Development of *Quercus ilex* plantations is related to soil phosphorus availability on shallow calcareous soils[1]

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Abstract

The objective of this study is to analyse the performance of *Quercus ilex* plantations established under semiarid conditions on different soils formed on calcareous and gypsiferous parent material. We studied eighteen 300 m^2 plots in which 1 year-old seedlings had been planted after subsoiling on the contour. Plots were stratified according to aspect (north and south) and previous land use/ parent material: shrubland on limestone (LM-SH), shrubland on gypsum rock (GY-SH), and cropland on colluvium (CO-AG). Soils developed on limestone and colluvium had average rooting depths of 27 and 37 cm, respectively, and mean concentrations of active lime and phosphorus (P) of 130 and 190 $mg.g^{-1}$ and 10 and 19 $mg.kg^{-1}$, respectively. Soils developed on gypsum had a mean rooting depth of 26 cm, a mean gypsum concentration of 73%. Differences in height and diameter of trees varied significantly according to parent material/previous land use but not to slope aspect. Mean height and diameter of trees were significantly higher in CO-AG plots than in LM-SH and GY-SH plots. Soil P and depth were the main variables explaining differences in dominant height across all 18 plots. In CO-AG plots mean height was negatively related to soil pH but positively related to soil P concentration. In LM-SH plots, mean diameter and height were negatively related to active lime concentration. This study suggests that soil P is a major determinant of holm oak performance in shallow calcareous soils and highlights the importance of conducting detailed soil studies in order to assess the viability of plantations with this species.

Keywords: active lime; afforestation; holm oak; Mediterranean; semiarid areas; gypsum

Introduction

Holm oak (*Quercus ilex* L.) is one the most common hardwood forest species in the dry areas of the Mediterranean Basin, extending over 5 million hectares (Terradas 1999), mainly on the western part of the basin. The extension of Mediterranean forests has been reduced and their structure has been changed after centuries of human pressure. Natural recovery of forests in areas where human pressure has decreased or completely ceased is slow due to the low density of remaining forests in semi-arid areas (Plieninger et al. 2010), that limits seed production, high seedling mortality caused by drought (Gómez-Aparicio et al., 2008; del Campo, 2010), herb competition (Prévosto et al. 2011), and grazing (Plieninger et al. 2011, Pulido & Díaz, 2005).

Holm oak plantations are frequent around the Mediterranean basin (Le Houérou, 2000). The success of these plantations frequently has been low mainly due to drought and poor seedling quality (Bocio et al. 2004; Valdecantos et al. 2009; del Campo et al. 2010). Research on afforestation of holm oak has focused on site preparation techniques (Bocio et al. 2004), vegetation management strategies (Valdecantos et al. 2009), and seedling qualities (Palacios et al., 2009). Some debate remains about the advantages of maintaining a certain cover of spontaneous vegetation, but a general consensus exists about the importance of localized site preparation on survival and growth of holm oak plantations.

Del Campo et al. (2010) have shown that potassium (K) has an important role in holm oak seedling survival in nursery experiments. These authors suggest that high soil active lime concentration may hinder seedling K nutrition. Nevertheless, studies on the response of *Q. ilex* to different soil conditions in the field are rare. Canadell and Vilá (1992) studied how tissue nutrient concentration in holm oak forests varied across soil types and showed a negative correlation between soil calcium (Ca) and plant magnesium (Mg) concentration. In the Luberon region in France, an area with relatively high rainfall and neutral to slightly acid soils, the mean height of trees was positively related to soil K and Mg and to soil depth (Bichard 1982). Curt and Marsteau (1997) measured the highest production for holm oak stands on deep soils without carbonates. Valdecantos et al. (2006) suggested that on basic soils of dry areas soil phosphorus (P) and K are major limitants of *Q. ilex* seedling performance. Previous work in semiarid areas of Lleida (Spain) has shown that growth of *Q. ilex* trees in abandoned croplands is negatively affected by increases in the penetration resistance of the upper 50 cm soil layer even after subsoiling (Cascales, 2005).

While most of these studies have worked under greenhouse conditions or with mature stands, the objective of this paper is to determine the soil characteristics limiting the development of *Quercus ilex* plantations on shallow calcareous and gyspsiferous soils.

