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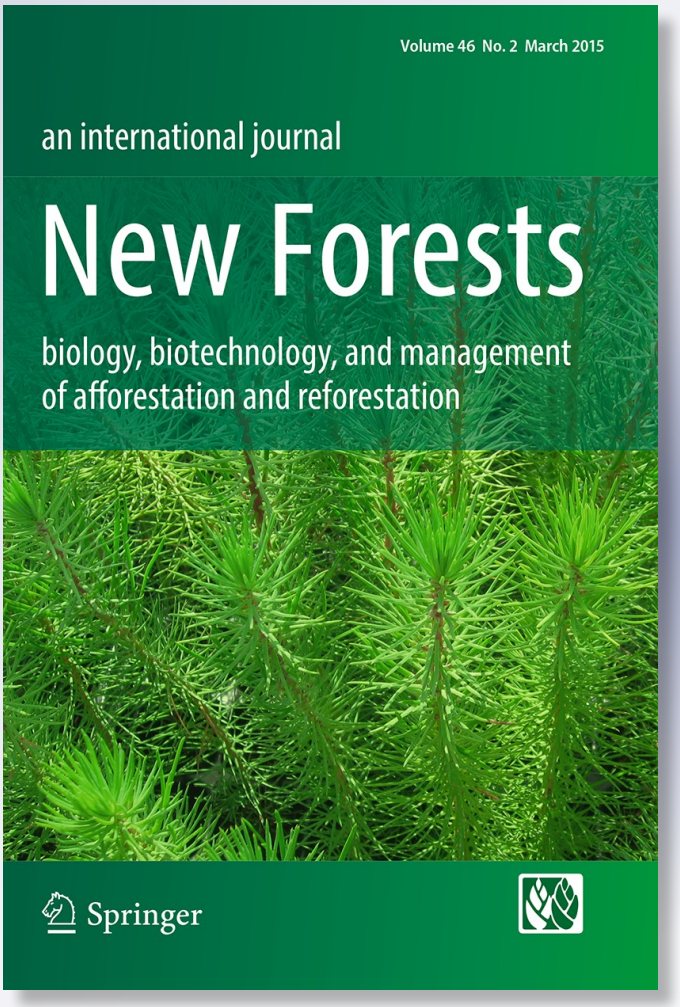

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The effect of soil compaction at different depths on cork oak seedling growth

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Abstract Soil compaction promoted either by inadequate management (pressure of livestock and machinery) or by soil natural conditions (podzolisation) can influence the growth of cork oak seedlings. We hypothesized that compaction could be related with the lack of natural regeneration and decline on cork oak stands. In this paper, we evaluated the response of cork oak seedlings growth in terms of area and biomass production for above and belowground parts at different compaction depths tested for a sandy-loam soil. This study was done in a greenhouse, with germinated seedlings. Three treatments were applied. One no-compaction treatment (control, C0) and two with a soil compacted layer at 60 cm (C1) and 30 cm depth (C2). The level of compacted layer was 1.37 MPa of mechanical resistance. Results show that tap root length is negatively affected by compaction at 60 and 30 cm depth. Below and aboveground biomass are affected by compaction at 30 cm depth. In addition, the leaf area results demonstrate that compaction is a sensitive factor for this parameter. In this 1-year stage, plants spend more energy in roots production. Due to soil formation and bad management of cork oak stands, soil compaction at depth could be a cause for the observed lack of natural regeneration, affecting the growth at earlier stages and probably for the decline of cork oak populations.

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Keywords Cork oak (*Quercus suber* L.) seedlings · Soil compaction · Above and belowground biomass · Fine roots distribution

Introduction

The actual area of the cork oak woodlands (*Montado*) in Portugal is approximately 715,922 ha, of which 601,906 ha are distributed in the southern region of Alentejo (AFN 2010), which accounts for 22 % of the total forest area in the country and 33 % of the total world area of cork oak distribution. Cork oak (*Quercus suber* L.) is a typical tree species present in Mediterranean agro-silvo-pastoral systems—*Montado*. The ecological and economic value of this species is already well documented (see Costa et al. 2010; David et al. 2007; Pinheiro et al. 2008; Pereira and Tomé 2004; Ribeiro et al. 2006, 2010).

