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

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A B S T R A C T

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.

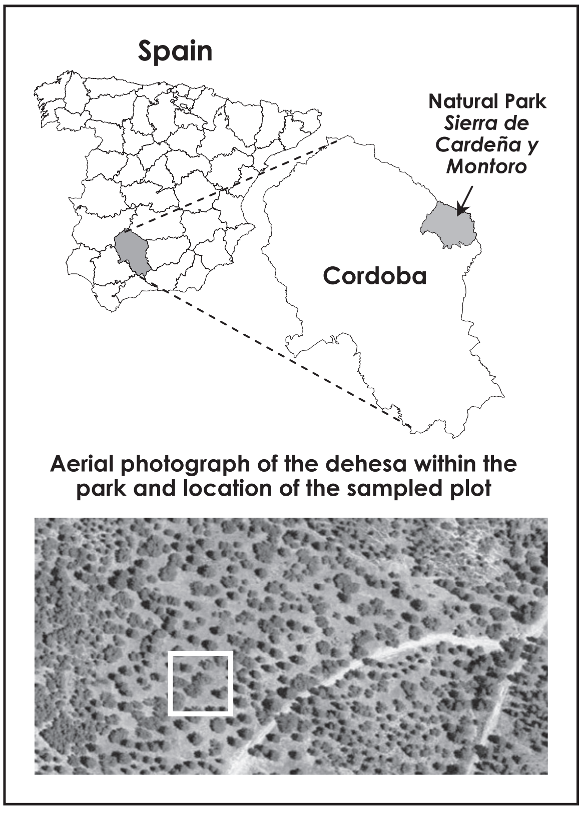

Fig. 1. Location of studied area in "Sierra de Cardeña y Montoro" Natural Park in southern Spain. The shaded area in the map of the province of Cordoba shows the location of the Park. Overview of the dehesa ecosystem where the study plot is found.

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

a total of 121 sampling points. At each sampling point, we first discarded the litter layer, which in some cases was between 5 and 10 cm deep below *Pinus* due to the very low decomposition rate of *Pinus* litter (Cornelissen, 1996). Soil samples were obtained with a metal cylinder of 5 cm in diameter and 5 cm height with a sharp edge to avoid soil compaction. Samples of the first depth range (2–7 cm) were taken discarding the first 2 cm of the soil surface to avoid any remaining litter in the sample. Similarly, samples of the second depth range (9–14 cm) were taken discarding the first 2 cm because the sample extraction method may modify the bulk density of the following depth. As bulk density has to be measured at soil field capacity, sampling was carried out a few days after a spring rainfall (28 April 2008). Each cylinder was sealed with plastic film to avoid water loss during sampling and transport from the field to the lab. Soil water content was calculated as: (wet soil mass-dry soil mass)/dry soil mass. Dry soil mass was obtained by drying the samples in an oven at 105 °C until constant weight was achieved. Bulk density was calculated as the ratio between dry soil mass and soil volume. Soil organic matter was measured by ignition in a muffle furnace at 550 °C for 5 h (knowing that there was a total absence of carbonates). Three measures of penetration resistance were taken per sample point by means of a penetrologger (Penetrologger, Eijkelkamp Agriserch Equipment, Giesbeek, The Netherlands) using a cylindrical probe of 3.3 cm^2 and 30° angle cone, taking force measurements each centimeter up to a total of 15 cm in depth. The three measurements were taken about 5–10 cm around the soil sample. The mean value of the three measurements of penetration resistance along the 2–7 and 9–14 cm profile was calculated.

2.3. Tree canopy, light conditions and herbaceous production

Tree canopy was estimated through the lineal intersection method between an imaginary vertical line at each sampling point, considering the absence (0) or presence (1) of tree canopy. The identity of each tree (*Quercus* or *Pinus*) was registered (see the projection of trees in Fig. 2). Light availability at each sampling point was estimated by two different approaches: GSF (Global Site Factor) and light intensity. In the spring of 2007, GSF was measured using hemispherical photographs (Rich, 1989) taken with a Coolpix camera fitted with a FC E8 fish eye lens (Nikon, Tokyo, Japan). Photographs were processed with the software Hemiview Canopy Analysis version 2.1 (Delta-T, Cambridge, UK). Light intensity was measured by a canopy transmission meter (with EMS7, PP-system, UK) on a clear day.

In July 2007 and 2008 total aboveground herbaceous biomass was harvested in a 25 × 25 cm square around each sampling point. It was then dried at 70 °C for at least two days to estimate herbaceous production as dry biomass.

