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Atypical morphology of technosols developed in quarry dumps restored with marble sludge: Implications for carbon sequestration

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ABSTRACT

Covering the surface of stony slopes with a layer of topsoil is one of the most commonly used techniques to restore quarries. However, in semiarid climates, the topsoil is frequently poor and has limited water availability, which significantly reduces the success of the restoration. The high water-holding capacity of the sludge from the cutting and polishing of marble, as highlighted in previous studies, could contribute to the success of the restoration of marble quarries. In this study, a quarry dump was restored both with and without the addition of marble sludge prior to being covered with topsoil. The aim was to analyse the effect of the sludge on the characteristics and properties of the soils that formed five years after topsoil reposition. In the soils of all plots, a horizon of accumulation of organic matter was formed on the surface, whereas in the plots with sludge, the root growth clearly increased in the contact between the topsoil and the sludge, forming a second organic-mineral horizon at the contact zone of the topsoil and marble sludge layer. The result was the formation of soils with an atypical morphology characterized by two horizons of accumulation of organic matter, one at the surface and another at depth, which encourage the accumulation of organic carbon in the soil (until $363 \pm 62\ g\ C\ m^{-2}\ year^{-1}$). Therefore, it could be considered that the soils with marble sludge behave as carbon sinks, especially considering that these soils do not seem to have reached equilibrium, and that the organic carbon content could continue to increase over time. Long-term monitoring these plots is needed to better constrain the true extent of carbon sequestration in these soils.

1. Introduction

Stony dump deposits lack soil and have steep slopes, therefore limited water availability, all of which create a high-stress environment for plants and constitute the main problems facing restorers (Clemente et al., 2004; Heneghan et al., 2008), especially in arid or semiarid climates. One of the most frequently used restoration techniques is to cover the surface with a layer of topsoil (approximately 30 cm thick) from areas close to the quarry (Brofas, 2001; Bote et al., 2005; Zhang and Chu, 2010) and then perform hydroseeding with different species (Tormo et al., 2007; García-Palacios et al., 2010). However, in semiarid climates, the pedogenesis is limited, and the soils are poor and have low water-holding capacity, which significantly reduces the success of the restoration (García-Fayos et al., 2000; Oliveira et al., 2011).

During the cutting and polishing of marble, significant quantities of a white sludge consisting of fine particles (silt) of marble are generated. Simón-Torres et al. (2014) used this sludge with high water-holding capacity ($0.256\ kg\ kg^{-1}$) to restore the dump of a marble quarry, adding an approximately 20-cm-thick layer of marble sludge on the dump prior to providing the topsoil. The results indicated that the mean volumetric water content of the topsoil was 3.6 times lower than that of the marble sludge; thus, in the plots where marble sludge was added, the volumetric water content was considerably increased in the contact zone between the topsoil and sludge (deepest 5 cm of the topsoil and the first 10 cm of the marble sludge). The soil morphology showed a strong increase in the roots in the zone where the volumetric water content was increased, forming a very dark brown horizon that was presumably enriched in organic matter in a few years. A study of the vegetation that developed in this dump restored with marble sludge (Gómez Mercado et al., 2015) highlighted an increase in dry biomass, plant cover and vegetation height and an increase in dry biomass from perennial species such as *Piptatherum miliaceum* L. Coss (with a dense and fasciculate roots system) and *Anthyllis cytisoides* L. (with an ability to fix nitrogen), which would facilitate long-term rehabilitation and accelerate plant succession (Pallavicini et al., 2015; Premrov et al., 2017).

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The particular morphology of these soils emphasized the need for a detailed study of their properties to understand their genesis and assess their role as a carbon sink, which is the aim of the present study.

2. Materials and methods

2.1. Studied site

The study was conducted in a dump of the Macael marble quarries (southeast Spain, 37°18′17″N, 2°17′5″W). The mean annual temperature is 16.8 °C, with a mean maximum of 32.0 °C in the summer and a mean minimum of 3.2 °C in the winter. The mean annual rainfall is 454 mm, and the mean annual water deficit (difference between the mean annual precipitation and the mean annual evaporation; Milly, 1994) is − 442 mm.

2.2. Restoration of the dump and the soils studied

In early September 2007, the stones of a dump, with an area of approximately 1100 m^2 (48 × 23 m) and a slope close to 72%, were rearranged, and an approximately 20-cm-thick layer of marble sludge was placed over the surface of the dump, save for a 5-m-wide strip in the centre, which served as a control (Simón-Torres et al., 2014). Finally, the dump was covered with a layer of topsoil coming from the soils near the quarries, which were developed mainly on the slates and shales located stratigraphically above the marble. The topsoil thickness ranged from 18 cm to 38 cm, and the marble sludge thickness ranged between 17 cm and 21 cm. To study the restored dump quarry, nine plots of 6 m^2 were selected (3 × 2 m), with three in the central sector where the marble sludge was not added (plots PT) and six in the sector where the sludge was added, three of which were to the west and three to the east of the central sector (plots PTS). In mid-September 2007, three samples of topsoil (n = 27) and two samples of marble sludge (n = 12) in each plot were collected and analysed. For more information about the studied site and the restoration work on the quarry dump, see Simón-Torres et al. (2014).

