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Carbon dynamics after afforestation of semiarid shrublands: Implications of site preparation techniques

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ABSTRACT

Climate change is a potential threat to soil organic carbon (SOC) in semiarid ecosystems. Several studies advocated afforestation as an important way to achieve soil C accumulation, but few deal with the mechanisms of C stabilization. The knowledge of these mechanisms is a key aspect in the preservation of SOC in the face of climate change. In a long-term experiment in southeast Spain, we analyzed the effect on C sequestration and stabilization mechanisms of two *Pinus halepensis* afforestation treatments: (a) terracing (T) and (b) terracing with soil amendment (AT). Twenty years after installing the pine plantations, changes were measured in: (a) chemical, physical, and biological soil properties, (b) ecosystem C stocks, and (c) three functional SOC pools: particulate organic matter (POM), sand and stable aggregates (S+A), and silt plus clay (S+C). The results show that the afforestation treatment had a distinct impact on soil properties. Compared with the adjacent native shrubland, the AT treatment led to improved soil fertility, while the T treatment had a negative impact on soil properties. In turn, AT led to a C gain in the ecosystem of 1.3 kg C m^{-2}, while with T there was a decline of 0.60 kg C m^{-2} over 20 years. This decline was due to the impact of the terracing work. The potential ecosystem C sequestration capacity of the afforestation was 160 and 65 g C m^{-2} $year^{-1}$ in AT and T, respectively. Focusing on sequestration in the mineral soil, the average annual sequestration rate was 28 g C m^{-2} $year^{-1}$ in AT and 17 g C m^{-2} $year^{-1}$ in T. In relation to the functional SOC pools, the C sequestered showed the following distribution: 30% POM, 46% (S+A), and 24% (S+C). The results show that C sequestration, through afforestation of semiarid areas, can be increased by using suitable afforestation techniques. Site preparation involving large soil disturbance is not recommended. Twenty years after planting, the potential capacity for C sequestration of the afforested ecosystems is far from being saturated and they will continue sequestering C as they reach maturity.

1. Introduction

In recent centuries, soils have released large amounts of CO_2 as a consequence of land use changes (e.g. conversion of forests to agricultural lands), soil degradation, and desertification (Jandl et al., 2007; Lal, 2005). This has led to a significant decline of soil organic carbon (SOC) pools and increased concentrations of greenhouse gases (GHG) in the atmosphere. This unfavorable scenario could be worsened, particularly in semiarid ecosystems, by current trends of climate change. In a study of the impact of climate change on SOC in southeast Spain, Albaladejo et al. (2013) reported decreases of SOC stocks with increased temperature and reduced precipitation, as expected in semiarid areas. Traditional approaches to ecosystems restoration have considered afforestation to be an important tool to rehabilitate the capacity of ecosystems to produce goods and services and increase C sequestration (Cao et al., 2010; Nosetto et al., 2006). However, despite the considerable SOC-sequestration potential of afforestation, many studies have reported contradictory findings: afforestation resulted in either a decrease (Wiesmeier et al., 2009) or an increase (Fernández-Ondoño et al., 2010) in the SOC stocks, or had a negligible effect (Laganière et al., 2010). There are many abiotic factors affecting the extent of change in soil C, including site preparation, previous land use, climate, soil texture, site management, and harvesting (Paul et al., 2002). In addition, although several studies have estimated the contribution of afforestation to C sequestration (Laganière et al., 2010), there are very few that discuss the

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mechanisms of C stabilization (Six et al., 2002; De Gryze et al., 2004), particularly in semiarid areas.

The fractionation of organic matter into different parts that are thought to be functionally homogeneous with respect to physico-chemical properties and turnover rates is an increasingly-used methodology in mechanistic studies of C sequestration (De Gryze et al., 2004). One of the most-promising approaches to obtain functional SOC pools is a combined physical and chemical fractionation method proposed by Zimmermann et al. (2007). This method isolates five soil fractions which can be combined into three functional pools: the active, the intermediate, and the passive SOC pool. The active pool is mainly composed of fresh plant residues, root exudates, and faunal and microbial residues with a short turnover time of 1–10 years (von Lützow et al., 2008). The intermediate and passive pools are characterized by organic matter (OM) with considerably-longer turnover times of 10–100 and >100 years, respectively. In these pools OM is stabilized against microbial mineralization by occlusion within soil macro- and microaggregates, selective preservation of recalcitrant compounds, and the formation of organo-mineral associations (Sollins et al., 1996; Christensen, 2001; Kögel-Knabner et al., 2008). The determination of functional SOC pools allows a precise evaluation of the C sequestration in afforested soils.

