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Topography and land use change effects on the soil organic carbon stock of forest soils in Mediterranean natural areas

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A B S T R A C T

In Mediterranean areas, through the years, natural forest (NF) areas have suffered land use change (LUC) mainly for economic reasons. This is the case of olive groves (OG) in Andalusia (south Spain), the main olive oil production area in the world. This LUC from NF to OG has caused soil erosion and the loss of soil quality. Also, this effect has been aggravated by climatic conditions and poor soil management practices. A field study was conducted to examine the effects of LUC from NF to OG in a toposequence (summit-SM, backslope-BS and toeslope-TS) and to determine soil organic carbon (SOC), nitrogen (N) and the stratification ratio (SR) of SOC in the Torredelcampo–Jaen–Spain (Mediterranean area) in a Calcisols–Regosols–Vertisols sequence.

Total SOC (T-SOC) was low for both NF and OG soils. In the case of NF, there was a pattern of decrease from the highest (SM) to the lowest topographical position (TS); whereas for OG, the highest T-SOC was found in TS (50.2 ± 1.1 g kg^{-1}). T-SOC was more than 40% higher in NF than in OG in SM and BS. The total SOC stock (T-SOCS) in NF soils remained evenly distributed in the three topographical positions. However, the trend for the OG soils was an increase of T-SOCS along the hillside (SM: 68.9 ± 4.8 Mg ha^{-1}; BS: 82.3 ± 12.3 Mg ha^{-1} and TS: 158.7 ± 15.4 Mg ha^{-1}). N followed a pattern of decrease with depth in the OG soils, but not in NF soils. As for N stock, it was higher in NF than in OG, with the exception of NF-TS and OG-TS. SR values in NF had a general trend of increasing from higher to lower topographical positions, despite the fact that T-SOC decreased from higher to lower topographical positions. This indicates that soil quality is higher in lower topographical positions even though there is less T-SOC. SR values in OG soils had a similar trend as in NF soils (but with lower values). However, T-SOC increased as well in the same way, which was opposite to the NF soils case. Therefore, soil quality was higher in lower topographical positions for both land uses.

1. Introduction

Over the centuries, olive groves (OG) have become a landscape and socioeconomic heritage of Mediterranean areas, being a way of life and the main economic support for its inhabitants (IOC, 2012). The area covered by OG has been gradually increasing up to 9.5 million ha in the whole Mediterranean basin. This increase is produced by the replacement of Mediterranean native vegetation (Nieto et al., 2013). Actually, this land use change (LUC) has been caused by the anthropogenic action of producing crops to ensure human development. Furthermore, subsidies and the increase of olive oil prices have made this feasible (Lozano-García and Parras-Alcántara, 2013a). Andalusia, with around 15% of its cultivated area covered by this crop (more than 2 million ha), is the main production area in the EU, with approximately 40% of the OG area in the EU-28 (EUROSTAT, 2009).

This activity, although it has brought economic benefits to the region, has also created serious problems for soils, causing land degradation and accelerating soil erosion (Nieto et al., 2013; Parras-Alcántara and Lozano-García, 2014). This land degradation is especially aggravated by the Mediterranean climatic conditions and by poor environmental practices such as planting on slopes and with low tree densities or conventional tillage (CT) (Gómez et al., 2009; Lozano-García and Parras-Alcántara, 2014). This so-called CT is done with mouldboard plow, disc harrow, herbicides and mineral fertilisation. Not only has this technique increased erosion rates and water losses, but it has also decreased soil quality due to the loss of organic matter (OM) (Calatrava et al., 2011; Lozano-García et al., 2011; Lozano-García and Parras-Alcántara, 2013b).

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In this line, soil management is one of the best tools for climate change mitigation and adaptation (Lal et al., 2011). The international community is concerned by the increase in greenhouse gases emissions and how these can influence climate change. As a result of this, the Kyoto protocol was signed, with the objective of mitigating and adapting to climate change using land sinks (Yimer et al., 2006). The second commitment period of this protocol (2013–2020) obliges parties to reduce greenhouse gases emissions by at least 18% compared to 1990 levels (United Nations, 2013). Little concern has been raised however, about the effect of soil degradation in climate change, which accounts for 20% of the total carbon emissions from 1850 to the end of the 20th century (Lal, 2004; Lal et al., 2011).

According to Smith (2008), LUC is the second greatest cause of carbon emissions after fossil fuel consumption. This may be linked to the fact that LUC could be the cause of soil degradation and soil organic carbon (SOC) losses, especially in Mediterranean areas (Eaton et al., 2008; Cerdà et al., 2010). Several studies have demonstrated that SOC is highly sensitive to LUC (Smith, 2008; Parras-Alcántara et al., 2013a). Climate, use and management are very influential in the carbon variability in Spanish soils (Rodríguez-Murillo, 2001; Muñoz-Rojas et al., 2012; Ruiz et al., 2012; Parras-Alcántara et al., 2013b), particularly in semiarid regions, which are characterized by low levels of soil organic matter content (10 g kg^{-1}) (Acosta-Martínez et al., 2003). Recently, some studies showed the influence of LUC in soil physical–chemical properties such as SOC, nitrogen (N) content, pH, texture, and C:N ratio (Parras-Alcántara et al., 2013a). Other studies demonstrate some variations in soil properties related to topographic positions (Yimer et al., 2006; Hattar et al., 2010). The study of topographic positions is connected to the concept of toposequence. Gessler et al. (1996) defined a toposequence as "a spatial object that maintains flow connectivity from summit (hillslope initiation) to base (hillslope conclusion)".

