Catena 143 (2016) 256–264

Contents lists available at ScienceDirect

Catena

journal homepage: www.elsevier.com/locate/catena

Restoration techniques affect soil organic carbon, glomalin and aggregate stability in degraded soils of a semiarid Mediterranean region

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A R T I C L E I N F O

Article history:
Received 27 January 2016
Received in revised form 12 April 2016
Accepted 17 April 2016
Available online 26 April 2016

Keywords:
Soil organic matter
Soil structure
Glomalin
Organic amendments
Mulches
Quarry reclamation

A B S T R A C T

The first step to restoring degraded mine soils from calcareous quarries in semiarid environments, usually without soil structure, mainly consists in creating a structured topsoil with suitable physical, chemical and biological properties. The aim of this study is to determine the effects of organic amendments and mulches on soil aggregate stability and aggregation-associated soil characteristics, six years after beginning experimental restoration in the Gádor Mountains (Almería, SE Spain). Experimental plots were set up to test two organic amendments (sludge and compost) and two mulches (gravel and woodchip) and their respective control plots. Soil samples from neighboring undisturbed soils were used as the quality reference threshold. The tested variables were total organic C (TOC), glomalin-related soil protein (GRSP), easily extractable glomalin-related soil protein (EE-GRSP) and water aggregate stability evaluated by both wet sieving (WS) and water-drop test (WDT). Relationships among the measured soil properties were checked in order to assess the best indicators for the most suited restoration practices. After 6 years, the results showed that the combination of organic amendments and mulches enhanced soil aggregate stability and the content of aggregate binding agents such as TOC and glomalin. Nevertheless, the role of organic amendments, especially compost, was more important than mulch treatments in increasing TOC and glomalin, showing the closest values to the undisturbed reference soils (over 30 g kg^{-1} for TOC and 3.5 g kg^{-1} for GRSP). Despite the considerable improvement in water stable aggregates found in sludge-amended plots (average mean weight diameter of 2.13 mm in WS, and 25-drop impacts in WDT), the reference soils provided the highest values (average mean weight diameter of 3.32 mm in WS, and 99-drop impacts in WDT). The lack of a good correlation between soil structure-related variables restricted the evaluation of the real effects of restoration treatments, and suggested considering other soil properties (e.g., hydrophobicity, hardening) associated to aggregate stability.

1. Introduction

Mining activities generate landscapes without soil or vegetation, and their restoration is mandatory in most countries. In arid and semiarid areas, restoration from previously removed topsoil is not always possible and mining spoils are used as revegetation substrates even though they are usually stony, have severe chemical deficiencies, lack in soil structure, and run serious risk of erosion. In particular, mining spoils from calcareous quarries normally have high bulk density and massive structure, which confer low infiltration rates, increase runoff, and trigger soil erosion processes (Moreno de las Heras et al., 2008). For several decades, the restoration of mining areas has focused on improving the soil quality required for successful recovery (Callaham et al., 2008), similar to the soils before their degradation (reference soils). Aggregate stability is a widely used indicator for evaluating soil physical quality and susceptibility to erosion (Barthès and Roose, 2002; Boix-Fayos et al., 2001). It has also been reported that changes in aggregate stability may serve as early indicators of degradation or recovery stages of soils and, more generally, of ecosystems (Cammeraat and Imeson, 1998; Cantón et al., 2009). Stable soil aggregates play a key role in soil quality, since they protect organic material from microbial decomposition (Bronick and Lal, 2005) and prevent soil structure degradation (Solé et al., 1992; Cantón et al., 2001), thereby ensuring movement and storage of soil water (Franzluebbers, 2002), decreasing erodibility and promoting root development and activity of the soil microbial community (Tisdall and Oades, 1982).

In restoration of degraded land under arid and semiarid conditions, several practices for improving soil quality and enhancing the establishment of vegetation have been recommended. Organic amendments are

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http://dx.doi.org/10.1016/j.catena.2016.04.013

suggested for the rehabilitation of highly degraded soils because they improve the soil properties in agriculture, mine soils and other disturbed ecosystems (Asensio et al., 2013; Kabas et al., 2014) by improving biological soil properties and formation of soil aggregates, positively influencing plant growth (Hemmat et al., 2010). Moreover, organic amendment application enhances soil carbon sequestration by replacing labile organic carbon in soil aggregates with more stable compounds (Ojeda et al., 2015). In recent years, stabilization of C in restored soils by different mechanisms (e.g., microbial production of binding agents, physical protection of organic C in soil aggregates, association of organic C with clay and silt particles) has gained more emphasis due to its contribution to climate change mitigation (Ryals et al., 2014; Garcia-Franco et al., 2014; Garcia-Franco et al., 2015). On the other hand, mulch is also used as a restoration practice in arid and semiarid climates, because it reduces soil erosion, limits evaporation, improves infiltration, enhancing the establishment of vegetation, as well as root growth (Cook et al., 2011; Shao et al., 2014). Roots in turn produce exudates which stimulate microbial activity and, as a result, extracellular polysaccharides and other compounds able to increase soil aggregate stability are produced (Wright et al., 1998).

Soil organic matter is a source of energy and C for soil microorganisms such as bacteria and fungi, which in turn enhance the formation of soil micro and macro-aggregates through mucilage (García-Orenes et al., 2005; Lehmann and Rillig, 2015; Six et al., 2004). An important group of soil microorganisms, arbuscular mycorrhizal fungi (AMF), produce a proteinaceous material called glomalin. Its presence in the hyphae, roots and soil plays a substantial role in aggregation and in maintaining soil structure (Wright and Upadhyaya, 1996), thus favouring carbon sequestration (Rillig, 2004). A strong relationship between glomalin concentration and the amount of water-stable aggregates has been demonstrated (Wright et al., 1998; Rillig, 2004; Bedini et al., 2009; Gispert et al., 2013). The recently produced glomalin fraction is quantified as easily extractable glomalin-related soil protein (EE-GRSP). Another fraction called glomalin related soil protein (GRSP) represents the strongly bound protein to the soil particles (Rillig, 2004). Nichols and Wright (2005) postulated that GRSP might be difficult to remove from soil as it is strongly recalcitrant and protected into the microaggregate crumb. There are hardly any studies that have shown the influence of organic amendments and mulches on both the glomalin content and soil aggregate stability (Alguacil et al., 2009).