The restoration of degraded semiarid lands by the reintroduction of woody species has become increasingly important (Maestre and Cortina, 2004). However, divergent results caused a lack of consensus about the strategies required to implement the restoration programs. In fragile ecosystems, such as semiarid lands, the increase of forest cover could exacerbate environmental degradation when the management of afforestation ignores climate, pedological, hydrological, and landscape factors that would make a site unsuitable for afforestation (Cao et al., 2011). In dry areas, the introduction of woody species is strongly limited by biotic and abiotic factors (Cortina et al., 2011). Abiotic constraints are likely to increase as temperatures increase and rainfall becomes more scarce (Giorgi and Lionello, 2008). These limitations could be diminished by suitable afforestation techniques.

In this study, we test the hypothesis that C sequestration, following afforestation in semiarid areas, can be increased by suitable techniques which aim to improve soil conditions and resource availability. In a long-term (20 years) experiment, we analyzed the effect of two afforestation techniques on C sequestration by directly measuring the net C accumulation in the afforested ecosystems. The two techniques tested were: (1) terracing, in order to improve the water efficiency, and (2) terracing combined with soil amendment, to improve the water efficiency and the physical and chemical soil fertility. The site was located on a degraded shrubland in the Iberian southeast, one of the areas most vulnerable to desertification (Fons-Esteve and Páramo, 2003), and the results may be a reference for extrapolation to other semiarid areas. The environmental conditions, such as scarce and irregularly-distributed rainfall, erodible soils, and steep terrain, make these areas unable to recover spontaneously (Puigdefabregas and Mendizabal, 1998; Albaladejo et al., 1998). Due to the widespread extent of degraded ecosystems and to the limited funds available, the selection of the areas to be restored is one of the major challenges faced by scientists and practitioners worldwide (Maestre and Cortina, 2004). This study may contribute to an increase in our knowledge of the suitability of afforestation with the purpose of C sequestration in these low-productivity ecosystems.

Initial results of this experiment were reported in Roldan et al. (1996a) and Querejeta et al. (2000). The specific objectives in this long-term study were to: (1) assess the impact of the afforestation technique on soil rehabilitation, (2) determine the changes in the organic carbon stocks for the different components of the ecosystems, according to the afforestation technique, and (3) increase our knowledge of the mechanisms involved in organic carbon accumulation and stabilization in afforested ecosystems under semiarid conditions.

2. Material and methods

2.1. Study area

The experimental area was located in the Sierra de Carrascoy, southeast Spain (37°53′N, 1°15′W, 180 m a.s.l.). The climate is semiarid with an average annual precipitation of 300 mm, which occurs mostly in spring and autumn. The mean annual temperature is 18 °C, and the mean annual potential evapotranspiration is 900–1000 mm year^{-1}. The soils are classified as *Haplic Calcaric Leptosol* with inclusions of *Leptic Calcisol and Haplic Calcisols* (FAO, 2006). The lithology of the area is constituted by hard and compact limestone rocks. The dominant vegetation is composed of characteristic species of Mediterranean shrublands (e.g. *Rosmarinus officinalis* L., *Thymus vulgaris* L., and *Anthyllis cytisoides* L.) with scattered stands of Aleppo pines (*Pinus halepensis* Miller). Fig. 1 shows a general overview of the study area and the current state of the pines in the afforested plots.

2.2. Experimental design

In October 1992, an area of 1800 m^2, consisting of three plots of 20 × 30 m, was established on an east-facing hillside (25% mean slope) to test the following afforestation techniques: mechanical terracing with soil organic amendment and *P. halepensis* plantation (AT), mechanical terracing and *P. halepensis* plantation without organic amendment (T), and Mediterranean shrubland adjacent to these reforested plots, which was considered as the control plot (S). The mechanical terraces (4 m wide and 30 m long) were excavated with a bulldozer. The organic amendment consisted of the organic waste of urban solid refuse (USR) from the Murcia Municipal Treatment Plant. The USR, with a C content of 253 g C kg^{-1}, was incorporated into the top 20 cm of the soil in the AT treatment, in a single application of 10 kg m^{-2} at the beginning of the experiment. The analytical characteristics of this organic amendment can be found in García et al. (1998). The Aleppo pine seedlings were planted in both treatments – in 40-cm-wide, 40-cm-deep pits – at least 1 m apart in a single row per terrace. The experiment

Fig. 1. General overview of the study area showing the current state of the vegetation in the experimental plots. Control plot (S), mechanical terracing (T) and mechanical terracing combined with soil amendment (AT).