In the last few decades, a decline in the cork oak density and population has been documented in the literature (David et al. 1992; Ribeiro and Surový 2008) as a response to the probable inadequate management applied in these areas during long periods of time, along with other factors. Human disturbances, including tree thinning and soil tillage to keep open areas for livestock (Gouveia and Freitas 2008), make natural regeneration difficult and also promote soil compaction (Kozlowski 1999). Ribeiro and Surový (2008) clearly observed indications of the soil depth limitations on the intensity of mortality in a national study, especially when combined with the slope factor. However, according to the FAO (2006), the common types of soils where these Mediterranean stands develop are Podzols, Luvisols, Leptosols, Cambisols and Regosols soils. In the case of Podzols soils, the main process in the formation is podzolization. This complex process, in which organic material and soluble minerals (commonly iron and aluminum) are leached from the A and E horizons to the B horizon (spodic horizon), can sometimes lead to a dense (compacted) layer in the profile (FAO 2006), known in Portugal as "*surraipa*". Fortunately, it is possible to break these formations with common low impact silviculture practices used both in establishing and maintaining the stands. Specifically, ripper subsoiling is advised for this purpose, where a ripper (with different depths) is coupled to a high power tractor. In accordance with Pagliai et al. (2004), this alternative tillage system promotes a more open and homogeneous soil structure, allowing better water movement. Because of these specific soil conditions, the cork oak growth and, specifically, the ability of their roots to reach deep layers to receive water and nutrients can be compromised.

Soil compaction is often responsible for the poor performance or failure of the establishment of trees (Sinnett et al. 2008). The compaction term is understood as the compression of unsaturated soil, especially affecting the larger soil pores (Kristoffersen and Riley 2005). Compaction typically alters the soil structure and hydrology by breaking down soil aggregates, decreasing soil porosity, aeration and infiltration capacity and by increasing soil strength, water runoff and soil erosion. All of these factors could lead to physiological dysfunctions in plants, mainly influencing the normal and healthy growth of roots and promoting a decreased supply of physiological growth requirements at meristematic sites; this will make mature trees more vulnerable to wind-throw. In addition, the quantity of oxygen in the rhizosphere on compacted soils can be limiting for regular metabolic processes (Queiroz-Voltan et al. 2000), stopping the detritus food chain, eliminating the diversity of living material and roots and favoring the emergence of "pests"

that attack organisms and roots that are unable to defend themselves (Coder 2007). This will affect the entire functionality of the trees.

As soils become increasingly compacted, the respiration of the roots shifts towards an anaerobic state. Compaction stops the respiration processes that are responsible for all tree functions. For instance, Kozlowski (1999) notes that the photosynthesis rate of plants growing in very compacted soil decreases because of both stomatal and non-stomatal inhibition. During growth, the roots use the soil water and nutrient uptake for structural support. Roots grow by following interconnected pores that occur between soil aggregates and through voids created by decomposing roots and animal burrows (Coder 2007). According to Hakansson et al. (1998), in compacted soils, the lower development of the root system results in a minor soil volume that could be explored by the roots, influencing water and nutrient absorption. However, Benghough and Mullins (1990) show that the decrease in root development in compacted soils occurs because of the minor cellular elongation rate, which is a consequence of the decrease in the meristematic cellular division rate.

As a strategy against compaction, a tree initially promotes tap root thickening and the production of more lateral roots with various diameters. Then, if the lateral roots are thin enough to pass through the compacted soil pores, these specific roots continue to grow, while the tap root growth is restricted. If the soil pore is too small for the lateral roots, lateral root growth stops and another site of the subsoil is explored (Russel 1997 in Coder 1999). In some cases, roots can also enlarge the smaller pores by squeezing soil material aside (Kristoffersen and Riley 2005). When the root-impeding layers are near the surface, they will slow the downward root growth (Bennie 1991; Ehlers et al. 1983 in Ganatsas and Spanos 2005).

