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How do soil organic carbon stocks change after cropland abandonment in Mediterranean humid mountain areas?

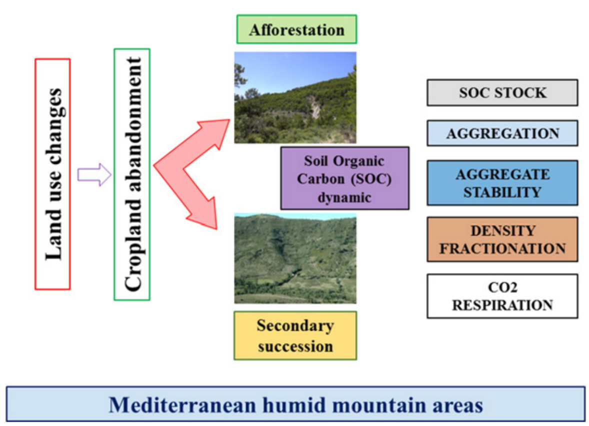
E. Nadal-Romero [a,b,*], E. Cammeraat [b], E. Pérez-Cardiel [b], T. Lasanta [c]

[a] Department of Geography, Environmental Sciences Institute (IUCA), University of Zaragoza, Spain
[b] Institute for Biodiversity and Ecosystem Dynamics, University of Amsterdam, The Netherlands
[c] Pyrenean Institute of Ecology (IPE-CSIC), Spain

HIGHLIGHTS

- This paper examines the effects of land abandonment on soil organic carbon.
- SOC dynamics have been studied in the bulk soil and in the fractions.
- Only afforestation with *Pinus nigra* accelerates the recovery of SOC in the topsoil.
- Aggregation is an important mechanism promoting SOC stocks after afforestation.
- Pastureland should be considered in land management due to the importance in SOC stocks.

GRAPHICAL ABSTRACT



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ABSTRACT

The effects of land use changes on soil carbon stocks are a matter of concern stated in international policy agendas on the mitigation of greenhouse emissions. Afforestation is increasingly viewed as an environmental restorative land use change prescription and is considered one of the most efficient carbon sequestration strategies currently available. Given the large quantity of CO_2 that soils release annually, it is important to understand disturbances in vegetation and soil resulting from land use changes. The main objective of this study is to assess the effects of land abandonment, land use change and afforestation practices on soil organic carbon (SOC) dynamics. For this aim, five different land covers (bare soil, permanent pastureland, secondary succession, *Pinus sylvestris* (*PS*) *and Pinus nigra* (*PN*) afforestation), in the Central Spanish Pyrenees, were analysed. SOC dynamics have been studied in the bulk soil, and in the fractions separated according to two methodologies: (i) aggregate size distribution, and (ii) density fractionation, and rates of carbon mineralization have been determined by measuring CO_2 evolution using an automated respirometer. The results showed that: (i) SOC contents were higher in the *PN* sites in the topsoil (10 cm), (ii) when all the profiles were considered no significant differences were observed between pastureland and *PN*, (iii) SOC accumulation under secondary succession is a slow process, and (iv) pastureland should also be considered due to the relative importance in SOC stocks. The first step of SOC stabilization after afforestation is the formation of macro-aggregates promoted by large inputs of SOC, with a high

* Corresponding author at: Department of Geography, Environmental Sciences Institute (IUCA), University of Zaragoza, Spain.
E-mail address: estelanr@unizar.es (E. Nadal-Romero).

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contribution of labile organic matter. However, our respiration experiments did not show evidence of SOC stabilization. SOC mineralization was higher in the top layers and values decreased with depth. These results gain insights into which type of land management is most appropriate after land abandonment for SOC.

1. Introduction

Soils are the primary terrestrial pool for organic carbon and account for >75% of the Earth's terrestrial organic carbon (Lal, 2004). However, soils can render either a sink or a source of carbon and atmospheric carbon dioxide (CO_2) with direct influence on the greenhouse effect (Lugo and Brown, 1993; Lal et al., 1995). The role played by soils in the sequestration of soil organic carbon (SOC) is so crucial that the Kyoto Protocol (article 3.3) and the Paris agreement included it as an important element for managing (see also Montanarella, 2015; Keesstra et al., 2016). The effects of land use changes on SOC stocks are a matter of concern stated in international policy agendas on the mitigation of greenhouse emissions. Anthropogenic activities have led to an increase in atmospheric concentration of CO_2 (Reicosky, 2002; WMO, 2008), and forestry is recognised as major sink for carbon but as well as accumulating carbon above ground (Lal, 1997). In that sense, afforestation is increasingly viewed as an environmental restorative land use change prescription and is considered to be one of the most efficient carbon sequestration strategies currently available (Farley et al., 2005). Since the United Nations Framework Convention on Climate Change there has been increasing interest in afforestation to sequester CO_2 from the atmosphere.