2.4. Spatial analysis

The spatial pattern of soil compaction related variables was analyzed by SADIE: Spatial analysis by distance indices (Perry, 1998). SADIE analysis was carried out by "freeware" SadieShell v1.3 available at www.rothamsted.ac.uk/pie/sadie. This analysis technique is based on indices which quantify the spatial pattern of a variable in terms of distance to regularity. Thus, SADIE computes two principal indices: the index of aggregation (I_a) and the clustering index (v). I_a provides information on the overall spatial pattern of the analyzed variable. When $I_a < 1$, it is assumed that the variable follows a regular pattern, when $I_a = 1$ a random pattern, and when $I_a > 1$ an aggregated pattern. The clustering index, v, quantifies the partial contribution of each sampling unit to the overall spatial pattern of the data. Thus, a v index is generated for each sample point on a continuous scale which allows them to be plotted in a contour map through an interpolation technique. Map interpolations were made by krigging using SURFER v8 (Golden Software Inc., Boulder, Colorado, USA). The resulting maps show patches, where values of the studied variable are above the mean ($v > 1.5$, named v_i by convention), and gaps where values of the studied variable are below the mean ($v < -1.5$, named v_j by convention) (see for example Fig. 2).

A covariation spatial analysis was carried out to compare the spatial aggregation patterns of variables. We computed an index of overall association (X, chi-p) ranging from −1 (variables spatially disassociated) to +1 (variables spatially associated) through SADIE. A local association index (χ) was also calculated to measure the partial contribution of each datum to the overall association pattern. Significant values ($P < 0.05$) for the SADIE indices (I_a, v_i, v_j, χ) were derived from a randomization test of 5967 permutations (see Perry, 1998). It is important to note that SADIE transforms each variable into a standardized value (v_i, v_j, χ) containing information about the spatial distribution of data. For instance, tree canopy was recorded as a categorical variable (0 and 1) which was then transformed into a continuous variable (−6 to +6) through the clustering index.

2.5. Structural equation model

Structural equation modeling (SEM) (Mitchell, 1992) develops a model as the result of conceptual hypotheses attempting to explain how variables interact. Hypotheses are then translated into a path diagram with arrows indicating which of the potential variables explain changes in a response variable, and the goodness of fit of the model to the data is obtained (Mitchell, 1992; Austin, 2007). In our study we used SEM to generate a model to explain the causal relations of tree canopy type on soil compaction variables (bulk density, penetration resistance, organic matter and mass water content) and their effects on herbaceous production.

The cluster indices (v) of each variable obtained in SADIE were used in SEM instead of the original values, because our objective was to relate these variables across space. Two limitations can be detected in this approach: the presence of spatial autocorrelation and the standardization procedure in the cluster index calculation. Concerning spatial autocorrelation, Legendre (1993) stated that "spatial heterogeneity is functional in an ecosystem and not the result of some random, noise-generating process". Thus, ecological studies focused on spatial heterogeneity must measure spatial autocorrelation to use it in a conceptual or statistical model. To do this, Moran's coefficient was calculated for each variable within the sampling scale. Thus, spatial autocorrelation was detected for each variable within a 4–40 m range. Because spatial autocorrelation violates the statistical independence principle, the resulting model can only be used to explain the spatial causal relationships in our studied area. With regard to the SADIE standardization process in the cluster index calculation, the cluster index smooths the differences between values inside a patch or a gap, maximizing differences between them. As SADIE imposes a restrictive significant value to establish the existence of a patch or gap, this standardization can be used to reflect spatial aggregation of a variable through its cluster index. Thus, Maestre et al. (2003) used cluster indices in a PCA analysis to incorporate spatial patterns into a multivariate analysis and determine the relationship between the studied variables. In our study, we used the cluster indices to include the spatial pattern in the structural equation model. The structure of the hypothesized causal relationships between selected variables was set starting from existing knowledge on the relationships between soil physical variables and our own hypotheses and later slightly modified as a function of the highest statistical support, according to the significance of χ^2 and two indices of goodness of fit: NFI (Bentler and Bonett's Normed-Fit Index) and GFI (Goodness of Fit

