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Spatial pattern of soil compaction: Trees' footprint on soil physical properties

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ABSTRACT

Soil compaction, a determinant of forest regeneration and ecosystem functioning (e.g., biomass production), can show an aggregated spatial pattern which can be shaped by the effect of tree canopy. This work studies the influence of tree canopy type (*Quercus ilex* subsp. *ballota*, and *Pinus pinaster*) on the spatial distribution of variables related to soil compaction in a Mediterranean forest in southern Spain. The spatial structure of this plant-soil interaction was analyzed using the spatial analysis by distance indices methodology (SADIE). Our results showed that variables related to soil compaction, such as bulk density, penetration resistance, water content and organic matter, showed an aggregated spatial pattern which was associated to the species' tree canopy and presence of open sites. Thus, high organic matter content and low bulk density were found under the *Quercus* canopy, whereas the contrary was observed under the *Pinus* canopy. Open sites showed similar soil properties to those than under the *Pinus* canopy. Soil compaction pattern and tree canopy had a clear effect on herbaceous production. In two consecutive years (2007 and 2008), herbaceous production was higher under the *Quercus* canopy than under the *Pinus* canopy. Mean values of herbaceous production in open sites were similar to those under the *Quercus* canopy, and no spatial association was found between open sites and herbaceous production. Structural equation modeling (SEM) was used to describe the causal relationships between tree canopy types, soil compaction related variables and herbaceous production. Results showed that tree canopy affects soil compaction variables and its effects on herbaceous production are mainly produced by a positive effect of organic matter (at 2–7 cm depth) and a negative effect of penetration resistance (at 9–14 cm depth). Therefore, forest management should consider that the replacement of one species for another or changes in tree density are likely to have important consequences in soil compaction and ecosystem functioning.

1. Introduction

In the Iberian Peninsula, most of the original *Quercus* forest has been transformed into savannah-like ecosystems called "*dehesas*" which are habitats of community interest (Annex 1 of the EU habitat directive, Council Directive 92/43/EEC, p. 18). *Dehesas* have been developed by selective clearcut to increase herbaceous production by diminishing tree density. *Dehesas* are characterized by their high productivity and diversity of herbaceous species (Marañón, 1986), which make them suitable for raising cattle. The holm oak (*Quercus ilex*) is the most common species in this ecosystem, but other tree species, such as *Quercus suber*, *Quercus faginea* and *Quercus pyrenaica* can also be found (Quero and Villar, 2009). In the Iberian Peninsula, *dehesas* are one of the most extensive systems together with pine forests. From 1950s to 1970s many pine plantations were established in Spain to enhance economic activity in rural areas and increase timber production (Quero and Villar, 2009). However, these forests were later left unmanaged due to the fall in wood prices and the high costs of timber extraction. From an environmental point of view, pine forests, especially high-density ones, present several inconveniences (e.g. high fire risk, low regeneration of autochthonous species, depletion of resources, very low species richness and scarce or even null herbaceous production) (Quero and Villar, 2009; Gómez-Aparicio et al., 2009). Nowadays, many pine forests are being managed to reduce their density and allow their naturalization, especially in areas where they coexist with *Quercus* species (Quero and Villar, 2009). In this context, it would be relevant to determine the roles played by *Quercus* (natural) and *Pinus* (naturalized) trees as soil-engineers in the *dehesa* ecosystem and the implications of the corresponding soil property changes on herbaceous production.

The main problem in the conservation of the *dehesa* ecosystem is the failure of oak trees to regenerate (Diaz et al., 1997; Plieninger and Wilbrand, 2001; Plieninger, 2007). Plieninger (2007) addressed the positive relationship between tree age and the length of agro-silvo-pastoral use and how holm oak stands are able to recover if grazing and cultivation are set aside. Soil degradation under livestock has been reported as one of the major effects of land use of *dehesas* (Shakesby et al., 2002) and soil compaction is one of the

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key results of this degradation process (Fernandez-Rebollo et al., 2004), reducing plant establishment (Bassett et al., 2005) and herbaceous biodiversity (Godefroid and Koedam, 2004). To limit these changes in ecosystem functioning (reduction of biodiversity and productivity) a change in management and land use may be needed. If trees are able to change physical soil properties such as soil compaction, is there a relationship between tree canopy and productivity, biodiversity or regeneration processes mediated by soil changes?

Soil compaction is generally measured as bulk density or penetration resistance. It is highly related to physical soil properties such as texture, porosity or structure, which are important due to their role in water and nutrient uptake by plants. Many studies on soil compaction emphasize its multifactor character, because it results from the interaction of different soil variables.

Soil compaction effects on plant growth are highly dependent on soil type (Whalley et al., 2008), compaction range and the species studied (Godefroid and Koedam, 2004; Alameda and Villar, 2009). In general, soil compaction limits root growth (Bejarano et al., 2010), which subsequently affects all the processes mediated by roots, such as anchorage, water and nutrient uptake (Alameda and Villar, 2012). An important side effect of this root distortion is the reduction of aboveground growth and crop production (Wolkowsky, 1990; Unger and Kaspar, 1994). The spatial pattern of soil compaction can be described in two directions: a multilayer structure in the vertical axis and a mosaic of gaps (low values) and patches (high values) in the horizontal plane. Spatial analysis by distance indices methodology (known as SADIE) can show the aggregation pattern of a variable on an x–y coordinate axis (Perry, 1998) (see material and methods section for more details). Such aggregated spatial pattern may be determined by the effect of tree canopy. SADIE has been successfully used in many ecological studies (Maestre and Cortina, 2002; Maestre et al., 2003; González-Rodríguez et al., 2011; Quero et al., 2011).