Cropland abandonment has been the main land use change in the northern rim of Mediterranean humid mountain areas over the last decades (Lasanta et al., 2016) leading to the expansion of forestland and scrublands (Sluis et al., 2014). These abandoned areas can be left to undergo secondary succession (passive restoration) or be subjected to afforestation (active restoration) that mostly consists of tree and shrub planting. Large areas of Europe are increasingly abandoned (Navarro and Pereira, 2015). After farmland abandonment, old fields are spontaneously slowly colonised by annual and perennial herb communities and then are partially or completely replaced by perennial grasses, shrubs, and/or trees (secondary succession, after 10–60 years), and >100 years are necessary to observe a forest stage (Molinillo et al., 1997). Nowadays, abandoned fields present a very dense vegetation cover composed mainly of shrubs and an herbaceous layer (Lasanta-Martínez, 2005; Reiné et al., 2014). At the same time, due to the idea of land degradation after abandonment, the slow process of secondary succession, and with productive and environmental objectives, extensive afforestation programs were conducted by national forest services all over the Mediterranean region (Ortigosa et al., 1990; Yaşar Korkanç, 2014). On the other hand, some scientists suggest that secondary succession has negative impacts on environment, landscape and socio-economy (García-Ruiz and Lana-Renault, 2011; San Román Sanz et al., 2013) and suggest keeping abandoned land in the first pastureland stage (Conti and Fagarazzi, 2005; Lasanta et al., 2015). Conversely, other scientists prefer rewilding methods (Navarro and Pereira, 2015).

Different studies have reported that soil properties recover slowly after land abandonment (Ruiz-Sinoga and Martínez-Murillo, 2009; Nadal-Romero et al., 2016b), and many recent studies have shown that SOC is strongly affected by land abandonment and revegetation processes in Mediterranean mountain areas (Muñoz-Rojas et al., 2011; Novara et al., 2014; Gabarrón-Galeote et al., 2015a). Observations about the effects of afforestation on SOC have been synthesized and reviewed worldwide by Post and Kwon (2000), Guo and Gifford (2002), Paul et al. (2002) and Li et al. (2012). Moreover, given the large quantity of CO_2 that soils release annually, it is important to understand disturbances in vegetation and soils resulting from land abandonment.

SOC consists of different fractions with contrasting resistance to decomposition (Schimel et al., 1985) that are differently affected by land abandonment and revegetation processes (Trigalet et al., 2016). Soil aggregation provides physical protection of SOC against rapid decomposition (Razafimbelo et al., 2008), and aggregate formation and stability is really closely linked with SOC storage (Salome et al., 2010). However, the role of soil aggregation and SOC fractions is far from well understood in Mediterranean humid mountain areas. Density fractionation is a useful tool to study the relevance of SOC stabilization in aggregates and in association with minerals. The use of physical density fractionation methods of soil organic matter has been successfully applied in different environments (Six et al., 2000; Cerli et al., 2012; Wang et al., 2014), but it has rarely been applied to full soil profiles. The method proposed by Golchin et al. (1994) (combining dispersion and sonication) became a widely applied method: (i) the Free Light Fraction (FLF) comprises relatively undecomposed labile organic matter (unprotected), (ii) the Occluded Light Fraction (OLF) comprises organic matter stabilized by aggregation, and (iii) the Heavy Fraction (HF) is strongly associated with soil minerals (Cerli et al., 2012). Knowing the degree of protection of the SOC is crucial because it allows a better understanding of SOC dynamics, aggregation and stabilization.

Moreover, it has been demonstrated that although SOC concentration is generally higher in the top layers, the total soil volume of the subsurface horizons is usually much higher. Jobbagy and Jackson (2000) showed that 60% of the total SOC is stored below a depth of 20 cm. However, most studies of SOC dynamics and stability were restricted to topsoil layers, and our understanding of subsoil SOC is still limited, even when subsoils are really sensitive to land use changes (Rumpel and Kögel-Knabner, 2011).

Despite the extensive land abandonment and the consequent revegetation process, and the time occurred after the first afforestation plans, few investigations have studied the consequences of land abandonment in Mediterranean humid mountains related to soil properties. Nadal-Romero et al. 2016b showed that there is still considerable uncertainty about the effects of afforestation practices on soil property dynamics, and so far, no comparing study has been carried out for the effects of secondary succession and afforestation in Mediterranean humid mountain areas after land abandonment.

The main objective of this study is to assess the effects of land abandonment and revegetation processes (secondary succession and afforestation practices) on SOC dynamics. The specific objectives were to (i) quantify total SOC in different land use soils and depths, (ii) isolate SOC in aggregate sizes and density fractions, and (iii) determine carbon mineralization by measuring CO_2 evolution.

This leads to the following research hypothesis: an increase in vegetation cover due to secondary succession and afforestation practices in Mediterranean humid mountain areas (after the abandonment of agricultural land and grazing activities) may lead to significant increases in SOC stocks and SOC sequestration. To test these hypothesis, five different land cover types (bare soil, permanent pasturelands, secondary succession and *Pinus sylvestris* and *Pinus nigra* afforestations), in the Central Spanish Pyrenees were analysed.