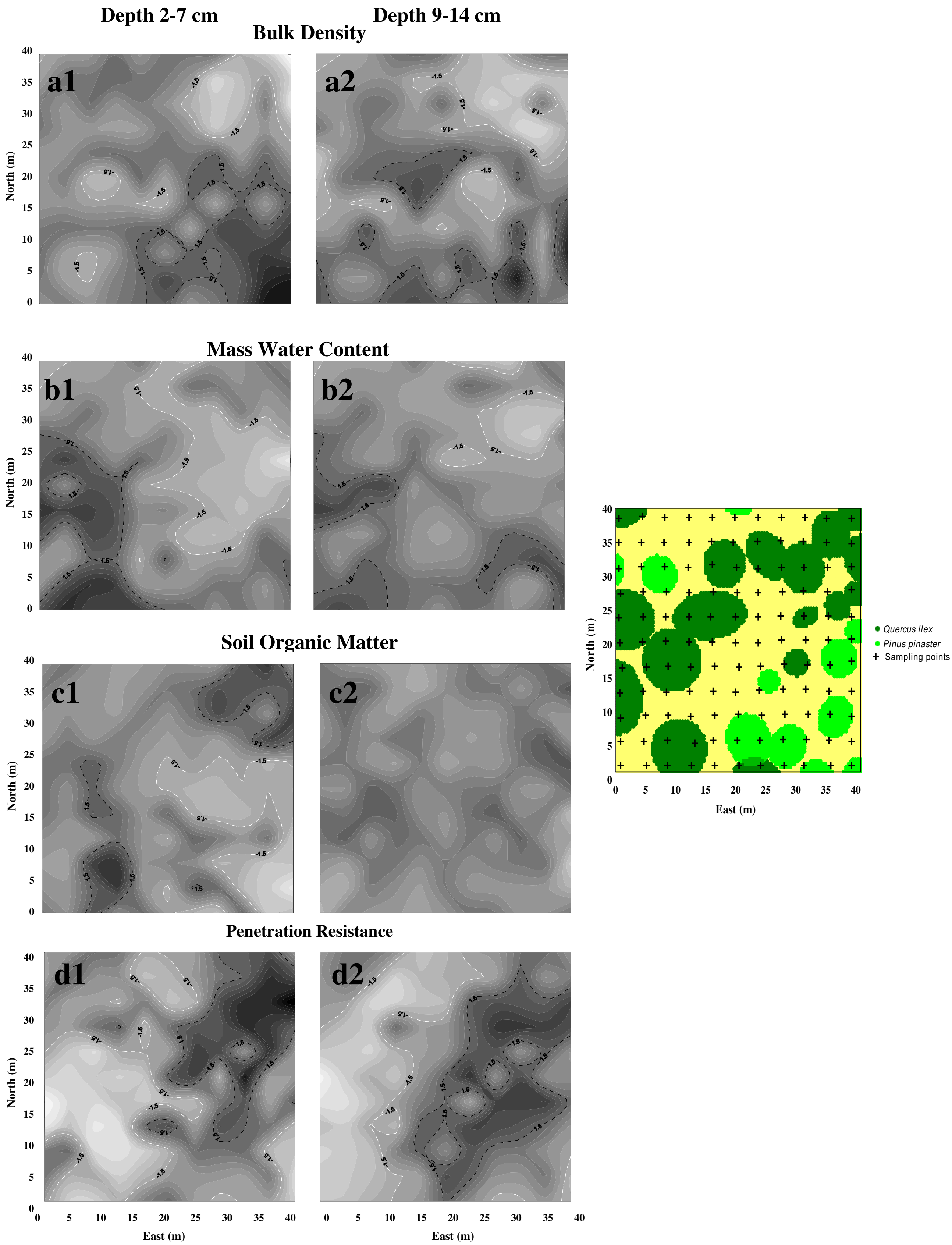

Fig. 2. Maps of SADIE index of clustering for soil physical properties. Panels in the left and right columns show the analysis for the 2–7 cm and 9–14 cm depth ranges, respectively. (a) bulk density; (b) mass water content; (c) soil organic matter content; (d) penetration resistance. The maps show patches and gaps. Patches are areas where values of the studied variable are above the mean ($v > 1.5$, named v_i by convention) and are represented by different shades from dark grey to black. Gaps are areas where values of the studied variable are below the mean ($v < -1.5$, named v_j by convention) and are represented by different shades from light grey to white. Key scale has no units. Next to the soil variables a plot shows the spatial distribution of canopy trees (*Quercus* and *Pinus*).

Index) (see Bollen, 1989). χ^2 must be non-significant ($P > 0.05$) indicating that the covariance pattern predicted by the model is not distinguishable from the observed (Hayduk, 1987). On the other hand, NFI and GFI must be greater than 0.9, indicating an acceptable fit of the model to the data (Bollen and Long, 1993). A first screening was made to choose which variables would fit the model. A conceptual path-diagram was drawn considering highly-related variables. Seven variables were included in the model: *Q. ilex* and *P. pinaster* canopy, bulk density, soil organic matter content, penetration resistance, mass water content and herbaceous production. One model was performed at each depth to determine whether the nature and intensity of effects change with depth.

The presented model was structured into three groups of variables: (1) tree canopy type (*Q. ilex* and *P. pinaster*) (2) soil compaction variables- bulk density, soil organic matter content, penetration resistance and mass water content; and (3) herbaceous production in 2007 (models for both years were similar). SEM analyses were carried out with AMOS v.18 software (IBM SPSS, Somers, NY).

3. Results

3.1. Spatial pattern of soil compaction

Bulk density, mass water content and penetration resistance showed an aggregated pattern at both the 2–7 cm and 9–14 cm depths (Table 2, Fig. 2). Organic matter content also showed an aggregated pattern at the 2–7 cm depth, but close to a random pattern at the 9–14 cm depth (Fig. 2c2).

In general, the variables measured in the first depth range (bulk density, mass water content and penetration resistance) were positively associated to the corresponding variables measured in the second depth range (Table 3), except for organic matter content.

Some variables showed a significant dissociation. For example, bulk density was dissociated with organic matter in both depth ranges (Table 3), indicating that patches (high values) of bulk density correspond to gaps (low values) of organic matter. Penetration resistance was also dissociated with mass water content at both sampling depth ranges (Table 3).

