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Surrogate descriptors of C-storage processes on crusted semiarid ecosystems

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ABSTRACT

Arid and semiarid crusted ecosystems occupy a large extent of the Earth's surface. In these ecosystems there is a delicate balance between C sequestration and biodegradation that could easily be altered due to human disturbance or global warming. These environments are characterized by the presence of biological soil crusts (BSCs) coexisting with shrubs in the interspaces. BSCs play an important role in the C-cycle in arid and semiarid areas, but there has been little research regarding C-storage in crusted soils. In this research, representative BSCs were studied in three different crusted semiarid ecosystems in Southern Spain. Chemical fractionation and characterization of the organic matter in BSCs and underlying soils were undertaken to compare the total amount and quality of humic substances and find surrogate indicators of the soil organic matter quality. After isolating the major organic fractions (particulate fraction, humic acid-like (HA) and fulvic acid (FA)), the macromolecular, HA fraction was studied by derivative visible spectroscopy and resolution-enhanced infrared (IR) spectroscopy. Our results show quantitative differences in organic matter fractions, in agreement with the structural characteristics of the HA-type substances. The more stable crusted ecosystem with more evolved vegetation cover tend to be associated with HAs with broadband IR profiles, high optical density and macromolecular condensation and presence of polycyclic fungal biomarker compounds. In contrast, in the crusted ecosystem with very low or almost absent vascular vegetation cover, the C sequestration depends almost exclusively on the activity of crust-inhabiting organisms. It is suggested that the organic matter in BSCs shares characteristics with aquatic humic matter derived from non-lignified plants, including structurally complex HA-type substances which may have been originated by abiotic condensation of unsaturated lipids and/or diagenetic alteration of aliphatic biomacromolecules. Although these humification mechanisms have not been extensively studied in terrestrial soils they may be very active mechanisms for C sequestration in some types of crusted ecosystems. In particular, the spectroscopic characteristics in the visible and IR ranges of the crust-isolated HA-type substances provide the above-indicated biogeochemical proxies informing on the organic matter stability and quality and their bearing on the potential of crusted ecosystems for maintaining their properties after external disturbance.

1. Introduction

Arid and semiarid ecosystems occur on every continent and represent nearly a third of the Earth's total land surface (Schlesinger et al., 1990). In particular, semiarid lands are dominant ecosystems under Mediterranean-type climates, with characteristic landscapes composed of scarce patches of vegetation and apparently bare soil surfaces (Domingo et al., 1999). However, these interplant spaces are very often covered by communities of biological soil crusts (BSCs), defined as associations of soil mineral particles, cyanobacteria, algae, lichens, bryophytes and microfungi (Belnap et al., 2003). These covers represent the predominant soil surface system in many arid and semiarid environments, such as some Mediterranean areas, where they may cover up to 70% of their surface (Belnap et al., 2001) and play an important role in controlling soil evaporation (Kidron and Tal, 2012), surface hydrology (Kidron et al., 2012) and soil stability (Chamizo et al., 2012). In these regions the BSCs may also carry out a principal role in the soil C-cycle and are considered as one of the main sources of soil organic carbon (SOC) in many arid and semiarid ecosystems (Housman et al., 2006; Mager, 2010). They increase the SOC pool by producing specific carbohydrates and other complex aliphatic macromolecules (Belnap et al., 2003; Mager, 2009, 2010; Mager and Thomas, 2011). Moreover, it has also been demonstrated that they strongly influence CO_2 fluxes in arid and semiarid areas (Castillo-Monroy et al., 2011; Maestre and Cortina, 2003; Thomas

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and Hoon, 2010; Thomas et al., 2008; Wilske et al., 2008). However, the role of BSCs in the C balance may be affected by global warming, since it is associated with enhanced soil mineralization rates and loss of C (Cox et al., 2000; Houghton et al., 2001; Lang et al., 2009). The role of BSCs as possible sink or source of carbon in arid and semiarid ecosystems is, therefore, uncertain. However, most studies have focused exclusively on the total amount of organic matter in BSCs (Barger et al., 2006; Beymer and Klopatek, 1991; Housman et al., 2006), rather than on its quality. Moreover, there has been little discussion about the biogeochemical processes responsible for long-term C stabilization in BSCs and the possible interactions between vascular plants cover and the characteristics of the organic matter materials of the BSCs.

Organic matter quality, defined in terms of its potential for contributing to soil quality and sustainability, is considered a key factor in forecasting C dynamics in the whole ecosystem (Almendros, 2008). The chemical characteristics of soil organic matter could also provide valuable information on the resilience of crusted ecosystems and its response to any global temperature increase or to inappropriate soil management practices. In this sense, the analytical characterization of BSC organic fractions could yield valuable data about biodegradation and humification dynamics in crusted ecosystems, consequently on the potential of these ecosystems to act as C sinks. The resistance to biodegradation of recalcitrant organic matter fractions has been reported to depend on its molecular characteristics (Almendros and Dorado, 1999). Some intrinsic structural factors of HA substances, such as the presence of a condensed, three-dimensional structure with large amounts of aromatic “building blocks,” have been shown to enhance its resistance to microbial attack (Oades, 1988; Stevenson, 1994). Nevertheless, it has also been shown that the disordered HA structure could play an even greater role in their resistance to biodegradation, since soil enzymes do not easily recognize substrata with chaotic macromolecular structures (Bachmann et al., 2008; Kelleher and Simpson, 2006; von Lützow et al., 2006). Moreover, extrinsic factors related to the retention of organic matter in soil (e.g., proportion and nature of clays, amorphous oxides, carbonates, etc.) may play a role in physical occlusion of organic particulate fractions within resistant microaggregates. This occlusion reduces accessibility of soil organic matter to soil microorganisms and can also lead to the formation of amorphous organo-mineral recalcitrant complexes. In particular, preservation of non-humified biomass and the early immobilization of soluble precursors of humic substances, very typical in calcimorphic Mediterranean soils, are also considered to play a positive role in the sequestration of raw organic matter forms in soils (Miralles et al., 2007).