Previous studies show that plant growth is, in general, negatively affected by soil compaction (Bassett et al. 2005; Kozlowski 1999). On the other hand, some other studies conducted under a low range of compaction show a positive effect of this factor on plants (Alameda and Villar 2009; Tubeileh et al. 2003). In the case of oak species, Laliberte et al. (2008) found that the long-term survival and growth of trees is largely dependent on first-year establishment. Severe soil compaction adversely influences the regeneration of forest stands by inhibiting seed germination and the growth of seedlings and by inducing seedling mortality (Kozlowski 1999). In greenhouses or in the field, roots show difficulties penetrating in compacted soil layers, promoting a higher root development on the less compacted upper or lower soil layers as a compensation procedure (Beulter and Centurion 2004).

With this study, we wanted to evaluate the behavior of cork oak seedling growth, specifically, the behavior of their root system under conditions of compacted layers at different depths. Studies on plant growth during this seedling stage are crucial because of the plants' higher vulnerability to environmental constraints (Silvertown and Charlesworth 2001). The way resources affect the plant at this stage are fundamental for understanding tree recruitment patterns (Villar-Salvador et al. 2004; Tsakaldimi et al. 2005; Gomez-Aparicio et al. 2006), which largely influence forest composition and dynamics. The starting hypothesis for this work was that soil compaction will be a negative factor for cork oak seedling growth in *Montado* because it limits tap root growth at a certain depth, causing a decrease in biomass production at the aboveground part. The other hypothesis was that fine roots will not have the same strength to penetrate a soil compacted layer and, consequently, will not explore the layers under compaction in the same way, in terms of distribution, as on the non-compacted layers.

Materials and methods

Design of the experiment

The research was carried out in a greenhouse at the Mitra campus of the University of Évora, a site close to Évora in southern Portugal. The acorns of cork oak were collected from a single, isolated tree. The acorns were washed with water, and the ones that showed signs of infection (verified by a water fluctuation process and visual analysis) were discharged. One hundred and fifty acorns were artificially germinated in humid cotton beds in recipients closed with film. The film was bored to allow respiration. The acorns were irrigated once a day and stayed in a room under 23 °C. One week after germination, acorns that had a minimum root length of 1 cm were selected. We selected 45 samples and attempted to choose as many similar weights and root lengths as possible to avoid different levels of seed mass factors, which could influence the results. According to the statistical analysis, no significant differences were obtained between treatments for weight (P value = 0.9255), length (P value = 0.872) and radicle length (P value = 0.717).

One large and homogenized soil sample was collected from a depth of 10–30 cm of the E horizon of a Podzol soil profile, avoiding the spodic horizon (FAO 2006). The soil was collected in the Canha region, in South Portugal. This soil was passed through a 5-mm mesh sieve to separate it from bigger aggregates, dust and residues. Three samples from this original soil were collected for chemical and textural analysis. According to the International Granulometric Scale (Attenberg), the soil used in the experiment was a sandy-loam soil. The percentage of pebbles was 2 %, and for the fine earth fraction, the percentages of sand, silt and clay were 89.5, 4.9 and 5.6 %, respectively. The pH[H_2O] was 6.66. The results for organic carbon and organic matter were 0.34 and 0.58 %, respectively.

To simulate the compaction of soil inside PVC tubes (inside diameter of 10.5 cm and height of 97 cm), we used a metallic weight of 2 kg made specifically for this specific diameter tube. The experiment was designed for three treatments, C0 (Control) "No compaction", C1 "Compaction at 60 cm" and C2 "Compaction at 30 cm". For compaction at a depth of 60 cm (C1) loose soil was introduced until it reached a tube height of 35 cm. A metallic weight was dropped 10 times, and more loose soil was introduced in the tube until it reached the top. For C2, the tubes were filled with loose soil until it reached a tube height of 65 cm, a metallic weight was dropped 10 times and the tubes were filled again with loose soil until the top. Through an evaluation of the bulk density, we obtained results of 1.66 g cm^{-3} for the non-compacted soil (treatment C0), with a penetrometer resistance of approximately 0.01 MPa, and 1.73 g cm^{-3} of bulk density for compacted layers of the soil (presented in C1 and C2 treatments), with a penetrometer resistance of 1.37 MPa. The low differences in the bulk densities between non-compacted and compacted soil can be related to the process of compaction that only had an effect on a thin layer of a few centimeters and that was difficult to sample by the method referred (missing the compacted layer).

