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Role of biological soil crusts in affecting soil evolution and salt geochemistry in hyper-arid Atacama Desert, Chile

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ABSTRACT

Eight soil profiles, either barren or covered with biological soil crusts (BSCs), were sampled at multiple depths in a remote valley in the Atacama Desert, Chile, to explore the impact of BSCs on soil evolution and salt geochemistry. BSC sites had thicker soil profiles compared to non-BSC sites, which could be a result of past geological processes and also partially accounted for by the establishment of BSCs that can help limit erosion and promote significant soil accumulation. The greater abundances of fine particles below BSCs could essentially be attributed to the ability of BSCs to trap more fine grains. The generally higher salt ion inventories but smaller salt ion concentrations in soil profiles beneath BSCs were probably due to that BSCs can promote the retention of salt ions and insoluble dust simultaneously, but the latter to a greater extent. Nitrate oxygen isotopes indicated the predominant existence of atmospheric nitrate in the soils, suggesting biological processes of BSCs may not significantly impact the ion accumulation or distribution in the underlying soils. A mechanism of consistent soil accumulation via the retention of atmospheric deposition and occasional interruption of subsurface collapsing due to erosion processes was proposed to explain the development of soil profiles and different landscape features as well as the role of BSCs in soil evolution in this study area. The soil ages were estimated to be around 440 ky based on the proposed soil accumulation mechanism.

1. Introduction

The Atacama Desert in northern Chile is one of the driest places on Earth, where hyper-arid climate precludes establishment of vegetation across much of the desert, resulting in a vast barren land susceptible to wind erosion (Ericksen, 1981; McKay et al., 2003). Wind erosion is significant in most parts of the Atacama as evidenced by high winds, high eolian particle loads and widespread wind erosional features (Stoertz and Ericksen, 1974; Flores-Aqueveque et al., 2012). In comparison, water erosion is relatively minor in the Atacama, only occurring during rare rainfall events or in certain regions with ephemeral rivers or groundwater systems (Placzek et al., 2010). Wind erosion can be offset by the deposition of dust (insoluble particles) and salts from the atmosphere (Michalski et al., 2004; Ewing et al., 2006; Wang et al., 2015), with the net balance between deposition and erosion being a function of the surface stability. Given the lack of vegetation in the Atacama, the surface stability is mainly modulated by surface geomorphology. Desert pavement is a ubiquitous geomorphic feature in arid environments, including the Atacama, characterized by a layer of loosely cemented, interlocking clasts that can protect the surface from erosion (Cooke, 1970) and lead to an inflationary surface (McFadden et al., 1987). Low solubility gypsum/anhydrite crusts often form beneath desert pavements in the Atacama via gypsum dissolution and rapid recrystallization, which further armors the underlying soil profiles from erosion (Ericksen, 1981). The balance between deposition and erosion at one of the Atacama's driest locations, with a sparse desert pavement and 15 cm deep gypsum blocks, indicated that these protection mechanisms only resulted in the retention of about 20% of the deposited dust (Wang et al., 2015), reflecting the generally weak surface stability and very slow soil accumulation rates in the Atacama.

Biological soil crusts (BSCs) are another kind of soil surface cover common in deserts. BSCs can significantly influence soil stability and nutrient cycling (Belnap, 2003, 2006). BSCs are living consortia of cyanobacteria, green algae, lichens, and mosses that can survive in extremes of cold, heat, and aridity (Belnap, 2003). BSCs can reduce wind erosion in deserts (Leys and Eldridge, 1998; Belnap et al., 2014) probably because of exuding extracellular polysaccharides that bind soil particles together (Belnap and Gardner, 1993). Further, BSCs

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potentially modify soil surface roughness, porosity, and aggregations to reduce water erosion by increasing infiltration and enhancing water retention (Belnap, 2006). More importantly, BSC communities are considered “unique” in that they are often key photoautotrophic microorganisms and primary producers in extreme environments (Büdel, 2001). They can become biologically active by absorbing brief pulses of water (Belnap et al., 2004), resulting in high instantaneous rates of carbon and nitrogen fixation (Evans and Lange, 2001; Belnap, 2002; Housman et al., 2006) as well as the ability to exude nitrate into soil (Gaio-Oliveira et al., 2005; Johnson et al., 2007). Therefore, BSCs contribute significantly to desert ecosystem fertility and aid in the evolution and spread of other terrestrial life forms.

Despite significant advances in our understandings of the role of BSCs in affecting soil evolution and geochemical cycling, there are still unanswered questions. For example, the rate of soil stabilization caused by BSCs has yet to be quantified and their role in altering soil grain size distribution is still not completely understood (Li et al., 2005; Belnap, 2006; Zhao et al., 2010). The amount of soil nitrate produced by BSCs versus deposited from the atmosphere, which is significant in deserts (Michalski et al., 2004; Wang et al., 2016), is another open question. On the whole, the detailed impact mechanism of BSCs on soil evolution and geochemical cycles in desert ecosystems is not sufficiently studied, especially in hyper-arid regions. Therefore, this study was conducted in the Atacama Desert to compare soil profiles with and without BSCs using physiochemical and isotopic techniques, aiming to constrain the role of BSCs in affecting soil evolution and salt geochemistry in hyper-arid regions.

