Ecological Engineering 71 (2014) 94–100

Contents lists available at ScienceDirect

Ecological Engineering

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

Restoration of dump deposits from quarries in a Mediterranean climate using marble industry waste

Mariano Simón-Torres[a,*], Fernando del Moral-Torres[a], Sergio de Haro-Lozano[a], Francisco Gómez-Mercado[b]

[a] Departamento de Agronomía, Área de Ciencia del Suelo, Universidad de Almería CITE IIB. Campus de Excelencia Internacional Agroalimentario ceiA3, Ctra. Sacramento s/n, 04120 Almería, Spain
[b] Departamento de Biología y Geología, Área de Botánica, Universidad de Almería CITE IIB, Ctra. Sacramento s/n, 04120 Almería, Spain

ARTICLE INFO

Article history:
Received 10 January 2014
Received in revised form 7 May 2014
Accepted 11 July 2014
Available online 3 August 2014

Keywords:
Quarries
Restoration
Marble sludge
Water retention
Biomass

ABSTRACT

One of the most frequently used techniques for restoring quarrying operations is to cover the surface of the dump deposit with a layer of topsoil. Sludge from the cutting and polishing of marble has a high water-holding capacity (0.256 kg kg^{-1}) and could increase the success of quarry restorations. In this study, a dump deposit located at the Macael marble quarries (SE Spain), which has a surface of approximately 1100 m^2 and a 72% slope, was restored with and without the addition of marble sludge prior to being covered with topsoil to analyse the impact of the sludge on the water-holding capacity and the development of vegetation. In the plots without sludge, the relatively low water-holding capacity of the topsoil and the capillary barrier, which forms when a fine-grained material overlays a coarse-grained material, tended to reduce the success of the restoration. In the plots with the sludge, the mean water content was more than double that of the plots without the sludge (61 dm^3 m^{-2} vs. 27 dm^3 m^{-2}). Water tended to accumulate between the deepest 5 cm of the topsoil and the first 10 cm of the sludge, which stimulated the development of the roots in this layer and significantly encouraged the development of aboveground biomass. However, the amount of stored water and the aboveground biomass were significantly related to the thickness of the topsoil; therefore, for a better utilisation of rainwater in semi-arid climates, restorations should include topsoil that is at least 30 cm thick.

1. Introduction

Agriculture, industrial operations and mining are the main human activities that lead to landscape degradation, and open-cast mining, which was carried out for centuries, is one of the main causes of the degradation of the Mediterranean landscape (Gams et al., 1993). Quarrying activities result in significant visual impacts because of soil depletion and the marked alteration of the original topography (Mouflis et al., 2008; Pinto et al., 2002). The mining of marble produces large quantities of dump deposits consisting primarily of unweathered clasts of different sizes (Gentili et al., 2011). These deposits lack soil and have limited water availability and steep slopes (>60%), 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). Thus, when the goal of restoration is to establish a plant community to reduce the visual impact of adverse conditions on a landscape, a substitute substrate is required to promote the establishment of drought-tolerant vegetal species. The drought-resistant plants subsequently improve the chemical and physical soil properties and facilitate the establishment of new species that have higher requirements for both water and nutrients (Bochet et al., 1999; Garner and Steinberger, 1989; Maestre et al., 2001). 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 (Bote et al., 2005; Brofas, 2001; Zhang and Chu, 2010) and then perform hydroseeding with different species (García-Palacios et al., 2010; Martínez-Ruiz et al., 2007; Tormo et al., 2007). However, in semi-arid climates, the pedogenesis is limited, and the soils are poor, which significantly reduces the success of the restoration (Bochet and García-Fayos,

Abbreviations: PT, plots with only topsoil; PTS, plots with topsoil and marble sludge; TT, thickness of the added topsoil; DB, dry biomass.

* Corresponding author. Tel.: +34 950 015923.
E-mail addresses: msimon@ual.es (M. Simón-Torres), fmoral@ual.es (F. del Moral-Torres), sdeharo@ual.es (S. de Haro-Lozano), frgomez@ual.es (F. Gómez-Mercado).

http://dx.doi.org/10.1016/j.ecoleng.2014.07.039
0925-8574/

2004; García-Fayos et al., 2000; Oliveira et al., 2011). In these cases, treatments with fertilisers, water-holding polymers, geotextiles and mycorrhizal inoculations have been used to enhance the growth of vegetation (Caravaca et al., 2003; Hüttermann et al., 1999; Yang et al., 2014; Mitchell et al., 2003; Sarvaš et al., 2007). However, these treatments are expensive and are of questionable effectiveness (Clemente et al., 2004; Oliveira et al., 2011), especially because a significant increase in the demand for restorations starting in the late 20th century required that practitioners use the most cost-effective techniques. To reduce costs, different wastes such as sewage sludge and slate processing fines have also been used in the restoration processes; these wastes produced even better results than the more expensive treatments (Ortiz et al., 2012; Rowe et al., 2005).

