Geoderma xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Geoderma

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

Small-scale spatial variation of soil organic matter pools generated by cork oak trees in Mediterranean agro-silvo-pastoral systems

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ARTICLE INFO

Article history:
Received 30 December 2015
Received in revised form 13 July 2016
Accepted 14 July 2016
Available online xxxx

Keywords:
Water extractable organic carbon
Particulate organic carbon
Mineral-associated organic carbon
Wooded grasslands

ABSTRACT

The aim of this study was to assess the role of cork oak (*Quercus suber* L.) trees on the small-scale variation of soil organic matter (SOM) pools in an agro-silvo-pastoral system under Mediterranean semi-arid conditions in northeastern Sardinia, Italy. Six cork oak trees were selected in a wooded grassland (30% tree ground cover). For each tree, and along two opposite transects (NE and SW), floor litter and soil (20-cm depth) were sampled at five points starting next to the trees' trunk and ending beyond the tree crown projection. Soil organic matter quality was characterized by measuring the content of water extractable organic matter (WEOM), free particulate SOM (POMf), occluded aggregates particulate SOM (POMo), and mineral-associated SOM (MOM). Carbon (C) input from floor litter was larger in the sampling points under the tree crown projection than in those beyond the tree crown. The C content of SOM pools differed among sampling positions regardless of the transect orientation, decreasing from the trunk to the positions beyond the tree crown projection, from 24.1 to 15.7 g C kg^{-1} for MOM, and from 9.9 to 5.7 g C kg^{-1} for the sum of WEOM, POMf and POMo. The C in MOM next to the tree trunk was above the saturation level sensu Hassink and Whitmore (1997), but below saturation beyond the tree crown projection. The nitrogen (N) distribution showed a similar trend. These results indicate that in these agro-silvo-pastoral systems, oak trees generate hot spots of soil C storage, by controlling the rate of C inputs via litterfall. Hence, conservation strategies designed to maintain cork oak trees in grasslands will also contribute to maintain a high stock of C stored and a resilient, multipurpose system.

1. Introduction

Soils in agroforestry systems can be an important reservoir of organic C (SOC). The reason is that the inherent large plant species diversity in these systems compared to treeless grasslands would allow greater capture and use of light, nutrients, and water (Nair, 2011). In agroforestry systems, SOC and vegetation are distributed more heterogeneously across the landscape than in tilled crop and pasture lands (e.g., Howlett et al., 2011). In these agro-ecosystems quantifying the SOC storage potential and characterizing its distribution is relevant to inform policies aimed at increasing SOC storage and mitigating the buildup of CO_2 in the atmosphere.

Among the most extended European agroforestry systems, the agro-silvo-pastoral systems called Dehesa in Spain and Montado in Portugal, cover about 3 million ha including areas such as Sardinia in Italy (Eichhorn et al., 2006; Caballero et al., 2009). These are multipurpose systems of scattered oak trees (holm oak, *Quercus ilex*; cork oak, *Quercus suber*; and a deciduous oak, *Quercus pyrenaica*) that form an open upperstorey that is mixed with grazed grasslands or intercropped with cereal and forage crops. The main product of these systems is livestock, which is integrated with the provision of cereal grains, forage, cork, firewood, and aesthetic amenities. These large scale grazing systems have been common since at least the Middle Ages (Gómez-Gutiérrez and Pérez-Fernández, 1996). Oak trees provide acorns and leaves for grazing animals, improve soil fertility (Gallardo, 2003), water regulation (Joffre and Rambal, 1993), and diversify the system microclimate (Moreno et al., 2005). Open grasslands are species rich and provide a wide range of ecosystem services e.g. forage for the grazing animals (Bagella et al., 2013a), protection from soil erosion, and habitats for wildlife and pollinators (Bagella et al., 2013b).