3.2. Tree canopy effects

SADIE covariation analysis showed that soil compaction variables were related to tree canopy type and open sites. However, the effect was mainly found in the first depth range (2–7 cm) (Table 4). In general, high bulk density values and low organic matter content were found under *P. pinaster* and open sites, while low bulk density values and high organic matter content were found under *Q. ilex* (at the two depth ranges). However, mass water content and penetration resistance did not show any association with tree canopy type or open sites. In general, open sites showed similar soil properties to those under the *Pinus* canopy.

No differences in light availability were observed between the *Pinus* and the *Quercus* canopy (considering both methods), and open sites had higher light availability (Fig. 3).

3.3. Soil compaction and tree cover effects on herbaceous production

Herbaceous production (in 2007 and 2008) was positively associated to organic matter content (2–7 cm) and *Q. ilex* canopy, but negatively associated to bulk density (2–7 cm and 9–14 cm), penetration resistance (9–14 cm) and *P. pinaster* canopy (Table 5). Mass water content was not associated to herbaceous production. Open sites were not associated to herbaceous production, but mean values were similar to those under *Quercus* canopy. A similar pattern of herbaceous production was found in both years (Fig. 4) with lower herbaceous production under *Pinus* canopy.

3.4. Models linking tree canopy type, soil compaction related variables and herbaceous production

Results of the model for the first depth range (2–7 cm) are summarized in Fig. 5a. Goodness of fit to this model was higher than 0.9 for both indices (NFI = 0.986, GFI = 0.993), and χ^2 was non-significant ($P = 0.54$ at 95% level). Tree canopy presented an expected negative relationship between the presence of *Quercus* and *Pinus*, which is probably due to site selection during pine plantation. With regard to soil compaction variables, only the *Quercus* canopy had a significant negative effect on bulk density. Organic matter content also had a significant negative effect on bulk density. In turn, bulk density negatively affected penetration resistance, but did not significantly affect mass water content. Organic matter content did not show any significant effects on penetration resistance or mass water content. However, mass water content negatively affected penetration resistance. Organic matter content was the only soil compaction variable that had a positive effect on herbaceous production, while *Pinus* canopy negatively affected herbaceous production.

Results of the model for the second depth range (9–14 cm; Fig. 5b) differed slightly from those of the model for the first depth range. Goodness of fit of this model was higher than 0.9 for both indices (NFI = 0.958, GFI = 0.982), and χ^2 was non-significant ($P = 0.10$ at 95% level). *Quercus* canopy had a negative effect on bulk density and a positive effect on organic matter content. Organic matter content also had a negative effect on bulk density. In turn, bulk density had a negative effect on mass water content, but no significant effect on penetration resistance (contrary to what was found in the first model). Organic matter content showed a significant positive effect on mass water content, whereas mass water content had a significant negative effect on penetration resistance.

Table 2
Results of SADIE analysis and descriptive statistics (mean, standard deviation, maximum and minimum) of soil compaction related variables at the two sampling depths (2–7 cm and 9–14 cm). P_a values are derived from a randomization test (5967 permutations). I_a, aggregation index. Mean ± SD for each canopy type (*Quercus*, *Pinus* canopy and open sites) are also shown.

	All						*Pinus*	*Quercus*	Open
Variable	Depth	I_a	P_a	Mean	Max	Min	Mean	Mean	Mean
Bulk density (g cm^{-3})	2–7 cm	**1.57**	0.003	1.41 ± 0.11	1.65	1.08	1.43 ± 0.10	1.36 ± 0.13	1.44 ± 0.09
	9–14 cm	**1.77**	0.000	1.46 ± 0.10	1.72	1.18	1.47 ± 0.13	1.44 ± 0.10	1.47 ± 0.10
Mass water content (%)	2–7 cm	**1.52**	0.006	10.40 ± 4.35	52.46	5.44	11.89 ± 8.49	10.71 ± 1.99	9.18 ± 1.83
	9–14 cm	1.30	0.059	9.71 ± 4.13	51.31	5.47	11.56 ± 8.28	9.58 ± 1.60	8.80 ± 1.35
Organic matter (%)	2–7 cm	**1.61**	0.003	2.60 ± 0.96	6.16	0.34	2.31 ± 0.83	3.07 ± 1.09	2.25 ± 0.55
	9–14 cm	0.99	0.457	2.20 ± 0.75	7.68	0.82	2.34 ± 1.20	2.30 ± 0.61	2.01 ± 0.50
Penetration resistance (Mpa)	2–7 cm	**2.22**	0.000	1.49 ± 0.66	4.54	0.50	1.28 ± 0.38	1.47 ± 0.76	1.64 ± 0.64
	9–14 cm	**2.11**	0.000	2.51 ± 1.16	5.78	0.69	2.41 ± 1.01	2.37 ± 1.23	2.73 ± 1.14

Table 3
SADIE association analysis between spatial patterns of soil physical properties. Significant values, using P-level corrected by Bonferroni ($P < 0.001$), are shown in bold ($n = 121$).