Thus the effects of different sources of organic inputs (compost and sewage sludge) and mulches (gravel and woodchips) were therefore examined in restored mine soils under semiarid conditions 6 years after their implementation. The improvement of soil structure after the addition of organic amendments and mulches is to be expected, but the effectiveness of individual treatments, or their combination, for restoring structural conditions comparable to the ones of the reference soil under native vegetation is not predictable. Moreover, the results may supply more evidence to identify the parameters mainly related to soil aggregate stability as indicators of soil restoration. Hence, the main objectives of the study were: i) to find out the effect of different restoration techniques on the stability of soil aggregates and aggregating agents, such as organic C and those related to AMF activity (EE-GRSP, GRSP), compared to adjacent natural environments selected as a reference of soil quality; ii) to analyze the relationships among TOC, EE-GRSP, GRSP and soil aggregate stability to determine the best indicators of structural stability.

2. Materials and methods

2.1. Study area

The experimental area is in a calcareous quarry located in the Gádor Mountains (Almería, SE Spain, 36°55′20″N, 2°30′29″W) in a semiarid Mediterranean climate. According to the climate data collected at the nearby meteorological station in Alhama de Almería, the mean annual temperature is 17.6 °C, the maximum absolute temperature is 42.7 °C in July and minimum −2.6 °C in February and the mean annual precipitation is 242 mm. Before mining, the natural vegetation mainly consisted of patchy grassland dominated by *Macrochloa tenacissima* (L.) Kunth including some dwarf perennial shrubs, or a mosaic formed by patches of grassland alternating with patches of dwarf shrub scrubland. Among the main species of dwarf shrubs are *Anthyllis cytisoides* L., *Anthyllis terniflora* (Lag) Pau, *Thymus hyemalis* Lange, *Ulex parviflorus* Pourr, *Genista umbellata* (L'Her) Dum. Cours, *Salsola genistoides* Juss. ex Poir. and *Salsola papillosa* Willk. Scattered individuals of *Pistacia lentiscus* L., *Maytenus senegalensis* (Lam.) Exell and *Rhamnus lycioides* L. are also present. The area is located in the contact zone between the Gádor range (Cenozoic dolomites and limestones) and the Tertiary intermountain basin formed by Tortonian (upper Miocene) marls, that is, calcitic-gypsiferous mudstones, and calcareous sandstones. The quarried rock is essentially the calcareous sandstones which overlays the marls, also partly quarried. Therefore, most of the restoration area rests on both types of rock. In undisturbed surrounding areas, soils are mainly Leptosols (FAO-IUSS-ISRIC Working Group WRB, 2014) over a variety of substrates: a) calcareous sandstone, b) calcitic-gypsiferous mudstone (marl) and c) slope deposits mostly fed by the shallow soils over limestone and dolomite from upper reliefs, which partly contain remains of pre-erosion *terra-rossa*.

2.2. Experimental design and soil sampling

In May 2008, a field trial comparing organic amendment treatments combined with different kinds of mulch was set up in 75-m^2 plots (15 m × 5 m) over a hillside with a 19% mean slope gradient at 370 m a.s.l. Nine treatments were investigated in a two-way crossed design: compost from the organic fraction of urban waste, sewage sludge from a wastewater treatment plant and no amendment, were combined with gravel, woodchips and no mulch respectively. The experimental study explored the use of residues valorized as low cost soil amendments. The main chemical properties of organic amendments, restored and reference soils are shown in Table 1. The added amount was calculated to reach 2% of organic matter content (from ~11.67 g kg^{-1} of total organic C) in the upper soil layer (0–20 cm), and mulch thickness was approximately 5 cm. The gravel mulch consisted of 50% siliceous fine gravel (2–5 mm) and 25% sand and 25% silt + clay, and the woodchip mulch was from *Pinus halepensis* silvicultural treatments (1 to 5 cm wide × 2 to 15 cm long × 1 cm thick). In each experimental plot, 75 native plants (35 *M. tenacissima*, 15 *A. terniflora* and 25 *A. cytisoides*) were planted.

After six years, three composite soil samples were collected from the surface layer (0–20 cm) in each plot upon removing the mulch if there was. A total of 27 samples were taken from the restored areas and three composite samples from the neighboring undisturbed soil, which was considered the reference soil (RS). A part of every composite soil sample was air-dried and used to determine aggregate size distribution and water aggregate stability. Another portion of each sample was sieved at 2 mm to analyze TOC and glomalin content (EE-GRSP, GRSP).

2.3. Analytical methodology

Total carbon stored in soil organic matter (TOC) was determined colorimetrically by the Walkley-Black wet oxidation method (Nelson and Sommers, 1996) for each replicate. GRSP and EE-GRSP were extracted from every composite soil sample using the procedures described by Wright and Upadhyaya (1998) with minor modifications. One gram of 2-mm sieved soil was placed in a centrifuge tube and GRSP was extracted with 8 mL of a 50 mM sodium citrate dihydrate solution (pH 8.0) by autoclaving at 121 °C for 60 min, following centrifugation at 5000 *g* for 15 min. After each extraction, the supernatant was decanted and stored at 4 °C, and sodium citrate was replenished for a subsequent extraction