Fifteen acorns were selected for each treatment, planted individually in each tube and completely under the soil surface, and irrigated with 200 ml of water. The samples were arranged randomly in a greenhouse (25 °C day/10 °C night temperature and 50 % air humidity). The plants were subjected to 100 % of the natural radiation inside the greenhouse (from an average of 275.5 Wm^{-2} for spring/summer seasons to an average of 138.5 Wm^{-2} for autumn and winter) (www.cge.uevora.pt). The seedling growth was observed for 1 year (the time period that tap roots of the control treatment (no compaction) needed

to reach the end of the tubes); during this period, irrigation was provided manually with 100 ml of water and was repeated every 48 h. No fertilization or pesticide products were used in this experiment.

Data collection

To evaluate the soil strength applied for this experiment, we used a penetrometer (Penetrologger, Eijkelkamp, Agrisearch Equipment) equipped with a conical steel probe (cone top angle 60° with a base area of 1 cm^2). During the destruction process, 4 compacted soil samples (2 for each treatment, between a 60–70 cm depth for C1 and between a 30–40 cm depth for C2) and 2 non-compacted soil samples (between a 30–50 cm depth) were collected randomly for bulk density analysis. For this purpose, we used cylindrical metallic samplers (with a diameter of 5 cm and a width of 3 cm). By evaluating the bulk density, we obtained results of 1.66 g cm^{-3} for the non-compacted soil (treatment C0), with a penetrometer resistance of approximately 0.01 MPa, and 1.73 g cm^{-3} of bulk density for compacted layers of the soil (presented in C1 and C2 treatments), with a penetrometer resistance of 1.37 MPa. The low differences in the bulk densities between non-compacted and compacted soil can be related to the process of compaction that only had an effect on a thin layer of a few centimeters and that was difficult to sample by the method referred (missing the compacted layer).

After the bulk densities analysis, the fine roots that were collected by the cylindrical samplers were integrated with the others from the original sample for biomass, length, area and volume analysis. For each sample, the leaves, branches and stem were separated for an analysis of the aboveground part and the tap root and fine roots for an analysis of the belowground part. The height, length and area of the branches and stem were measured. For the fresh leaves, the number of leaves and leaf area were also evaluated using scanned images (with 254 dpi resolution) and *ImageJ* software. The stem and branches were dried at 103 °C and the leaves at 75 °C for 48 h, and the dry mass was found, thus obtaining the biomass of the components. The belowground part was divided into segments of 10 cm depths, in which the fine roots (diameter less than 2 mm) and coarse roots (diameter higher than 2 mm) were separated, which, for all cases, corresponded to the tap root structure. The fine root area, for each 10 cm of depth, was measured through scanned images with a 400 dpi resolution and *ImageJ*. For both the tap root and fine roots, dry weights were taken after 48 h of drying in an oven at 103 °C, thus obtaining the respective biomass. The variables collected were stem height (SH) and biomass (SB); branch length (BL) and biomass (BrB); leaf area (LA), biomass (LB) and leaves number (LN); aboveground biomass (AB) and area (AA); tap root length (TRL), biomass (TRB) and number (TRN); fine roots biomass (FRB) and length (FRL); and belowground biomass (BB) and area (BA).

Data analysis

The soil was analyzed in the laboratory for texture using the SediGraph 5100 equipment; the organic carbon and organic matter were evaluated using the Leico Carbon Analyser (SC-144DR); humidity, pH[H_2O](1:2) and bulk density. The soil bulk density was calculated as the ratio of soil dry mass to soil volume (g cm^{-3}).

From the data obtained, the following parameters were determined and analyzed: specific leaf area (SLA), as the ratio between the leaf area, and leaf biomass (cm^2 g^{-1}); specific root length (SRL), as the ratio between the fine root length and fine root biomass

(cm g^{-1}); total biomass (TB), as the sum of all tree components' biomass (g); shoot:root ratio (S:R), as the ratio between the aboveground and belowground biomass; fine roots belowground biomass ratio (FRB:BB); fine root length leaf area ratio (FRL:LA) (cm cm^{-2}); and fine roots length total biomass ratio (FRL:TB) (cm g^{-1}).

