Río Blanco stock (“Tqd” in Fig. 1; Seiders, 1971). This intrusion created a zone of contact metamorphism in the host volcaniclastics (stippled region in Fig. 1). All three sites are in the contact zone, but site A likely experienced the most metamorphism because it is only a few hundred meters from the contact with the Río Blanco. We conjecture that this proximity to the intrusion may explain the more variable chemistry at site A.

A key advantage to sampling bromeliad tanks for atmospheric inputs is that it is fast and inexpensive. One general limitation is that it requires tank bromeliads, which only grow in wet climates. Also, over the course of three sampling campaigns, we observed that the amount of material in each tank can vary considerably. During our sampling in 2009 and 2015, ten and five tanks, respectively, were sufficient to yield > 0.1 g of ashed solids. In 2017, tanks typically contained less material, making it necessary to commingle up to 50 tanks to yield > 0.1 g of ashed solids. We do not know what caused the difference in 2017: rainfall in the month leading up to sampling was fairly typical (www.ncdc.noaa.gov), except that the two days directly before sampling were very sunny and without rain (a rare occurrence in a cloud forest). Regardless of the underlying reason, this temporal variability means that it is difficult to anticipate in advance how much sampling is required.

We do not know if the metals measured here steadily accumulate in the tanks over the plant's lifetime, or instead (partly) dissolve and become incorporated into the plant's tissue. Thus, at present, the method cannot quantify dust fluxes. More generally, though, the method likely integrates dust over a period of time that is in between sampling dust directly (typically days to weeks) vs. from soils (hundreds to thousands of years). Depending on project goals, this intermediate temporal resolution could be advantageous.

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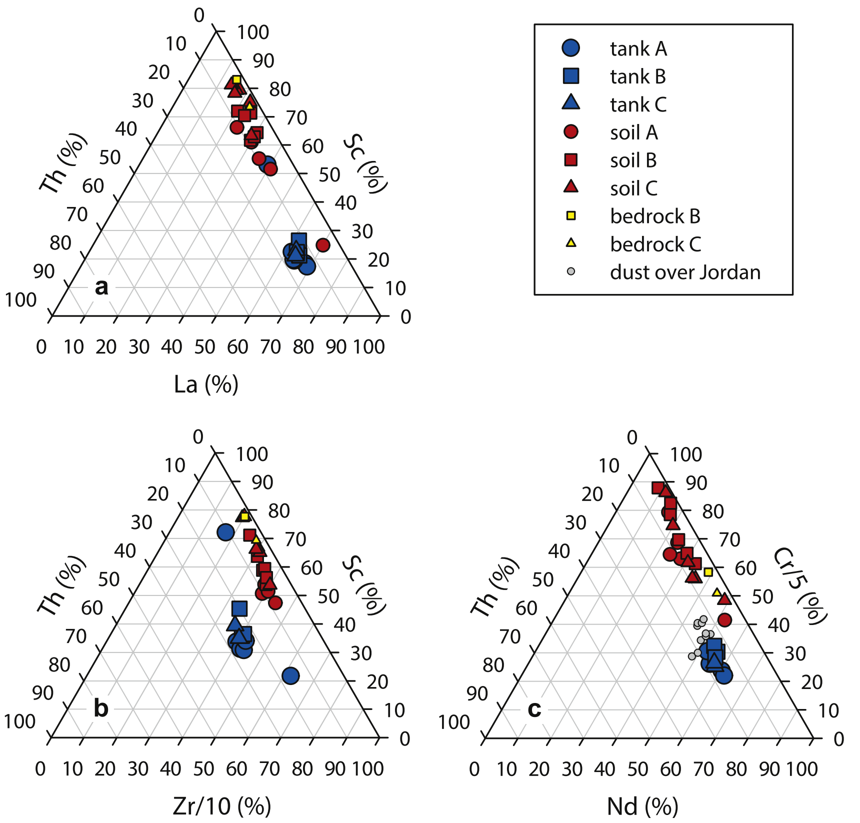

Fig. 5. Ternary plots of metal concentrations. Individual samples are plotted (not site means). Jordan data come from Abed et al. (2009).

Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.atmosenv.2017.11.018.

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