Soil gypsum and increased penetration resistance restrict early growth of *Quercus ilex* plantations[1]

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Abstract

The objective of this study is to analyse the influence of soil characteristics on the early growth of *Quercus ilex* in order to support planning of future plantations. We studied thirty-one 200 m^2-plots on 10 year-old plantations in fields set-aside from agriculture in a semiarid area in northeast Spain. Tree height and diameter, slope, geomorphic position, and various soil characteristics were measured. On north-facing slopes height and diameter of trees were significantly greater (150-200%) in soils without gypsum than in soils with gypsum. In soils without gypsum, increased penetration resistance in the upper 50 cm of soil (from 4.4 MPa to more than 7.0 MPa) decreased dominant height of trees to 40% of the maximum. While plantations of *Quercus ilex* can achieve satisfactory growth in semiarid conditions, detailed field studies of soil and site conditions are required for successful plantation establishment. The actual need for soil preparation treatments should be carefully evaluated considering species response and soil penetration resistance.

Keywords: afforestation, calcareous soils, land evaluation, soil rootable depth.

Introduction

Common Agricultural Policy (CAP) in the European Union encourages the set-aside of agricultural land and its use for forestry purposes, some of the aims being soil protection and an increase in biodiversity. Important afforestation schemes with similar objectives have been developed also in countries around the Mediterranean (Le Houérou, 2000). Nevertheless, some of these efforts have been hampered by the use of very aggressive site preparation techniques or by the choice of inappropriate forest species (Romero-Díaz et al., 2010).

Holm oak (*Quercus ilex* L.) is one of the most common forest species in the Mediterranean Basin and the Middle East, extending over 3 million hectares in Spain and 2 million hectares in northern Africa (Charco, 1999; Terradas, 1999). But most afforestation schemes in the region have been performed with *Pinus halepensis* Mill., which has limited success in some soils (Olarieta et al., 2000). Furthermore, these plantations do not always encourage the recovery of natural resprouter species, such as *Q. ilex*, that would create ecosystems more resilient and diverse than those dominated by obligate seeder species, such as *P. halepensis* (Valdecantos et al., 2009).

Plantations with holm oak have been performed in different areas around the Mediterranean (Le Houérou, 2000) but usually face various limiting factors, such as climatic dryness or poor seedling quality (Bocio et al., 2004; Valdecantos et al., 2009). But most studies with this species concentrate on the effect of different site preparation techniques or on the quality of seedlings (Bocio et al., 2004; Palacios et al., 2009), and little information is available on the soil and site characteristics required for successful growth. These plantations are intended as ecosystem restoration tools and do not have a productive or commercial purpose. Therefore, it is important to achieve a successful establishment because little or no management will be invested in them after the first few years.

Growth of forest species under semiarid conditions is mostly controlled by moisture availability, with a minor influence of nutrients (Olarieta et al., 2000; Sardans et al., 2004). Studies conducted in relatively humid regions of France confirmed the improved growth of *Q. ilex* in deeper soils with lower contents of calcium carbonate (Bichard, 1982; Curt & Marsteau, 1997).

Soils with gypsum provide a very specific environment for plants and promote a highly specialist flora (Pueyo and Alados, 2007), and their productivity is constrained due to physical (Poch and Verplancke, 1997; Poch et al., 1998) and chemical limitations (Kordlaghari and Rowell, 2006). Previous studies show reduced height and diameter of forest species growing in these soils (Verheye and Boyadgiev, 1997; Olarieta et al., 2000; 2009).

Greenhouse experiments using substrates with very low values of penetration resistance (less than 1.0 MPa) show a positive response of *Q.ilex* stem height to increased values of this soil variable (Alameda & Villar, 2009). But on the other hand, Cubera et al. (2009), found a decrease in holm oak root density with values of bulk density increasing from 1.38 $Mg.m^{-3}$ to 1.62 $Mg.m^{-3}$. And previous work in our study area showed a decrease in the diameter of *Juglans regia* L. with increasing penetration resistance from 5.6 MPa to 7.4 MPa (Olarieta et al., 2009).