For the statistical analysis, we used the *SPSS software* (version 20.0, SPSS Inc., Chicago, IL). Because of non-normality (Shapiro–Wilk) and non-homocedasticity (Levene's test), we applied the Kruskal–Wallis test for K independent samples to verify the statistically significant differences among treatments.

Results

Effect of compaction on growth and allocation

Soil compaction had a clear negative influence on every evaluated variable (Table 1). The stem and branch biomass decreased by 35 and 55 %, respectively. The leaf biomass was also negatively affected. The total aboveground biomass produced in compacted soils was 33 % lower than the one produced in non-compacted soil. The leaf area and aboveground area were also affected by this factor and decreased by almost 30 %. The difference between the C1 and C2 treatments for these parameters was small and statistically insignificant. However, the degree of this influence should be studied more thoroughly.

The results of belowground biomass production (Table 2) were similar to those in aboveground biomass production. The belowground biomass lost more than 40 % of the potential growth compared to non-compacted soil. The tap root area was reduced by 42 %. Compaction at 60 cm (C1) had a negative impact on the length per unit of mass (specific root length, SRL) response.

Compaction significantly reduced the total biomass (TB) by 36 and 39 % for C1 and C2, respectively (Table 3). In spite of not being statistically significant between treatments, the results obtained for the shoot:root ratio (S:R) (Table 3) demonstrated that, during earlier stages, cork oak seedlings allocate more energy to belowground plant tissue compared with the aboveground organ production (Fig. 1). However, for the fine roots belowground biomass ratio (FRB:BB), it was possible to verify the significant effect of compaction at 60 cm (C1) compared with the no compaction treatment.

Depth distribution of the fine roots

The distribution of fine roots through the profile depth was clearly influenced by compaction (Fig. 2). Figure 2 shows a decrease in fine roots below the compacted layers of the respective treatment, as we hypothesized. For non-compacted treatment, we verified that the seedling strategy was to produce and spread fine roots for all of the soil interval layers. Higher values of the fine root biomass were observed in the deepest layers (80–90 and 90–93 cm), representing 19 and 16 % of the total biomass evaluated for this treatment, respectively. For compaction at a depth of 60 cm (C1), higher values, each representing 17.2 % of the total biomass evaluated, were observed on 50–60 and 60–70 cm layers. In compaction at 30 cm, higher values were observed in the 10–20 cm layer, where 22.4 % of the belowground biomass occurred.

Table 1 Aboveground part evaluation of the cork oak seedlings developed under different depths of soil compaction

	Variable	Compaction treatments			*H*
		0 cm (C0)	60 cm (C1)	30 cm (C2)	
Biomass	SB (g)	9.51 ± 0.98a	6.04 ± 1.04ab	6.18 ± 0.60b	7.123*
	BrB (g)	6.26 ± 0.54a	4.68 ± 0.89ab	3.42 ± 0.56b	9.357**
	LB (g)	9.32 ± 0.74a	6.53 ± 0.98ab	6.96 ± 0.49b	9.654**
	AB (g)	25.10 ± 0.74a	17.25 ± 2.63ab	16.56 ± 1.06b	13.397**
Area	LA (cm^2)	717.50 ± 65.36a	493.70 ± 71.08ab	509.62 ± 38.93b	7.800*
	AA (cm^2)	802.15 ± 68.98a	553.47 ± 79.68ab	575.02 ± 42.46b	8.342*
	SLA ($cm^2\ g^{-1}$)	76.33 ± 2.00	77.10 ± 2.32	72.75 ± 1.30	2.055
	SH (cm)	75.14 ± 3.54	66.30 ± 6.86	68.77 ± 3.14	2.333
	BL (cm)	273.33 ± 33.27	168.65 ± 27.07	180.78 ± 24.22	0.067
	LN	379.07 ± 44.21	260.90 ± 36.91	300.54 ± 36.86	3.175

Mean ± SE. $n = 45$

H-values for Kruskal–Wallis test

SB stem biomass (g), *BrB* branches biomass, *LB* leaves biomass, *AB* aboveground biomass, *LA* leaves area, *SLA* specific leaf area, *AA* aboveground area, *SH* steam height, *BL* branches length, *LN* number of leaves