The positive effect of trees is usually attributed to the their capacity to capture water and nutrients from deep soil layers (Young, 1997) and

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http://dx.doi.org/10.1016/j.geoderma.2016.07.021
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Please cite this article as: Cappai, C., et al., Small-scale spatial variation of soil organic matter pools generated by cork oak trees in Mediterranean agro-silvo-pastoral systems, Geoderma (2016), http://dx.doi.org/10.1016/j.geoderma.2016.07.021

from areas laterally distant from the trunk (Scholes and Archer, 1997), and subsequently returning nutrients to the soil beneath the tree crown via leaf litter (Escudero et al., 1992; Gallardo and Merino, 1998) or indirectly via animal excreta. Trees also influence soil temperature and water content, which affect soil microbial quantity and activity (Simón et al., 2013; Tardy et al., 2015). In Mediterranean wooded grasslands, litterfall was found to be the most prominent factor by which the tree exerts direct effects on soil properties (Rossetti et al., 2015). Moreover, several studies have demonstrated the important role of roots in the C balance, since they transfer large amounts of C into the soil (Högberg et al., 2001; Kuzyakov and Cheng, 2001; Nair et al., 2009). Spielvogel et al. (2014) found that single trees can contribute to the formation of high SOM patches derived from the decomposition of root litter. However, the mechanism by which C inputs from litterfall and roots cascade through different soil organic matter pools were not investigated in these systems. Carbon inputs to the soil from root decay, litterfall, and animal excreta are decomposed by macro- and micro-fauna. Most of the decomposed C is lost as CO_2 through respiration, with a fraction becoming "humified" and incorporated in soil organic pools with slower turnover rates than that of the original litter (Swift et al., 1979). Different pools of SOM have different residence times that range from labile to stable forms (Carter, 1996; Collins et al., 2000; Haile et al., 2010), and respond differently to management practices and land uses (Cambardella and Elliot, 1992; Chan, 2001; Romanyà and Rovira, 2011). Two main mechanisms of SOM stabilization that limit microbial degradation have been proposed: selective preservation due to recalcitrance of SOM, and spatial inaccessibility of SOM due to hydrophobicity and occlusion in soil aggregates and interaction with mineral surfaces (von Lützow et al., 2006; Wiesmeier et al., 2014). Chemical recalcitrance plays a lesser role than previously assumed as summarized by Lehmann and Kleber (2015). Soil texture and structure, in particular the clay and silt content, are the main attributes controlling SOM physical protection (Hassink, 1997). Furthermore, clay and silt content define the maximum capacity to protect organic matter (Hassink and Whitmore, 1997) and the degree of soil C saturation would affect the humification rate of fresh C inputs (Hassink and Whitmore, 1997; Kemanian and Stöckle, 2010). It is not known if C saturation controls C flows and soil C storage in Mediterranean wooded grasslands, which limits our ability to develop strategies to enhance C storage.

The hypothesis of this study is that in wooded grasslands, the trees' litterfall influences soil organic C and N storage by generating SOM-rich hot spots. This spatially variable process can influence, in turn, spatial patterns of soil C and N storage, and SOM quality. The objectives of this study were: (1) to evaluate the small-scale variation of physically-separated SOM pools as influenced by cork oak trees in wooded grasslands under Mediterranean semi-arid conditions; (2) to assess the relationships between the amount and quality of floor litter and SOM pools; and (3) to estimate the potential amount of C that can be protected physically in organo-mineral associations, and how far a soil, which has been used as wooded grassland for many decades, is from its putative saturation level in relation to increasing distances from cork oak trees.