The objective of this study was to analyse the soil characteristics affecting early growth of *Quercus ilex* in plantations on former agricultural fields in semiarid conditions. We tested these hypotheses in particular: i) height and diameter of *Q. ilex* increase as soil rootable depth increases while ii) they decrease with increasing gypsum content in soils and iii) with increasing values of penetration resistance.

Materials and methods

Experimental layout

We studied 10 year-old *Quercus ilex* plantations in fields set-aside from agriculture in a rainfed semiarid area in Lleida, northeast Spain (41º50' N, 0º37' E; 300-400 m altitude). Mean annual temperature is 14.2 ºC, with a minimum of 4.7-4.9 ºC in December and January and a maximum of 23.2-24.3 ºC in the period July-August. Mean annual rainfall is 390 mm with a dry period from June to September and an estimated accumulated soil moisture deficit of 500-700 mm. Fields had been planted with 1 year-old seedlings protected with a plastic tube after subsoiling down to 50 cm in the plantation line along the contour with an agricultural tractor. The distance between plantation lines was 3-5 m. No records are kept of the actual planting densities and therefore no assessment of the survival rates was possible.

We studied thirty-one sampling plots with a size of 200 m^2 each and a relatively homogenous height of holm oak trees: twenty on soils without gypsum and eleven on soils with gypsum. As a results of previous agricultural use, all plots showed a scarce cover of spontaneous vegetation.

The eleven plots with soils developed on Tertiary gypsum rock and colluvium were located on north-facing slope. Plots on soils without gypsum covered a wide range of soil rootable depths in order to test our first hypothesis, and were distributed on two geomorphic positions: ten on flat summits (river terrace); and ten on north-facing slopes for comparison with plots with gypsiferous soils. All these soils on north-facing slopes had developed on colluvium from the river terrace.

Measurements

In each plot, the total number of tree was counted and the height and diameter at the base of each tree were measured during the winter. For each plot, we calculated the mean height and diameter as the mean values of the heights and diameters at the base of all trees alive in the plot. Dominant height and diameter for each plot were calculated as the mean value of the height and diameter at the base of the two tallest trees within the plot and of the two with the largest diameter, respectively.

The slope of the plot was measured with a clinometer. A soil pit was excavated at the centre of each sampling plot to a depth of 130 cm, or underlying rock or root-limiting horizon, and described following the SINEDARES criteria (CBDSA, 1983). An Eijkelkamp hand penetrometer (model IB) with a 0.25 cm^2 surface-area cone and a compression spring of 220 N was used to obtain penetration resistance values for each genetic horizon on the vertical surface of the soil pit. In these conditions, the maximum possible reading was 8.8 MPa, so that in those cases when the penetrometer had not entered completely into the horizon, a value of 9.0 MPa was assigned. Readings in which the penetrometer encountered rock fragments were not taken into account, so that 10 readings were finally obtained for each soil horizon. The presence or absence of gypsum in the soil was confirmed in the field with the $BaCl_2$ method (Porta et al., 1986). Briefly, a drop of $BaCl_2$ (10%) reacts with an aqueous soil extract producing a milky cloud if sulphate is present in the soil.

Samples were taken from each soil genetic horizon and taken to the laboratory where they were air-dried and sieved to 2 mm. Those from horizons down to 50 cm depth were analysed for pH (1:2.5 in water), electrical conductivity (EC) (in a 1:5 extract in water), organic carbon (Walkley-Black method), total nitrogen (Kjeldahl method), Olsen phosphorus, exchangeable potassium (determination by atomic absorption spectrophotometry after extraction with 1N NH_4OAc at pH7), calcium carbonate-equivalent (volumetric calcimeter method), gypsum (Artieda et al., 2006), and texture (only for soils without gypsum) (pipette method). Fresh samples from 20 horizons with contrasting penetration resistance values were used to determine moisture content after oven-drying at 40ºC in order to avoid losses of water from gypsum minerals. Soils were classified according to Soil Taxonomy (SSS, 1999).

Data analysis

Statistical analyses were performed with the SAS package (SAS Institute, 1999). Soil variables obtained in the laboratory and rock fragment content and penetration resistance values were introduced in the analyses as means of the values for the horizons in the upper 50 cm weighted according to their depth.