		Bulk density		Mass water content		Organic matter		Penetration resistance	
	Sampling depth	2–7 cm	9–14 cm	2–7 cm	9–14 cm	2–7 cm	9–14 cm	2–7 cm	9–14 cm
Bulk density	2–7 cm		**0.340**	−0.072	0.177	−**0.595**	−0.231	−0.122	−0.042
	9–14 cm			0.175	**0.244**	−**0.293**	−**0.410**	−**0.278**	−0.188
Mass water content	2–7 cm				**0.638**	0.282	−0.003	−**0.503**	−**0.540**
	9–14 cm					−0.026	0.093	−**0.505**	−**0.456**
Organic matter	2–7 cm						0.188	0.018	0.007
	9–14 cm							−0.010	0.084
Penetration resistance	2–7 cm								**0.645**
	9–14 cm								

Table 4
SADIE association analysis between spatial patterns of soil physical properties and spatial patterns of tree canopy type (*Pinus pinaster*, *Quercus ilex*). Open sites were those without any tree canopy. *X* (chi-*p*) is the index of overall association at *P* probability level. Associations are significant when $P < 0.025$; dissociations are significant when $P > 0.975$. Significant results are shown in bold.

		Bulk density		Mass water content		Organic matter		Penetration resistance	
		2–7 cm	9–14 cm	2–7 cm	9–14 cm	2–7 cm	9–14 cm	2–7 cm	9–14 cm
Pinus pinaster	χ	**0.405**	0.186	−0.165	0.018	−**0.311**	−0.045	0.145	−0.022
	P	0.000	0.032	0.955	0.436	1.000	0.675	0.079	0.587
Quercus ilex subsp. *ballota*	χ	−**0.671**	−**0.346**	0.076	−0.157	**0.491**	**0.256**	−0.010	0.106
	P	1.000	1.000	0.217	0.942	0.000	0.003	0.539	0.124
Open sites	χ	**0.229**	**0.216**	−0.112	−0.122	−**0.243**	−**0.300**	0.094	0.158
	P	0.011	0.012	0.886	0.892	0.993	1.000	0.179	0.045

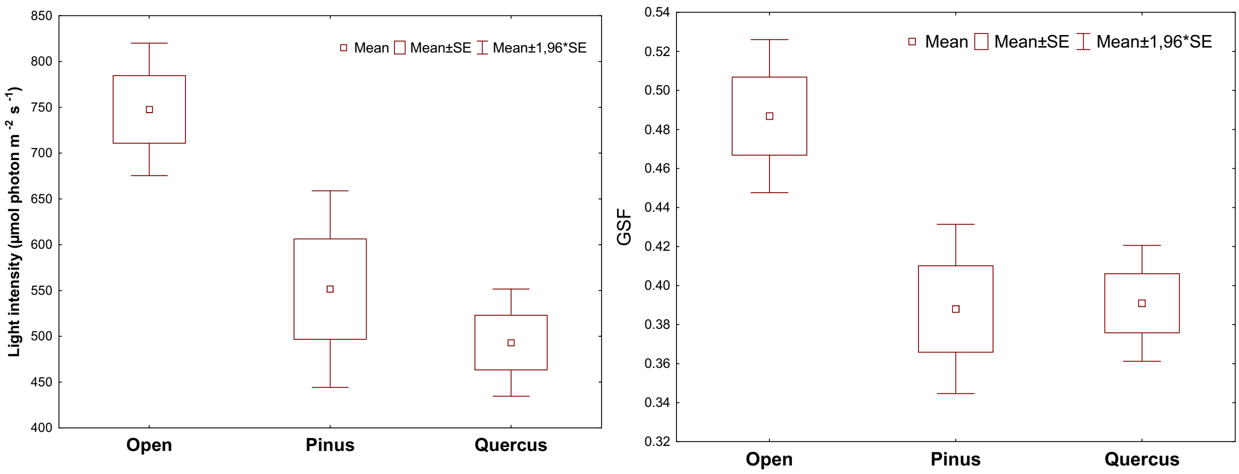

Fig. 3. Mean values ± SE of light availability depending of the canopy type. Light availability was measured using two methods: (1) light intensity measured by a canopy transmission meter on a clear day and (1) hemispherical photographs giving data on Global Site Factor (GSF).

Table 5
SADIE association analysis between spatial patterns of soil physical properties, cover type and annual herbaceous production for two consecutive years. *X* (chi-*p*) is the index of overall association at *P* probability level. Associations are significant when $P < 0.025$; dissociations are significant when $P > 0.975$. Significant results are shown in bold.