2.3. Hydroseeding

At the beginning of October 2007, hydroseeding was conducted with a slurry containing 8 g L^{-1} of mixture of seeds of common native species in the study area (*Agropyron cristatum* (L.) Gaertn., *Cynodon dactylon* (L.) Pers., *Lolium rigidum* (Gaudin) Weiss ex Nyman., *Medicago sativa* L., *Melilotus officinalis* (L.) Pall., *Anthyllis cytisoides* L., *Artemisia campestris* L., *Atriplex halimus* L., *Bituminaria bituminosa* (L.) C.H. Stirt., *Rumex induratus* Boiss & Reut., *Piptatherum miliaceum* (L.) Coss., *Moricandia arvensis* DC. and *Zygophyllum fabago* L.), 35 g L^{-1} of short fibre (100% cellulose) mulch, 7 g L^{-1} of stabiliser (terpene-phenol resins with ethylene-vinyl acetate adhesives) and 15 g L^{-1} of a complex chemical fertilizer, grade 15-15-15 (15% N, 15% P_2O_5, 15% K_2O). The applied dose of this slurry was 3 L m^{-2}.

2.4. Soil morphology in 2013

In May 2013, the soils of the nine selected plots were collected again, thoroughly describing the different horizons (FAO, 2006). Soil morphology was different depending on the addition of marble sludge and the thickness of the added layer of topsoil. The topsoil of the three plots in which marble sludge was not added (PT) were sampled at three depths (Ah, C1 and C2 horizons) without clear morphological differences between them, except for a slight darkening of the surface layer (Fig. 1a). The soils of the plots in which sludge was added were sampled at different depths depending on the thickness of the added topsoil and morphology of each soil. In the soils of the three plots in which the thickness of the topsoil provided was less than or equal to 25 cm

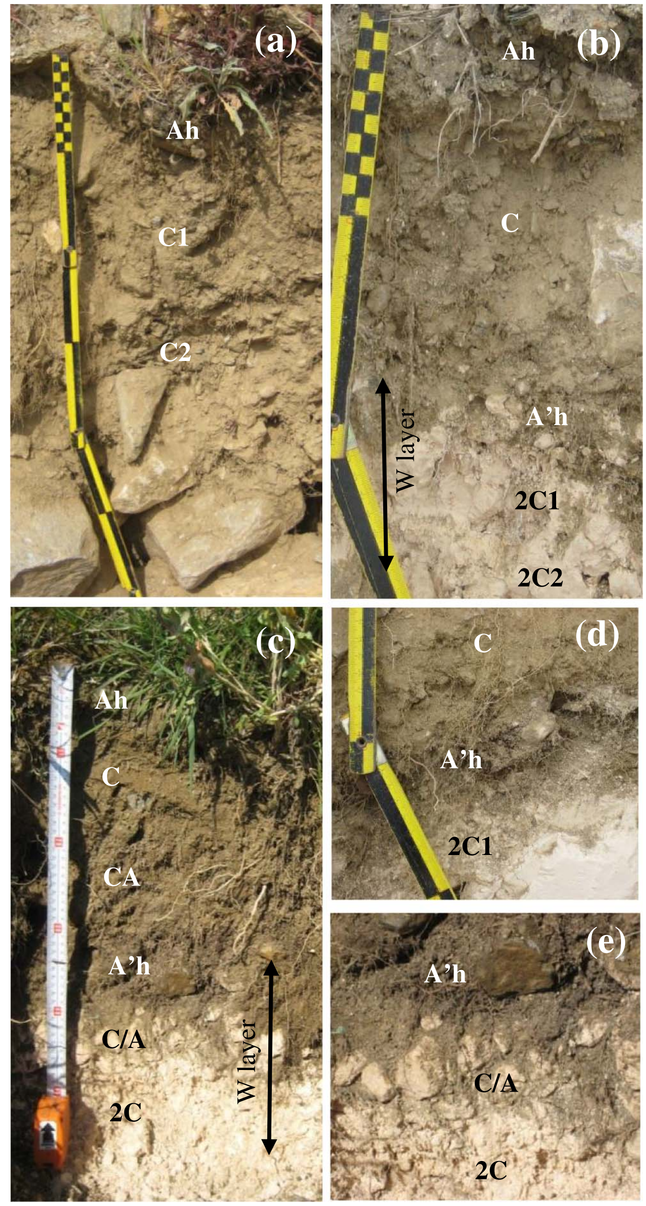

Fig. 1. (a) Soil of the PT plots (without sludge), (b) soil of the PTS ≤ 25 plots, (c) soil of the PTS > 30 plots, (d) high growth of roots in A'h and 2C1 horizons of the PTS ≤ 25 and (e) detail of the C/A horizon of the PTS > 30 plots.

(PTS ≤ 25), five horizons were sampled (Fig. 1b, d), three of which were located in the topsoil (Ah in the surface, C in the subsurface horizon and A'h in the deepest part of the topsoil in contact with the sludge and with a clearly darker colour) and two in the marble sludge (2C1 with relatively high density of roots and 2C2 with lower density of roots). In the soils of the three plots in which the thickness of the topsoil provided was higher than 30 cm (PTS > 30), six horizons were sampled (Fig. 1c), of which four were located in the topsoil (Ah in the surface, C in the subsurface, a transitional horizon labelled CA and A'h in the deepest part of the topsoil, in contact with the sludge and with a clearly darker colour), including a transitional horizon labelled C/A (Fig. 1d) that was formed by a mixture of A'h horizon (minority) and sludge (majority) and a 2C horizon formed exclusively by the marble sludge. The deepest 5 cm of the topsoil and the first 10 cm of the marble sludge were labelled W layer. The density of roots in the A'h, 2C1 and C/A horizons was estimated visually.