This work attempts to: (i) determine the existence of a spatial pattern of soil compaction in a Mediterranean forest; (ii) analyze the effect of tree canopy type on soil compaction variables; and (iii) elaborate a model to explain the effects of tree canopy type on soil compaction variables (bulk density, penetration resistance, organic matter and mass water content) and on herbaceous production in an integrated way using structural equation models (SEM) (Mitchell, 1992). This approach is important because few studies have so far explained the role of different tree species on soil compaction related variables and herbaceous production using an integrative perspective. From an applied perspective, knowledge of tree effect on these characteristics will be useful in formulating forest management strategies.

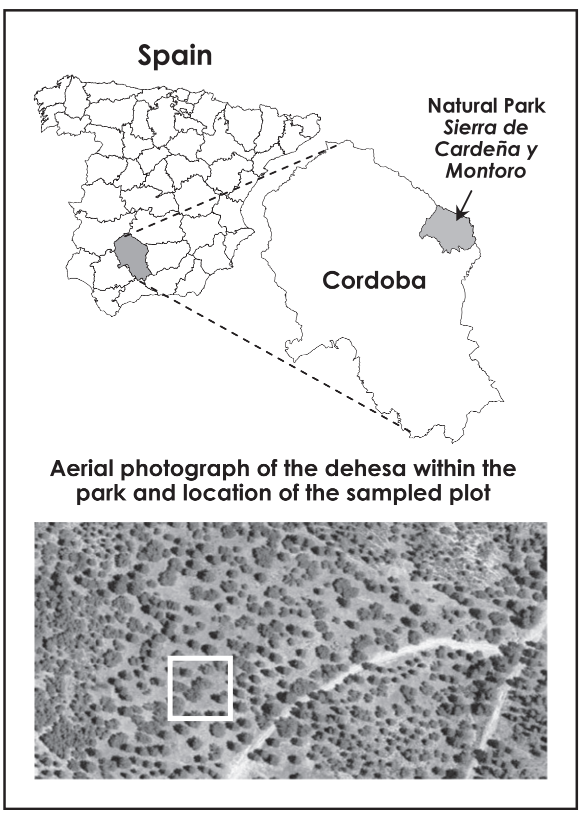

Fig. 1. Location of studied area in "Sierra de Cardeña y Montoro" Natural Park in southern Spain. The shaded area in the map of the province of Cordoba shows the location of the Park. Overview of the dehesa ecosystem where the study plot is found.

2. Material and methods

2.1. Site description

The study site is located in the Natural Park of Sierra de Cardeña y Montoro (Córdoba, Spain) (38°14′9″N, 4°21′55″W) within a fenced area to exclude ungulate herbivory (Fig. 1). Annual rainfall ranges from 570 to 970 mm, and mean annual temperature is 15.3 °C. Soils are regosols and mainly consist of sand with granite bedrock (Quero and Villar, 2009).

Tree vegetation is dominated by *Q. ilex* L. subsp. *ballota* (Desf.) and *Pinus pinaster* Aiton (Table 1). Shrub vegetation is scarce and composed of *Cistus ladanifer* L. and *Cistus albidus* L. individuals. Pines were planted in 1970 in holes made by hand in open spaces between oaks at an initial density of 2000 plants ha^{-1} (J.M. Quero, personal communication). *P. pinaster* trees in the plot are remnant individuals after successive events of mortality due to summer drought (J.M. Quero, personal communication). Selected individuals of *Q. ilex* and *P. pinaster* were measured for height, diameter at breast height (DBH) and canopy projection. Although *Pinus* trees were younger than the *Quercus* trees, they showed a higher DBH and height, due to their faster growth rate.

This area has not been managed or subjected to ungulate herbivory for at least 10 years. Ungulate density in nearby areas is low (0.15 heads ha^{-1} and 0.3 heads ha^{-1} for wild boar and deer density, respectively; J.M. Quero, personal communication). The study was carried out in a square plot (40 × 40 m) with a four-meter resolution.

2.2. Soil measurements

In the spring of 2008, soil sampling was carried out at two depths (2–7 cm and 9–14 cm) at every four meters in the plot for

Table 1
Mean ± SD of characteristics of a sample of the tree population. N, number of trees measured. DBH, diameter at breast height. Tree age for *Quercus ilex* was estimated following Panaiotis et al. (1997).

	N	Tree density (plants Ha^{-1})	DBH (cm)	Height (m)	Canopy diameter (m)	Estimated age (years)
Pinus pinaster	9	56	39.9 ± 4	14.2 ± 1.6	4.9 ± 0.6	40
Quercus ilex	12	75	31.8 ± 7.4	7 ± 1.2	6.89 ± 1.75	168.9 ± 39.9