		Bulk density		Mass water content		Organic matter		Penetration resistance		*Pinus pinaster*	*Quercus ilex*	Open sites
Sampling depth		2–7 cm	9–14 cm	2–7 cm	9–14 cm	2–7 cm	9–14 cm	2–7 cm	9–14 cm			
Herbaceous Production 2007	χ	−**0.4268**	−**0.1875**	0.0770	−0.1170	**0.3773**	0.0900	−0.0576	−**0.2611**	−**0.4548**	**0.4346**	0.0601
	P	0.9999	0.9770	0.1975	0.8804	0.0001	0.2482	0.7396	0.9976	0.9999	0.0001	0.2683
Herbaceous Production 2008	χ	−**0.4808**	−**0.2731**	0.1501	−0.1149	**0.3718**	0.0947	−0.1020	−**0.3771**	−**0.4766**	**0.4648**	0.0040
	P	0.9999	0.9986	0.8488	0.8949	0.0001	0.1680	0.8576	0.9997	0.9999	0.0001	0.4844

With regard to herbaceous production, negative effects of penetration resistance and mass water content on herbaceous production were found. Herbaceous production was negatively affected by *Pinus* canopy, but positively affected by *Quercus* canopy (Fig. 5b).

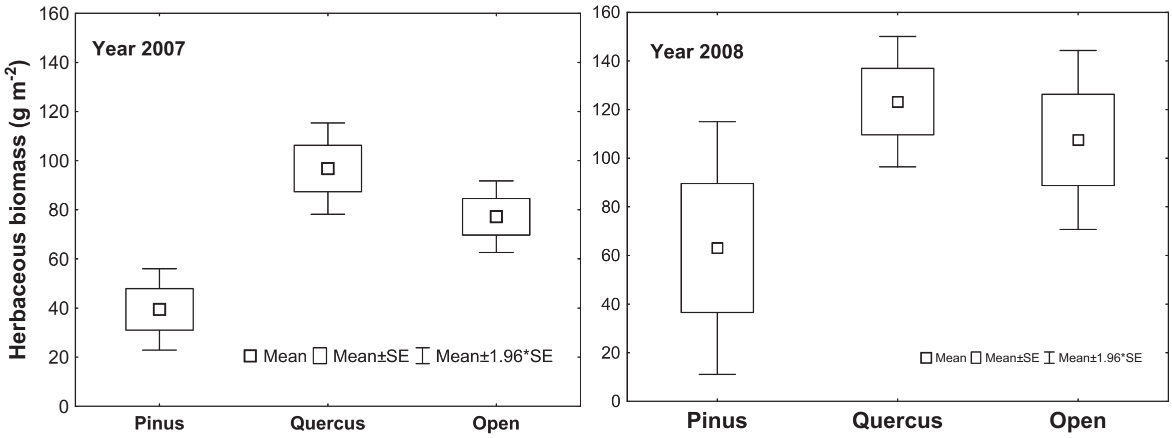

Fig. 4. Herbaceous production for each canopy type for the two years analyzed.

4. Discussion

4.1. Spatial pattern of soil compaction

Soil physical properties (bulk density and penetration resistance), organic matter and mass water content were aggregated throughout space and at the two sampling depths in a consistent pattern (Tables 2 and 3, Fig. 2). These variables were also spatially associated: high organic matter content was associated to low bulk density, and high penetration resistance was associated to low mass water content (Table 3). Previous studies have obtained similar results (Godefroid and Koedam, 2010; Quero et al., 2011). Quero et al. (2011) found that penetration resistance in an autochthonous forest of *Pinus sylvestris* was spatially dissociated with humidity. However, this relationship disappeared in shrubby areas and became positive (spatial association) in *P. sylvestris* plantations. Sojka et al. (2001) addressed the close relationship between penetration resistance, water content and bulk density under field conditions, and found that penetration resistance increased with increasing bulk density and decreasing water content. Concerning organic matter content as an important factor in ameliorating compaction, Franzluebbers and Stuedemann (2006) found that the benefits of organic matter-enriched surface soil are due to a buffer-function against compaction forces. Higher amounts of organic carbon can also result in lower bulk density, because organic matter has a lower particle density than mineral particles (Logsdon and Karlen, 2004). On the other hand, high bulk density values can be considered an impediment to the mineralization process due to reduced aeration and microbial activity (Breland and Hansen, 1996) which reduces soil carbon levels (Brevik et al., 2002).

In general, open sites showed similar soil properties to those under *Pinus* canopy. Several studies have found that *Pinus* litter is poor in nutrients, and its recalcitrant character (García-Plé et al., 1995) explains why soils under *Pinus* do not differ from those in open sites (Navarro-Cano et al., 2009).