2. Study area

Widespread BSC communities were identified in a remote valley (~21.22°S, 69.90°W, ~800 m a.s.l.) in the Atacama's Coastal Range during field work in December of 2011 at the southeastern edge of the Salar Grande, a basin filled with massive salt mineral deposits (Stoertz and Ericksen, 1974) (Fig. 1). Halite (NaCl) is the principal mineral of the Salar Grande evaporites and is the underlying strata on which soils developed (Stoertz and Ericksen, 1974). Despite the modern mean annual precipitation (MAP) < 2 mm as recorded at the Iquique (100 km northwest) and Quillagua (60 km southeast) rain gauge stations (Houston, 2006), there are likely repeated occurrences of fog (~20 days per year) in the valley (Fig. 2A) based on its geographic similarities to some other foggy sites along the coastal Atacama (Cereceda and Schemenauer, 1991) and field observations. Because of the steep Coastal Range, fog condensation is concentrated in a narrow belt extending the elevation from 300 to 800 m (Rundel, 1978) that sufficiently supports the vegetation evolution (Fig. 2B). The Salar Grande region has been reported to have abundant lichen epiphytes (association of cyanobacteria, algae and fungi) (Conley et al., 2006; Follmann, 2008), and the association of cyanobacteria and bacteria were even found on the near surface of salt nodules (Stivaletta et al., 2012).

The landscape along the southeastern rim of the Salar Grande contains three major features: barren ground, BSC-covered ground and depression pits, with transitions between these three features occurring over a narrow distance (10–100s of meters) (Fig. 2). On the barren ground, there are typically no visible BSC communities. The surface is sparsely covered with 0.5–1 cm reddish to tannish pebbles, with decimeter to meter-sized polygonal fracture patterns observed beneath (Fig. 2C). Marginal open fissures along the polygon edges, likely caused by desiccation or thermal expansion, are filled with salt-cemented sand, silt, and rock debris and have been termed “sand dikes” (Ericksen, 1981). The BSC-covered grounds have a hummock relief of ~50 cm and 80–90% of their surfaces are covered with BSCs. The BSC colonies are fractured into small brittle patches (Fig. 2D), typically 10 cm in diameter, probably because of differential drying between the upper and lower crust surfaces (Belnap, 2006). The hummocky BSC-covered grounds are intervened by depression pits (~2–5 m in diameter) that are scattered across the surface and were likely formed by ephemeral streams causing subsurface salt dissolution and surface collapse (Stoertz and Ericksen, 1974). There are no BSCs but widespread white salt nodules, mainly halite, in the depression pits (Fig. 2E), which probably formed from hard, dense and crystalline halite by slow solution and recrystallization due to frequent wetting with coastal fogs (Stoertz and Ericksen, 1974). These salt nodules (Site 8) suggest that strong capillary rise of concentrated brines occurred in the past, and this extreme salinization was probably harmful and thus prevented the BSC establishment in the depression pit (Amit et al., 2010).

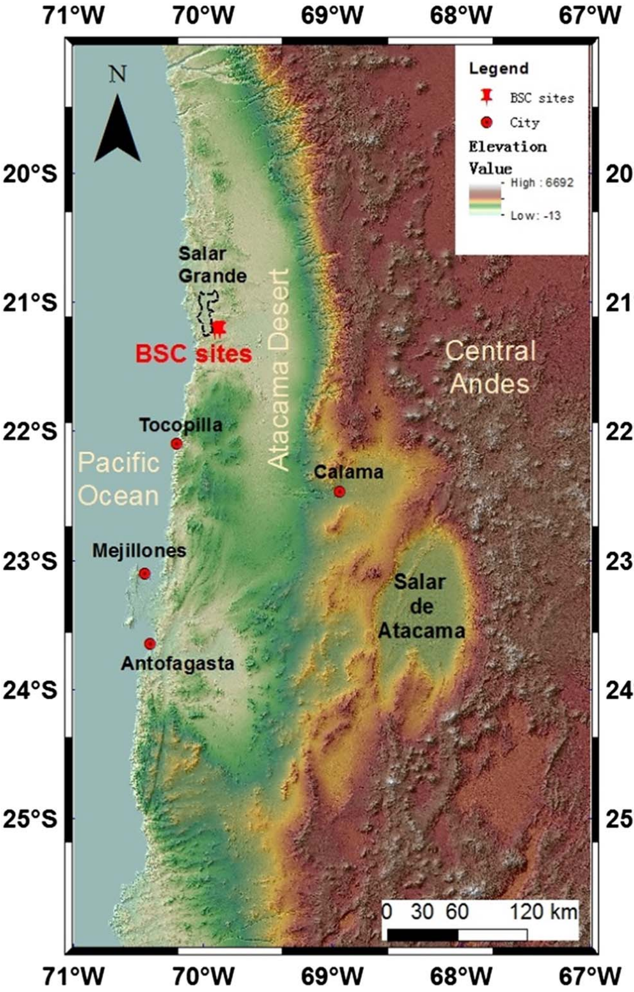

Fig. 1. Map of the Atacama Desert in northern Chile showing the location of the BSC soil sampling transects (red pin) near the edge of Salar Grande (outlined by black dash lines), just north of the city of Tocopillo (red dot). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

3. Sampling and analysis methods

Eight soil pits were dug along two approximately north-south transects that are ~4 km apart; Transect 1 spanned over 1000 m from the north side to the south side of a hummocky ground, while Transect 2 was only 70 m long and located on the south side of another hummocky ground (Fig. 2F). Sites 2, 3, 5 and 6 were BSC sites with BSC coverage all located on the BSC-covered grounds, but Sites 3 and 6 were in the transition zones (the edge of the depression pit and the edge of BSC-covered ground, respectively) with slightly less BSC coverage (Fig. 2F). Sites 1, 4, 7 and 8 were non-BSC sites with no BSC coverage; Sites 1, 4 and 7 were located on the barren grounds while Site 8 was located in a depression pit on the BSC-covered ground (Fig. 2F). Each