2. Materials and methods

2.1. Study area

The study area is located in the Berchidda-Monti long term observatory, a Mediterranean agro-forestry system in north-eastern Sardinia (Italy) (40° 47′ 0″ N 09° 10′ 0″ E, elevation 320 m). The bioclimate is pluviseasonal oceanic low meso-Mediterranean low sub-humid (Rivas-Martínez and Rivas-Saenz, 2014), with mean annual precipitation of 630 mm (70% from October to March), mean annual air temperature of 14.2 °C and an aridity index of 0.53 (annual rainfall/annual reference evapotranspiration). The soils of the area developed from granite and are classified as Typic Dystroxerept (Soil Survey Staff, 2010). Soil texture in the top soil is sandy loam (USDA, 2010) with average pH of 5.8, organic C 29.3 g kg^{-1} and total N 2.0 g kg^{-1} (Table 1). Detailed soil descriptions for the experimental site are reported in Rossetti et al. (2015). The potential vegetation of the area is cork oak woods or *Violo dehnhardtii-Quercetum suberis* association (Bagella and Caria, 2011). The study area has been managed for many decades according to a flexible rotational scheme consisting of a fallow pasture which is replanted every two to five years with an annual hay crop mixture depending on the dynamics of the thorny vegetation (Seddaiu et al., 2013). Grazing with Sarda dairy sheep occurs throughout the year with an average stocking rate of 3 ewes ha^{-1}. This land use has been stable at least for the last six decades as assessed through aerial photographs and farmer interviews. At the time of samplings, the study area was a five-year old fallow grassland with scattered cork oak trees at an average tree cover of about 30%.

Table 1
Mean, range and standard error (SE) of the soil characteristics for the top 20 cm at the study site.

Characteristics	Mean	Range	SE
Gravel, g kg^{-1}	147	98–222	
Coarse sand (1000–500 μm), g kg^{-1}	119	82–149	2
Medium sand (500–250 μm), g kg^{-1}	120	79–154	2
Fine sand (250–50 μm), g kg^{-1}	298	172–425	5
Coarse silt (50–20 μm), g kg^{-1}	55	40–80	1
Fine silt (20–2 μm), g kg^{-1}	149	130–173	1
Clay (<2 μm), g kg^{-1}	112	80–155	2
pH	5.8	5.1–6.1	0.03
Total N, g kg^{-1}	2.0	1.2–3.7	0.1
Organic C, g kg^{-1}	29.3	19.0–48.4	1.0
C/N	14.7	11.6–17.8	0.1

2.2. Experimental layout

The experimental layout was designed to measure floor litter and soil properties around six cork oak trees in the wooded grassland (Fig. 1). The trees had a crown diameter of 11.8 ± 0.9 m, height of 10.1 ± 0.3 m, and diameter at breast height of 0.35 ± 0.01 m. For each tree, two transects with opposing North-East (NE) and South-West (SW) orientation were identified following the procedure proposed by Fernández-Moya et al. (2010). The prevailing wind in the study area is from South-West and this direction shapes the tree crowns that are typically flag-shaped. Our hypothesis was that this characteristic of the crowns can influence the litterfall distribution into the ground, and that the trunk could represent a sort of barrier that facilitates a higher accumulation of the litter in the SW than in the NE direction; hence the soil monitoring was carried out along the two transects. For each transect, measurements were made at five sampling positions located in relation to the horizontal projection of the crown onto the ground: two positions were fully underneath the tree crown (positions 1 and 2), one position was in the edge of the crown (position 3) and two positions were beyond the tree crown (positions 4 and 5). Distances from the trunk were 1.2 ± 0.1 m, 3.5 ± 0.3 m, 5.9 ± 0.5 m, 8.2 ± 0.7 m and 10.7 ± 0.9 m respectively in the positions 1 to 5. All the studied variables were measured in all the positions along the two transects for a total of 60 sampling units (6 trees × 2 transects × 5 positions).

2.3. Floor litter

Floor litter samples were collected at each sampling position in May and November 2011, within a 25 × 25 cm quadrat. The mineral soil was separated from the floor litter using a brush and a spoon (Hoosbeek and Scarascia-Mugnozza, 2009). Samples were oven-dried at 60 °C until constant weight and fractionated by dry sieving (<2, 2–10, >10 mm) following the procedure described by Hoosbeek and Scarascia-Mugnozza (2009). The 2–10 mm fraction consists primarily of fragmented and partly decomposed leaves and small twigs. The fraction

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