4.2. Trees' footprint on soil physical properties

Although tree density at the site is relatively low (Table 1), we found effects of tree canopy on soil variables. We found that heterogeneity in soil physical properties was related to the presence-absence of certain tree species. For instance, there was higher organic content and lower bulk density under the *Q. ilex* canopy than in open sites (Table 4). These results are coherent with Gallardo (2003), who found that *Q. ilex* canopy increased soil organic matter content and open sites presented lower *N*, *P* and *K* concentrations. It is well known that trees modify soil properties, mainly by increasing nutrient concentration in the upper layers through litter deposition from the canopy (Augusto et al., 2002; Gallardo, 2003; Gómez-Aparicio et al., 2005). However, in our study *P. pinaster* did not seem to modify soil physical properties, as values were similar to those in open sites (Table 4; Fig. 5). Similar results were obtained by Shukla et al. (2006) with *Quercus gabelli* and *Pinus edulis*. Differences in the effect of trees may be related to leaf habit and chemical and physical traits of leaves. Leaf chemical traits such as lignin content and tannin concentration (Nicolai, 1988), toughness (Gallardo and Merino, 1993) or physical barriers are important quality traits affecting decomposition and mineralization rates (Cornelissen, 1996). These results highlight not only the importance of tree species as ecosystem engineers (Jones et al., 1997; Van Breemen and Finzi, 1998), but also that their effects greatly depend on the species considered. For instance, *Quercus* litter seems to modify soil properties due to its high litter decomposition rate, increasing organic matter content and nutrient availability (Gallardo, 2003), enhancing water retention, decreasing soil compaction and facilitating seedling establishment. However, *Pinus* litter may not affect soil compaction due to its low decomposition rate (Cornelissen, 1996) and recalcitrant character (García-Plé et al., 1995). Therefore, the pine litter layer can be expected to have very little effect on topsoil properties. Furthermore, soil compaction under *Pinus* canopy could enhance water runoff and fine soil particle loss, which could increase bulk density.

These differences in soil properties cannot be explained by past land use, particularly the differential activity of browsers under *Quercus* and in past open areas, as (a) the area has not been subjected to ungulate herbivory for over 10 years; (b) *Quercus* and *Pinus* are mixed in the study area, the effect of previous ungulate herbivory would be similar; and (c) in any case, herbivore density in the area was low (0.15 heads ha^{-1} and 0.3 heads ha^{-1} for wild boar and deer density, respectively; J.M. Quero, personal communication), so the effect of herbivory would also be low.

There was a difference in age between *Q. ilex* and *P. pinaster* trees, as *P. pinaster* trees were planted about 40 years ago and *Q. ilex* trees are older. One may think that the higher effect of *Q. ilex* may be due to its longer interaction with the soil. Although this may partially explain the different effects of these two species, tree size and amount of litter production are also very important factors in the effect of trees (Gómez-Aparicio and Canham, 2008). As *Pinus* individuals showed a higher DBH and height than *Quercus*, *Pinus* could be expected to have a higher impact, which is not the case. In fact, sites under *Pinus* do not differ from open sites. Pines also have a high amount of fine roots at the surface (Achat et al., 2008), but their effect on soil properties is nil. Therefore, pines