We used generalized linear models (GLM) to study differences in soil characteristics and in tree height and diameter between soils with gypsum and soils without gypsum. When comparing these tree variables for both types of soils in order to test our second hypothesis, and in order to avoid influences from other factors, we only used plots on north-facing slope (n=10 for soils without gypsum; n=11 for soils with gypsum). Separation of means was performed with Duncan's test.

For each group of plots we first performed an exploratory correlation analysis among all quantitative variables: tree height and diameter, soil variables, and slope. We then used multiple linear regression analysis performed with the backward elimination procedure to detect from all the soil and site variables those that significantly explain the tree variables in each group of plots (n=20 for plots with soils without gypsum; n=11 for plots with soils with gypsum). In the case of plots with soils without gypsum geomorphic position was also introduced as a dummy independent variable (north-facing slopes=1; plateau=0) in the regression analysis. Models were accepted only if they complied with the basic statistical assumptions of homocedasticity, independence and normality of residuals, and if individual P values for independent variables were smaller than 0.05. In all cases, relationships were only considered significant if $P<0.05$.

Results

Soils

Soils without gypsum were mostly classified as either Typic Calcixerept or Petrocalcic Calcixerept. They were non-saline (EC values of 0.15-0.18 $dS \cdot m^{-1}$), well drained, had a rootable depth between 30 cm and over 130 cm, a silty-loam to loam texture, a high and variable content in $CaCO_3$ (240-600 $g \cdot kg^{-1}$), basic pH (8.0-8.7), a low content in organic C (0.5-2.7 $g \cdot kg^{-1}$, but mostly 0.8-1.7 $g \cdot kg^{-1}$), and variable contents of labile P (8-31 $mg \cdot kg^{-1}$) and exchangeable K (75-135 $mg \cdot kg^{-1}$). Petrocalcic Calcixerepts belonged to the skeletal particle-size families and had smaller rootable depths (28-60 cm; limited by a petrocalcic horizon) than soils with few rock fragments, which frequently had a rootable depth of more than 100 cm.

Soils with gypsum were mostly classified as Gypsic Haploxerept. They were also non-saline (EC values of 1.8-2.1 dS·m^{-1}) and well drained, and had a similar range of rootable depth, texture and organic C content to that of soils without gypsum. On the other hand, they had significantly lower contents of $CaCO_3$ (110-440 g·kg^{-1}) (P=0.01) and labile P (0-24 mg·kg^{-1}) (P=0.006), significantly lower pH (7.5-8.2) (P<0.001), and a significantly higher content of exchangeable K (119-645 mg·kg^{-1}) (P=0.008). Their gypsum content in the upper 50 cm ranged from 20 g·kg^{-1} to 720 g·kg^{-1}.

Penetration resistance in the upper 50 cm of soils without gypsum varied between 4.4 MPa and over 8.8 MPa, and between 2.2 MPa and 4.9 MPa in soils with gypsum. Soil moisture content varied between 140 g·kg^{-1} and 180 g·kg^{-1}, and was not significantly correlated with penetration resistance in any of the two groups of soils (P>0.15). The pattern of penetration resistance in relation to soil depth showed non-gypsum soils to have shallower relative maxima of over 8.8 MPa at depths of about 20 cm, 60 cm, and 110 cm, while soils with gypsum had relative maxima of 7-8 MPa at depths of 60 cm, 90 cm, and 130 cm (Figure 1). Soils without gypsum showed higher values of penetration resistance than those with gypsum throughout the soil depth down to 100 cm.

Tree height and diameter

The height and diameter of *Q. ilex* trees was quite variable, ranging from 0.2 cm to 3.4 cm for mean diameter, and from 10 cm to 104 cm for mean height. Mean and dominant diameter and height of trees were significantly correlated between themselves (r>0.80; P<0.003).

Effect of soil characteristics on tree height and diameter

On north-facing slopes, height and diameter of trees in soils with gypsum were significantly smaller than those in soils without gypsum. Mean and dominant diameter of the former were 50-55% of those of the latter, while mean and dominant height of trees in soils with gypsum were 67% of those in soils without gypsum (Table 1).