* Significant at 0.05 level, ** at 0.01 level. Means with different letters are significantly different ($P < 0.05$)

Table 2 Belowground part evaluation of the cork oaks seedlings developed under different depths of soil compaction

	Variable	Compaction treatments			*H*
		0 cm (C0)	60 cm (C1)	30 cm (C2)	
Biomass	TRB (g)	39.86 ± 3.33a	20.93 ± 3.57b	21.67 ± 1.30b	17.011**
	FRB (g)	2.94 ± 0.52	3.03 ± 0.55	2.93 ± 0.44	0.044
	BB (g)	42.80 ± 3.33a	23.96 ± 3.74b	24.60 ± 1.56b	18.295**
Area	TRA (cm^2)	65.68 ± 7.58a	48.49 ± 7.15ab	38.24 ± 2.48b	6.532*
	FRA (cm^2)	191.46 ± 22.95	156.70 ± 27.27	175.00 ± 23.48	1.541
	BA (cm^2)	257.14 ± 28.31	205.19 ± 31.65	213.24 ± 24.56	1.954
Length	TRL (cm)	93.07 ± 0.75a	63.80 ± 1.39b	43.46 ± 1.15c	32.985**
	FRL (cm)	202.89 ± 24.35	163.58 ± 26.27	185.42 ± 24.90	1.541
	SRL ($cm\ g^{-1}$)	76.30 ± 4.80a	57.04 ± 4.33b	66.80 ± 3.68ab	6.828**
	TRN	2.86 ± 0.61	2.10 ± 0.31	1.85 ± 0.15	0.643

Mean ± SE. $n = 45$

H-values for Kruskal–Wallis test

TRB tap root biomass, *FRB* fine root biomass, *BB* belowground biomass, *TRA* tap root area, *FRA* fine root area, *BA* belowground area, *TRL* tap root length, *FRL* fine root length, *SRL* specific root length, *TRN* number of tap roots

* Significant at 0.05 level, ** at 0.01 level. Means with different letters are significantly different ($P < 0.05$)

Table 3 Evaluation of plant functionality variables

Variable	Compaction treatments			*H*
	0 cm (C0)	60 cm (C1)	30 cm (C2)	
TB (g)	67.90 ± 4.87a	43.18 ± 5.87b	41.16 ± 2.45b	17.605**
S:R	0.65 ± 0.07	0.74 ± 0.09	0.68 ± 0.04	4.488
FRB:BB	0.08 ± 0.15a	0.15 ± 0.34b	0.12 ± 0.01ab	6.866*
FRL:LA (cm cm^{-2})	0.29 ± 0.03	0.35 ± 0.42	0.36 ± 0.34	2.322
FRL:TB (cm g^{-1})	3.08 ± 0.35	4.49 ± 0.77	4.38 ± 0.44	5.235

Mean ± SE. $n = 45$

H-values for Kruskal–Wallis test

TB total biomass, *S:R* shoot:root biomass ratio (no units), *FRL:LA* fine root length leaf area ratio, *FRL:TB* fine root length total biomass ratio

* Significant at 0.05 level, ** at 0.01 level. Means with different letters are significantly different ($P < 0.05$)

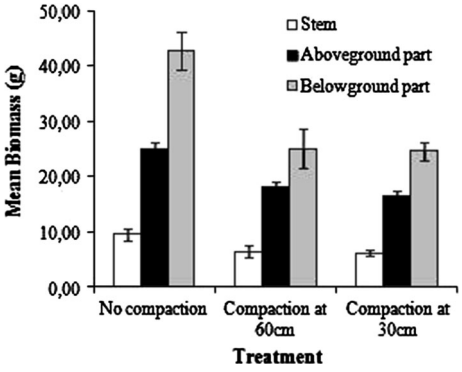

Fig. 1 Effects of treatments on stem, aboveground and belowground biomass (g) of cork oak seedlings. Mean biomass ± SE