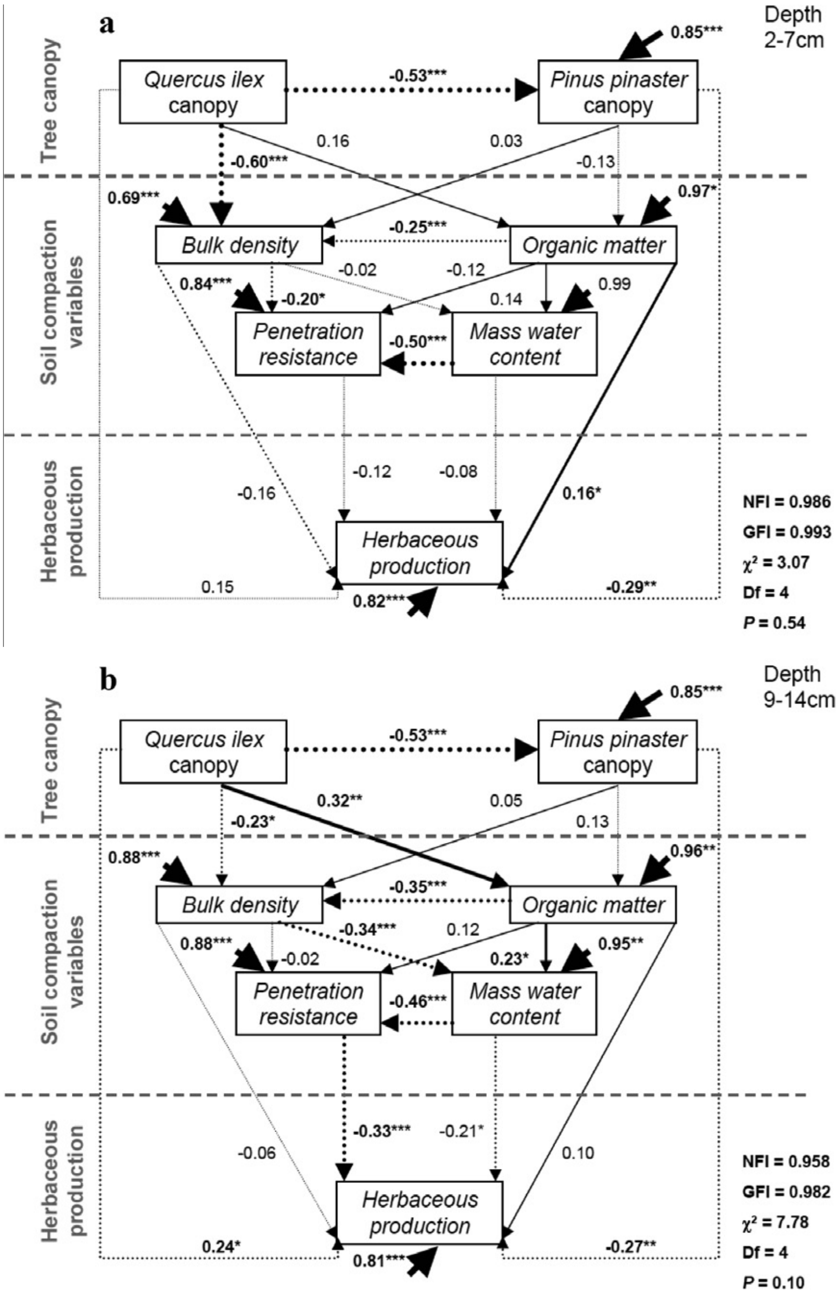

Fig. 5. Structural equation model relating tree cover, soil compaction related variables and herbaceous production. Model *a* corresponds to the 2–7 cm depth range, and Model *b* to the 9–14 cm depth range. Continuous arrows indicate positive effects and discontinuous arrows negative effects. Arrow widths are proportional to path coefficient. Significant paths are indicated in bold. See text for more details.

may have such a small effect on soil properties, not because of the difference in age or root distribution, but because the decomposition rate of litter for *Pinus* genus is so low (Cornelissen et al., 1999), resulting in low organic matter content and consequently high bulk density (Table 4).

4.3. Herbaceous production in a mosaic of tree canopy and soil compaction

Herbaceous production was linked to both soil physical properties and tree canopy type (Table 5, Figs. 4 and 5). Thus, spatial patterns of herbaceous production were different between sites covered by *Q. ilex* and those covered by *P. pinaster*. Some studies have shown that pines decrease herbaceous production because of its allelopathic exudates (Singh et al., 2006; Bulut and Demir, 2007). At the same time, *Quercus* effects have been reported as beneficial as they increase organic matter (Gallardo, 2003), resulting in greater cation exchange capacity, lower bulk density, and higher concentrations of nutrients (Frost and Edinger, 1991). Despite this positive effect, we would expect a trade-off with other abiotic factors such as light. However, as light availability was similar under *Pinus* and *Quercus* canopies (Fig. 3), this factor cannot explain the difference in herbaceous production between the *Pinus* and *Quercus* canopy. The allelopathic effect on herbaceous plants and the effect of soil compaction variables may explain the lower herbaceous production under *Pinus* canopy. Another cause of the lower herbaceous production under *Pinus* canopy could be the effect of a thick litter layer, which has been shown to decrease seedling emergence and performance in *Stipa tenacissima* (a perennial herb) (Navarro-Cano et al. 2009).

Godefroid and Koedam (2004) described herbaceous species response to compaction under field conditions as a wide spectrum varying from positive to null or negative. In general, soil compaction has a negative effect on herbaceous production (Kozlowski, 1999). The higher herbaceous production associated with high organic matter content may be caused by a feedback loop. On one hand, sites with higher organic matter have higher nitrogen concentration, which is one of the limiting factors for herbaceous production (Niinemets and Kull, 2005). On the other hand, sites with high primary production tend to have higher litter deposition rates. Therefore, the increase in organic matter would be the result of litter decomposition, providing a reserve of new nutrients for the next annual species generation.

These association patterns between tree canopy, soil variables and herbaceous production (Figs. 4 and 5) were consistent in time and were practically the same for the two studied years (2007 and 2008). Therefore, there seems to be a strong link between tree canopy type and soil through space and time.

4.4. The integrative models: a tool for forest management

Some *dehesas* in the Iberian Peninsula have experienced important changes in land use which have implied relevant changes in tree species composition (conversion to pine forest or mixed forest). As our study shows, these changes in tree species composition may affect several soil physical properties that are important for forest functioning (or the ecosystem services it provides) and its potential use. The development of models that integrate the causal relationships among the variables of interest (tree density and composition, soil properties and herbaceous production) (Fig. 5) may allow us to better assess the changes involved in these land use change processes. Our study may indicate a general pattern occurring in many of these mixed *Quercus-Pinus* forests, but this would have to be tested in other areas.

5. Conclusions

Soil variables associated to compaction (bulk density, penetration resistance, water and organic matter content) exhibit an aggregate spatial pattern. This pattern was closely related to tree canopy, but the effects depend on the species. *Q. ilex* had an important effect on soil properties including higher organic matter content and lower bulk density. *P. pinaster* did not modify soil physical properties, having similar properties as those found in open sites. These relationships between soil compaction and tree canopy have implications in herbaceous production. Our study supports the biotic origin of the compaction pattern in nature, underlining the important role of trees as ecosystem engineers and the high dependence of effects on the species considered. From the perspective of forest management, this compaction pattern linked to a tree species might be relevant when considering silvicultural treatments that attempt to replace some tree species for others. As the study was conducted in one site, the extrapolation of the conclusions of this study to other sites should be taken with caution. Additional studies in other sites of similar and different features are needed to assess the generality of these results.

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