Resistance to penetration in the upper 50 cm of soil was the only variable that significantly explained differences in height and diameter of *Q. ilex* in soils without gypsum in the multiple linear regresion analysis (R^2 between 0.45 and 0.54 for the four tree variables analysed; $P<0.0004$; n=20) (see Figure 2 for the case of dominant height). Penetration resistance values over 7.0 MPa in the surface soil imposed an upper limit of 100 cm at the age of 10 years to the dominant height of *Quercus ilex* seedlings, which represents 40% of the maximum height measured in this study and was obtained in soils with a penetration resistance of 4.4 MPa. Geomorphic position and soil rootable depth had no significant effect.

In soils with gypsum, pH was the only variable with a significant effect so that dominant height decreased with increasing soil pH values ($R^2=0.45$; $P=0.02$; n=11). Gypsum content in the upper 50 cm of soil had no significant effect.

Discussion

The negative effect of soil gypsum on the development of *Q. ilex* (Table 1) agrees with the results obtained for other forest species, such as *Pinus halepensis* and *Quercus faginea* Lam. in nearby areas (Olarieta et al., 2000; Olarieta et al., 2009). Various factors may be involved in constraining holm oak growth in soils with gypsum. Gypsum recrystallizes around roots creating and impervious layer that reduces water and nutrient extraction and root elongation (Mashali, 1996). In horizons with gypsum content up to 400 $g\cdot kg^{-1}$, available water is low and decreases as gypsum content increases, and in horizons with contents over 600 $g\cdot kg^{-1}$, water can hardly be used by plants as gypsum crystal packing prevents root development (Poch et al., 1998). Furthermore, the availability of nutrients such as phosphorus, manganese, and zinc decreases in soils with gypsum (Oyonarte et al., 1996; Kordlaghari & Rowell, 2006).

Contrary to our initial hypothesis, soil rootable depth did not have a significant effect on any of the tree variables measured. This may be the result of the young age of the plantation and of the root system of trees not being fully developed, because mature stands of holm oak significantly increase their growth in response to increased soil water availability (Curt & Marsteau, 1997; Rodà et al., 1999). We would not expect trees to extract a significant amount of water from below the rootable depth for various reasons: annual rainfall values are low enough (200-500 mm) to suggest that little water will enter below depths of 50-100 cm (Seyfried et al., 2005; Schiller et al., 2007); the underlying mudstone and gypsum rock are not so porous as to retain significant amounts of water available for plants; and finally, if the root system is not fully developed, it will not be able to access deep layers.

Penetration resistance generally increases as soil water content decreases, although the relation varies according to soil characteristics (Poch & Verplancke, 1997; Zou *et al*., 2001; To & Kay, 2005). But in some studies no relation has been found between soil strength and water content (Salako *et al*., 2007). This was also the case in our plots and may have been the result of the narrow range of soil water content at the time when penetration resistance was measured (140 $g\cdot kg^{-1}$ to 180 $g\cdot kg^{-1}$).

The negative effect of increased soil penetration resistance on the growth of *Q. ilex* is consistent with the proposals of Curt & Marsteau (1997) and Cubera et al. (2009), and with the results obtained for *Juglans regia* L. in the area (Olarieta et al., 2009). While linear ripping has improved early growth of holm oak in some experiments (Bocio et al., 2004), our results suggest that subsoiling may not be sufficiently effective in completely restoring soil conditions, as proposed also by Froehlich (1984) and Håkansson (2005). In general, amelioration practices are more successful on coarse soils than on fine-textured soils (Wronski & Murphy, 1994), and some authors have also suggested that subsoiling may not really break up compacted soil horizons but just compress them sideways (Mason et al., 1988). Experiments with agricultural crops in the UK discussed by Batey (2009) also show that deep loosening of silty soils produced significant fissuring but was associated with structural instability and did not result in increased yields. In other cases the improvement is short-lived (Hamza & Anderson, 2005; McBeath et al., 2010). It is generally considered, therefore, that subsoil compaction is a very persistent or irreversible process (Horn & Rostek, 2000; Håkansson, 2005; Hamza & Anderson, 2005).