The main marble producing area in Spain, in terms of reserves and quality, is located in Macael (Almería, SE Spain) and has approximately 200 marble quarries spread over an area of 67 km^2. The marble production is approximately 10^6 t per year and reached a peak of 1.76×10^6 t in 2007. During the cutting and polishing of marble, significant quantities of a white sludge consisting of fine particles (silt) of marble are generated. This white sludge is deposited on the landscape around the industrial area and, similar to the marble quarries, has a great visual impact. We analysed the marble sludge for its use in reducing the mobility and bioavailability of heavy metals in the polluted soils (González et al., 2012), found that it had a high water-holding capacity and surmised that it could be useful in restoring dump deposits in semi-arid climates. In the present study, marble sludge was used in the restoration of a dump deposit located at the Macael marble quarries (SE Spain) to analyse its impact on the water-holding capacity of the soil and the development of vegetation.

2. Materials and methods

2.1. Study area

The study was carried out in a dump deposit at a quarry site in Macael (southeast Spain, 37°18′17″N, 2°17′5″W), which is located in the central-eastern region of the Sierra de los Filabres (Internal Zone of the Betic Cordilleras). The mean annual rainfall is 454 mm, which is mainly concentrated in the autumn and winter months, and the mean annual water deficit (difference between the mean annual precipitation and mean annual evapotranspiration; Milly, 1994) is −442 mm, which is mainly concentrated in the summer months. The mean annual temperature is 16.8 °C, with a mean maximum of 32.0 °C in the summer and a mean minimum of 5.3 °C in the winter. The bioclimate is Mediterranean pluviseasonal-oceanic (Rivas-Martínez and Loidi, 1999), and the area is included in the *Paeonio coriaceae-Querceto rotundifoliae sigmetum* vegetation series (Valle et al., 2003).

The “Centro Tecnológico Andaluz de la Piedra” (CTAP) includes all quarry owners and various official entities, such as the City of Macael, the Provincial Council and the Andalusia Government, and it is responsible for both restoring the dump deposits scattered around the quarry sites and for managing the marble sludge. At present, the restoration technique is mainly based on rearranging the marble stones to reduce the roughness of the surface and covering the surface with a layer of topsoil approximately 25 to 35 cm thick and hydroseeding. However, as is the case for most quarries restored in semi-arid climates, the topsoil provided in the restoration has a high gravel content, low nutrient content and low water-holding capacity, which considerably limits the success of the restoration.

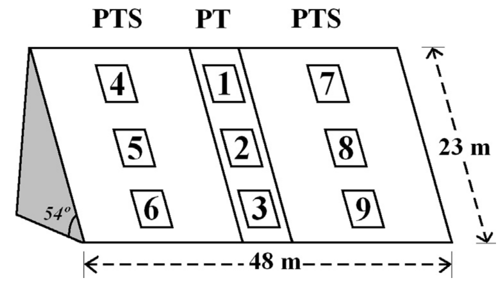

Fig. 1. Size, slope angle and sectors of the restored dump deposit. (PT) Sector with only topsoil (control) and (PTS) sectors with topsoil and marble sludge. Location of the nine study plots in which the moisture probes were placed in the centre.

2.2. Technique proposal

Vegetation grown in Mediterranean semi-arid climates is limited mainly by scarce and unevenly distributed rainfall (Aronson et al., 1993). Therefore, the proposed technique would add a layer of marble sludge on the dump deposit prior to adding the topsoil to increase the water-holding capacity of the substrate and to shorten the period of plant water stress. The high cost of restoration of the slope (transport of sludge, heavy machinery, and hydroseeding), specifically prepared for this experience, required that the study take place in a single slope of relatively reduced dimensions. In early September 2007, the stones of a dump deposit with an area of approximately 1100 m^2 (48 × 23 m) and a slope close to 72% (slope angle 54°) were rearranged, and nine steel rods with diameters equal to that of the access tubes of the PR2 moisture probe (Delta-T Devices Ltd., Burwell, Cambridge CB25 0EJ, UK) were inserted (Fig. 1). Subsequently, an approximately 20 cm thick layer of marble sludge was placed over the surface of the deposit, save for an approximately 5 m wide strip in the centre of the deposit that served as a control (Fig. 2A). Finally, the dump deposit was covered with a layer of topsoil (Fig. 2B). Once the slope was restored, the steel bars were removed, and access tubes for the PR2 probe were installed. For subsequent studies, nine plots of 6 m^2 (3 × 2 m) were selected such that the access tubes were in the centre of each plot (Fig. 1). Because the marble sludge had white-stained the steel bar, the depth of the sludge in each plot was easy to establish. Although efforts were made to ensure that the added topsoil had a thickness of approximately 30 cm and the marble sludge layer was approximately 20 cm, the end result differed. The topsoil thickness ranged from 18 cm to 34 cm in plots 4 and 9, respectively, and the marble sludge thickness ranged from 17 cm to 21 cm in plots 4 and 6, respectively.

2.3. Hydroseeding

At the beginning of October 2007, hydroseeding was carried out with a slurry containing 8 g L^{-1} of a mixture of seeds of common native species in the study area (*Agropyron cristatum*, *Cynodon dactylon*, *Lolium rigidum*, *Medicago sativa*, *Melilotus officinalis*, *Anthyllis cytisoides*, *Artemisia campestris*, *Atriplex halimus*, *Bituminaria bituminosa*, *Rumex induratus*, *Piptatherum miliaceum*, *Moricandia arvensis* and *Zygophyllum fabago*), 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 fertiliser, 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. Analysis of the topsoil and marble sludge provided

Once the slope was restored and prior to hydroseeding, three samples of the topsoil and marble sludge were taken for each