If we consider SOC and N as soil quality indicators (Sharma et al., 2005; Brevik, 2009), it is necessary to explain the relationship between soil properties and topographic position. It is then necessary to establish soil quality indicators that relate properties and topographic positions. In this regard, the stratification ratio (SR) (Franzluebbers, 2002) is mostly used. The SR of SOC can be used as an indicator of soil quality and has been effectively used in other studies to monitor soil carbon and N responses to LUC, soil management and climate (Franzluebbers et al., 2007; Sá and Lal, 2009). Furthermore, an increase in this ratio can be correlated to SOC sequestration (Franzluebbers, 2002).

To the best of our knowledge, very little literature has compared the effects of LUC in natural forest (NF) areas and its relationship with topographic positions – toposequence. In addition, there seem to be few reports on stratification of SOC as affected by topography. In this context, the aims of this study are: (i) to quantify SOC and nitrogen (N) contents and their vertical distribution in OG (after LUC) and NF soils; (ii) to assess the SOC and N stocks differences in soil along a topographic gradient and their relationship with soil depth for both uses (OG and NF); and (iii) to analyze the accumulation and SR of SOC in a toposequence (summit-SM, backslope-BS, toeslope-TS) of a Calcisols–Regosols–Vertisols sequence (IUSS-ISRIC-FAO, 2006) affected by LUC in NF of a Mediterranean natural area.

2. Material and methods

2.1. Study site and experimental design

The study was carried out in Torredelcampo–Jaen (30H-414,182–4,198,827; 415,310–4,199,191; 425,903–4,177,169; 421,389–4,176,841, 647 m. a. s. l.). The underlying bedrock within the studied area consists of Miocene marl and marlaceous lime. The soils are Calcisols, Regosols and Vertisols (IUSS-ISRIC-FAO, 2006). The climate is typical Mediterranean with 3–5 months of summer drought, usually from late June to September and moderately wet cool winters. According to the nearby weather station in Torredelcampo (Jaen), the annual average temperature is 17 °C, with a maximum air temperature of 40.6 °C in August and a minimum air temperature of −5.2 °C (January). The annual average precipitation is 645.7 mm, and monthly rainfall ranges from 4.7 mm (July) to 87 mm (February). This area was naturally covered by Mediterranean forest (*Quercus rotundifolia, Quercus faginea, Quercus coccifera, Bupleurum fruticosum*, *Cistus albidus, Pinus halepensis and Pinus pinaster, Ophrys lutea* and *Gladiolus illyricus*). However, part of this NF was transformed into OG during the 1940s.

The experimental design consisted of studying the LUC from NF to OG in three topographical positions with the same aspect: SM, BS and TS. The NF was an unaltered natural area and the OG (Picual variety) was an unirrigated land cultivated under conventional tillage (CT) with a density of 90 trees ha^{-1} and having 2–3 trunks each. The management system in OG was: once the olives were harvested, mineral fertilization (100 kg ha^{-1} Urea (46% N) in alternate years) was applied in winter. After this, a disc harrow (25 cm) was used, and then a manual cultivator pass to diminish soil clod size in summer. Finally, herbicides were added to control weeds in autumn (the last two practices are applied solely under trees).

One observation plot per topographical position was established for each land use (NF and OG), each with an area of 400 m^2 (20m × 20 m). In both cases (NF and OG), five sampling points per plot (SM, BS and TS) were taken. At each sampling point a soil profile was opened (Fig.1). The main topographic variables (altitude, slope and aspect) and the soil profile descriptions were recorded. The soil samples were taken from four soil sections of 25 cm (S1:0–25; S2:25–50; S3:50–75; S4:75–100) in order to establish a better comparison between the different topographical positions.

2.2. Sampling and analysis

In order to determine bulk density (BD), a sample of 3 cm diameter and 10 cm length (70.65 cm^3 core volume) was taken from each soil section (Blake and Hartge, 1986). In the laboratory, soil samples were air-dried and passed through a 2 mm sieve to remove gravels and roots. The distribution of the soil particle size was analysed by sieving and using the Robinson method (USDA, 2004). Soil pH was determined in a 1:2.5 soil to water ratio. SOC was determined by wet oxidation with dichromate according to the Walkley–Black method (Nelson and Sommers, 1982). N was determined with the Kjeldahl method (Bremner, 1996) and the C:N ratio calculated by dividing the SOC concentration by the N concentration.

Likewise, SOC stock (SOCS), expressed for a specific depth in Mg ha^{-1}, was computed as the product of SOC concentration, BD, depth and gravels, as follows (IPCC, 2003):

$$\mathrm{SOCstock} = \mathrm{SOCconcentration} \times \mathrm{BD} \times d \times (1 - \delta 2\mathrm{mm}\%) \times 10^{-1}$$

where SOC is the organic carbon content (g kg^{-1}), BD (Mg m^{-3}), *d* is the thickness of the control section (always 25 cm in our case), and δ2 mm is the fractional percentage (%) of gravel larger than 2 mm size in the soil. The N stock (NS) (Mg ha^{-1}) was also computed similarly.

The total SOCS (T-SOCS) (Mg ha^{-1}) was calculated for each soil according to (IPCC, 2003) as follow:

$$\mathrm{T-SOCS} = \Sigma_{\mathrm{horizon-edaphic\ controls\ 1,\ldots,n}} \mathrm{SOCS}_{\mathrm{horizon-edaphic\ controls}}$$

The total NS (T-NS) (Mg ha^{-1}) was also computed similarly.

The SR of a soil property is the ratio of its value at the soil surface to that at a lower depth as defined by Franzluebbers (2002). In this