On the other hand, penetration resistance values in the upper 50 cm of soils of forest and shrublands that have not been used for agriculture in the past in this area very rarely exceed 5-6 MPa (unpublished data). In these circumstances, therefore, it would be hardly advisable to perform site preparation treatments aimed at loosening the soil as the response obtained in terms of improved *Q.ilex* growth would be very limited (Figure 2).

In these soils without gypsum, penetration resistance is only correlated significantly with rock fragment content in the upper 50 cm of soil (r= -0.57, *P*=0.003, n=24), so that horizons with more than 35% rock fragments have penetration resistance values less than 7.0 MPa. Ravina and Magier (1984) also found that increasing coarse fragment content increased resistance to compaction.

The presence of these rock fragments may have had a positive effect in the response of holm oak because it is related to smaller values of soil bulk density (Torri et al., 1994) and higher topsoil moisture content (Katra et al., 2008). But we suggest that the mechanical impedance for root development may be the most important factor explaining the poorer development of *Q. ilex* in soils without gypsum with penetration resistance values increasing from 4 MPa up to 9 MPa (Figure 2). Although these values were obtained with relatively low soil moisture contents, they nevertheless reflect high values of soil strength. Root development of forest species such as *Pinus radiata* D. Don decreases with increased penetration resistance (Zou et al., 2001), and values higher than 3 MPa are considered limiting for root development, in general (Håkansson, 2005), and specifically for some agricultural crops in fine-textured soils (Glinski & Lipiec, 1990). Sinnet et al. (2008) recorded 90% of the roots of various forest species in soil horizons with penetration resistance values under 3 MPa in a restored sand and gravel quarry, but no roots in horizons with values over 6 MPa. In soils with high values of penetration resistance, the availability of water and nutrients for plants decreases (da Costa et al., 2009; McBeath et al., 2010; Ribeiro et al., 2010), and we therefore suggest that the smaller height and diameter of *Q. ilex* trees growing in these conditions is also the result of indirect water and nutrient deficiencies (Rodà et al., 1999; Sardans et al., 2004).

The range of penetration resistance values obtained in gypsum soils, between 2 and 4 MPa, is similar to that obtained by Poch and Verplancke (1997), and was not significantly related to tree variables. These results suggest that on this kind of soils, site preparation treatments such as subsoiling may not be necessary after all. These low values of penetration resistance may be the result of the pores produced by the growth of the gypsum crystals in the soil matrix (Poch and Verplancke, 1997).

The negative effect of the increase in soil pH on the dominant height of holm oak in soils with gypsum agrees with the results of Curt & Marsteau (1997), who found that in soils with neutral to acid pH dominant height of this species was bigger than in calcareous soils. But no significant relationships were found for the other tree variables, and the soil factors influencing the variability in the growth of *Q. ilex* on soils with gypsum remain unclear.

Conclusions

Growth of *Quercus ilex* plantations on abandoned agricultural plots in areas with annual rainfall of 400 mm and non-saline and well-drained calcareous soils can be satisfactory with appropriate soil conditions, reaching up to 112-230 cm in dominant height and 4.3-8.7 cm in dominant diameter 10 years after plantation.

Two soil characteristics showed a significant influence on the development of this species: the presence of gypsum and the penetration resistance in the upper 50 cm of soil. Height and diameter of trees growing on soils with gypsum was 50-67% of those in soils without gypsum. Although all plots had been subsoiled down to 50 cm depth before plantation, penetration resistance values over 7.0 MPa in soils without gypsum resulted in a dominant height that was 40% of that in soils with resistance values of less than 5.0 MPa in the upper soil horizons. These results suggest that for future plantations careful consideration should be given to the need for subsoiling or for other treatments aimed at loosening the soil.

Soil and site information at a detailed scale, especially the assessment of physical soil properties, is required to properly assess the viability of *Quercus ilex* plantations.

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Table 1.- Effect of the presence of gypsum in soil on the mean values of mean and dominant diameters and heights of *Q. ilex* trees on north-facing slopes.