Discussion

Cork oak seedling growth was evaluated in this work. Souch et al. (2004) state that this can be the most sensitive stage because the young roots, of slight thickness, have to colonize the soil and have to overcome the soil resistance. In this work, to diminish the possible noise in the experimental results, promoted by variations in seedlings, we decided to germinate acorns from one single tree and with similar length and weight. As far as we know, there has not been any study on these compaction levels for cork oak stands in Portugal; however, there are some studies available in Spain. Soil compaction levels from 0.9 to 3.4 MPa were found by Pérez-Ramos et al. (2010) in a *Quercus* forest in SW Spain and from 0.14 to 4.2 MPa by Quero et al. (2008) in a Mediterranean forest in Granada (SW Spain). Alameda and Villar (2009) evaluated *Quercus* species under a range of 0.14–1.16 MPa. As we hypothesized, the tap root length of cork oak seedlings are constrained by soil compaction (Table 2). As observed here for *Quercus suber*, a reduction in the rooting depth in compacted soils has also been reported by Pérez-Ramos et al. (2010). The same growth behavior was also verified for other *Quercus* species [(*Q. Ilex* (Cubera et al. 2009) and *Q. pyrenaica* seedlings (Bejarano et al. 2010)]. Whalley et al. (1995) showed that root growth in many plants is restricted above a soil penetration resistance of 2 MPa. Bejarano et al. (2010) found that the length of the main root in seedlings grown in a soil compacted to approximately 3 MPa was approximately 50 %

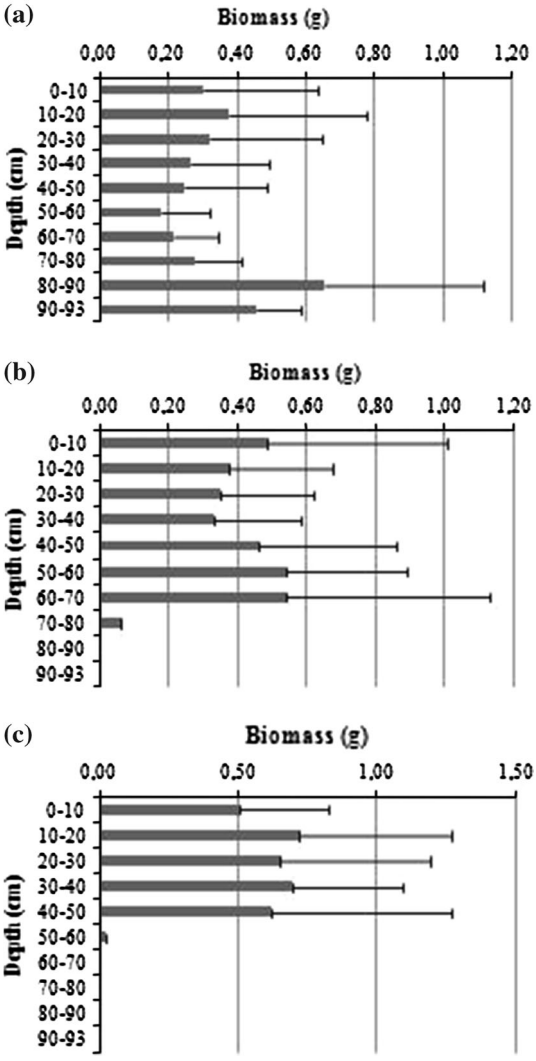

Fig. 2 Distribution of the fine roots biomass (g) in depth (cm). Treatments: **a** C0; **b** C1; and **c** C2. Mean biomass ± SE

smaller than in less compacted soil. In our case, 1.37 MPa was the soil mechanical resistance limit that stopped vertical growth. According to Cubera et al. (2012), cork oak will develop deeper root systems in the absence of root impedance, probably as would other oak species.