Although there is a large body of literature on humification of biomass from vascular plants, far too little attention has been paid to BSC biomass. The role of humification in soil carbon sequestration by BSCs requires specific research on the poorly-known diagenetic transformation of specific biomacromolecules in primitive organisms, such as cyanobacteria, lichens or mosses. Organic matter stabilization in semiarid BSCs could be regarded as having some characteristics in common with the formation of aquatic humic substances, where autochthonous biomass does not contain lignin, and where a special kind of biodegradation-resistant HA substances accumulate from the abiotic condensation of lipids and diagenetic transformations of carbohydrate and protein (Harvey and Boran, 1985; Huc et al., 1974).

Assuming the above considerations, it appears that important information for predicting the potential contribution of the SOC to long-term C sequestration can be gleaned, not only from quantitative analyses of the SOC in different crusted ecosystems, but also through analysing the quality and resilience of their different forms. The aims of this study are, therefore, to: i) undertake a quantitative analysis of organic matter fractions (labile and resilient), followed by a molecular characterization of the HA fraction on different crusted semiarid ecosystems with different influence of neighbor formations with vegetation of vascular plants and, ii) to use results from (i) to define surrogate indicators of the resilience or biodegradability of the organic matter in these semiarid crusted ecosystems.

2. Materials and methods

2.1. Characteristics of study areas

Three semiarid sites were selected in the Province of Almería, SE Spain (Fig. 1) where BSCs are abundant and their spatial distribution is highly representative of semiarid crusted ecosystems. The sampling sites were selected from field criteria focused to (a) collecting BSCs and soil material reflecting the variability in the different types of local landscapes, and (b) representing the different ecological succession stages. Two of the sites were situated in the localities of Balsa Blanca (BB) and Amoladeras (AMO) within the Cabo de Gata Natural Park and the third in Tabernas Desert (TAB) located in the Sorbas–Tabernas basin.

Sites BB and AMO are characterized by a semiarid climate with long hot summers and random precipitation patterns with severe inter-annual variation. The mean annual rainfall is 240 mm, falling mainly in winter, and the mean annual temperature is 17.8 °C (Aranda and Oyonarte, 2005). Both sampling sites, located about 15 km apart, are representative of the flat coastal-steppe ecosystems widely distributed in the Cabo de Gata area. The dominant soils are classified as Lithic Calcaric Leptosols (WRB, 2006) and both sites have similar lithological, pedological and climatic characteristics. Nevertheless, they differ in their conservation, as there is important grazing pressure in AMO, as reflected by its lower plant cover and shallower soils.

The main BB geomorphological features are alluvial fans (glacis). The BB landscape consists of open, vegetation-free areas, where stones (cover around 8%) and BSCs (*Diploschistes diacapsis* (Ach.) Lumbsch., cyanobacteria and mosses, which cover around 25% of the surface), are associated with areas with complex vegetation cover patterns. The vegetation cover is dominated by *Macrochloa tenacissima* (L.) Kunth, but with a large number of other species such as *Chamaerops humilis* L., *Rhamnus lycioides* L., *Asparagus horridus* L., *Olea europaea* L. var. *sylvestris* Brot., *Pistacia lentiscus* L. and *Rubia peregrina* L. Perennial plants cover around 45% of the soil surface, whereas annual plants represent around 5%. The AMO site, on an exhumed and dissected caliche area in the flat part of an alluvial fan system, has scarce vegetation cover (perennial plants around 20% and annual around 10% of the total surface), mainly dominated by *M. tenacissima* frequent stones (around 13%) and rock outcrops (around 14%), and shallow soils as a consequence of intensive grazing. BSC coverage (mainly lichen-*D. diacapsis*, cyanobacteria and mosses) is lower than in BB (around 27% of the soil surface) and occurs in open areas among scattered shrubs.

The other site, the Tabernas Desert (TAB) contains some of the most extensive badlands in Spain. The basin is partially surrounded by the Betic cordillera system and is located at the South of the Filabres mountain range, and at the leeward of the Nevada and Gádor ranges, all of which are over 2000 m above sea level. Altitude within the study site ranges between 240 and 385 m a.s.l. The main geological materials in the basin are calcaric-gypsiferous mudstone and calcareous sandstones (Cantón et al., 2003). A stepped landscape of multiple-age badlands has resulted from episodic uplifting and dissection during the Quaternary. The climate is semiarid Thermo-Mediterranean (Lázaro and Rey, 1991) with long dry summers and severe water deficits in summer. This site present a similar mean annual rainfall of 235 mm (mostly in winter) and a mean annual temperature is 18 °C (with an absolute maximum of 45 °C and absolute minimum of −5.5 °C), as recorded over a period of 30 years (Lázaro et al., 2000) in Tabernas (5 km from the site), which is one of the driest areas in Europe (Capel-Molina, 1986). The most frequent type of rainfall event is short, high intensity and associated with thunderstorms, but there are also low-intensity rainfall events lasting several hours. The landscape is made up of asymmetric NW–SE valleys. The