	Mean diameter (cm) ($p<0.0001$)	Dominant diameter (cm) ($p=0.012$)	Mean height (cm) ($p=0.007$)	Dominant height (cm) ($p=0.03$)
Soils without gypsum (n=10)	2.0 (1.1-3.4)	5.1 (1.7-8.6)	72 (48-104)	150 (67-239)
Soils with gypsum (n=11)	1.0 (0.4-1.9)	2.8 (0.7-4.9)	48 (16-73)	99 (34-163)

Values in parenthesis are minima and maxima.

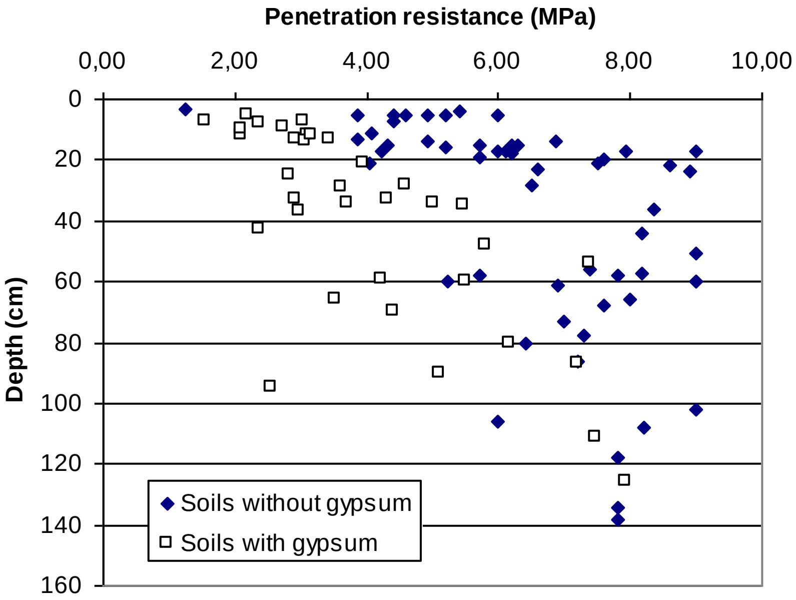

Figure 1.- Variation in depth of penetration resistance in soils with and without gypsum.

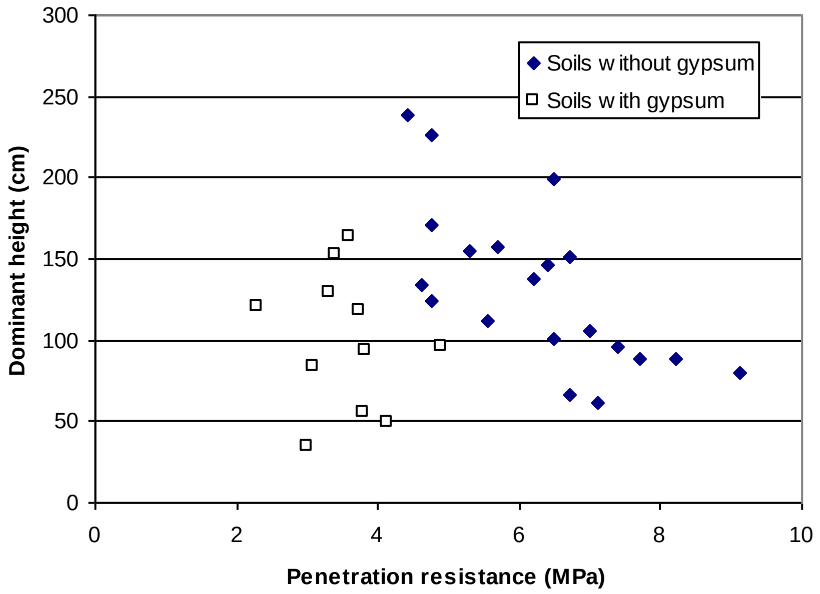

Figure 2- Relationship between penetration resistance in the upper 50 cm of soil and the dominant height of *Q. ilex* seedlings.