For total seedling root system evaluation, in terms of biomass, we confirmed that compaction has a negative effect (Table 2). This is in line with the results of Chirino et al. (2008), specifically for a depth of 30 cm. Our findings are also similar to those of Cubera et al. (2009), who reported reduced root development and, consequently, reduced aboveground plant growth. With our study, it was also possible to confirm that the strategy of the fine root distribution in the depth due to compaction is to decrease the volume of soil exploited per unit biomass (lower SRL), promoting the construction of thicker roots or roots with more tissue density. Alameda and Villar (2012) also observed this strategy in their work. As in the results for tap root evaluation, the decrease of fine roots below 10 cm of the compacted layers was noticeable (Fig. 2). Arvidsson (1999) showed that decreased small pore space can be positive

by facilitating root-soil contact, thus promoting better water and nutrient absorption. In our study, we verified that seedlings established the same amount of fine roots, but only where the production costs can be balanced with the benefits, increasing access to water and nutrients. Our second hypothesis was also confirmed; fine roots have more difficulty penetrating small pore spaces when presented in compacted soils with a mechanical resistance of 1.37 MPa.

For aboveground plant tissue, our results (Table 1) show that the stem biomass, branches biomass, leaf area, leaf biomass, aboveground area and biomass of the seedlings subjected to soil compaction at a depth of 30 cm significantly decreased when compared with non-compacted soils. Pérez-Ramos et al. (2010) also observed an exponential reduction of the total leaf area for *Quercus canariensis.* Because of that effect, photosynthesis can be compromised. Despite that, for some variables calculated for plant allocation, the results show that no significant differences were found (Table 3). It was possible to evaluate that soil compaction at different depths had a negative effect on the total tree biomass, and the fine roots belowground biomass ratio was affected by this soil factor. As the fine root length per unit of the leaf area presented no significant differences, we can probably assume that, at least for this experiment, the water and nutrient requirements for the development of seedling structures must have been met despite the reduced root length observed, similar to findings reported by Bejarano et al. (2010). The results of this study are not statistically significant between treatments, probably because of the short experiment time, and demonstrate that for biomass allocation, cork oak seedlings invest more energy in roots formation, than with aboveground plant tissues, in this stage. This is consistent with findings by Chirino et al. (2008) when they referred that one of the main strategies of this species is to develop a deep tap root during the early stages of plant development. Yet, we can also assume that compaction effect, at seedling stage, will compromise the adult tree stabilization, in sandy loam soils, limiting the tap root fixation at major depths. Lloret et al. (1999) in Alameda and Villar (2009) referred that this effect will also determine that, in situations of water deficit (such as Mediterranean case), plants with a lower root development may suffer drought more severely and, therefore, and it could seriously limit seedling survival.

Pérez-Ramos et al. (2010) in their work, defended that acorn mass is responsible for most of the growth and morphological variables during the first year and hence, soil factors did not play an important role in seedling growth during this stage. However, our results demonstrate that for the same acorn mass (no significant mean differences were observed between treatments) cork oak seedling growth is affected by soil compaction. This reinforces our thesis of relating soil compaction with the lack of natural regeneration in Mediterranean typical soil types (especially Podzols soils) as a reduced length of tap root in earlier stages of growth. Therefore, it will compromise the mature cork oaks survival by limiting not only their ability to reach water in dry periods, but also to remain erect and anchored to the substrate. By so, the practice of silviculture should be based on a sufficient knowledge about the response of each species to different environmental conditions (Cardillo and Bernal 2006). As far as cork oak stands are concerned, the possibility to break the compacted layers will allow the trees to spread their root systems through the entire profile depth, as it is reported by Surový et al. (2011). Soil tillage practices, specifically the ripper subsoiling is advised for this purpose hence improves the soil pore system, preventing soil structural degradation and soil losses, as results of Pagliai et al. (2004) demonstrate. This effect will, consequently, promote a major root distribution on profile depth, as a consequence of compaction soil break and an increase of available water for plants (Pagliai et al. 2004). More studies should be taken to reinforce the importance of the tillage management on cork oak seedlings and mature trees. Moreover, studies about tree root systems morphology, behavior and dependent factors are of huge emergence because it is necessary to understand and justify the better choice and less damageable management of *Montado*, promoting the maintenance of multifunctionality.

Conclusions

We found that compaction at different depths with a mechanical resistance of 1.37 MPa, limits the tap root growth of cork oak seedlings. Seedling root biomass, aboveground biomass and total seedling biomass are negatively affected by this factor. The effects of soil compaction also influence the distribution of fine roots at the profile depth, where the absence of these structures was verified below the compaction layer.

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