Materials and methods

Sampling plots were located in a semiarid area in Lleida, northeast Spain (41º51' N, 0º35' E; 380-500 m altitude). Mean annual temperature for the 1997-2010 period is 14.1 ºC, with a mean minimum of 4.8 ºC in January and a mean maximum of 24.2 ºC in July and August. Mean annual rainfall is 348 mm with a dry period from June to September. Estimated accumulated soil moisture deficit varied between 400-700 mm.

Eighteen 300 m^2 sampling plots (with 21 to 56 trees in each plot) in 15 year-old plantations of *Quercus ilex* L. ssp. *ballota* (Desf.) Samp. The plantations were established using one year-old seedlings that were protected with a plastic tube after subsoiling down to 50 cm depth along the contour with an agricultural tractor. The distance between plantation lines was 3-5 m, but no plantation density records are kept.

All plots were located on slopes and categorized according to two variables, slope aspect and soil parent material/past land use. We selected north and south slope aspects as representative of extreme moisture availability. Aspect of north-facing plots ranged between 315ºNW and 45ºNE, and that of south-facing plots between 135ºSE and 225ºSW. Potential evapotranspiration was estimated by the Turc method using the ECOSIM package (Gracia, 1991) and ranged between 730-770 mm and 1050-1100 mm in north- and south-facing slopes, respectively.

Three parent materials on which shallow soils develop in the area were chosen: limestone, gypsum rock, and colluvium in which a petrocalcic horizon had developed. The former use of these plots was related to this factor, so the plots on limestone and gypsum were previously shrubland (LM-SH and GY-SH plots, respectively), and plots on colluvium had been used for winter cereals (CO-AG plots). Three plots were studied for each combination of slope aspect and parent material/past land use.

Plots were chosen to have more than 50% cover of spontaneous vegetation. The species composition of vegetation varies among the three groups of plots. Vegetation is mainly composed of *Rosmarinus officinalis*, *Ononis tridentata*, *Gypsophila struthium* ssp. *hispanica*, *Thymus vulgaris*, and *Brachypodium retusum* in GY-SH plots, while *Aphyllantes monspeliensis*, *Brachypodium retusum*, *Quercus coccifera*, and *Rosmarinus officinalis* are the main species in LM-SH plots. CO-AG plots are dominated by herbaceous species such as *Foeniculum vulgare*, *Ericastrum nasturtiifolium*, *Eryngium campestre*, and *Papaver rhoeas*. The cover estimated by visual assessment ranges from 75 to 90% in GY-SH plots, 55 to 95% in LM-SH plots, and 70 to 95% in CO-AG plots. The height of this vegetation was always less than 70 cm.

In each plot, the total number of trees was counted. The number of dead trees was also estimated, considering all the plastic tubes that contained a dead tree or no tree. The height and the diameter at the stem base of each alive tree was measured during the winter. For each plot, we calculated the mean height and diameter as the mean height and diameter of all alive trees in the plot. Dominant height and diameter for each plot were calculated as the mean height and diameter of the three tallest trees and of the three thickest trees, respectively.

Slope steepness and aspect were measured with a clinometer and a compass, respectively. A soil pit was excavated to the depth of the underlying rock or root-limiting horizon at the centre of each sampling plot 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 10 penetration resistance measurements in each soil genetic horizon. The presence of gypsum in the soil was confirmed in the field with the $BaCl_2$ method (Porta et al., 1986).

Samples taken from each soil genetic horizon were analysed for the main variables following Porta et al. (1986), namely pH (1:2.5 in water), organic matter (estimated considering it contains 58% organic carbon, which was determined by the Walkley-Black method), total nitrogen (N) (Kjeldahl method), Olsen P, exchangeable K (determined by atomic absorption spectrophotometry after extraction with 1N NH_4OAc pH7), calcium carbonate-equivalent ($CaCO_3$) (determined by the volumetric calcimeter method), active lime (determined by the Nijelsohn method), and gypsum (determined according to Artieda et al., 2006). Texture was determined with the pipette method but only for soils without gypsum due to several problems with this procedure in soils with gypsum (Porta et al., 1986). Soils were classified according to Soil Taxonomy (SSS, 1999).

Statistical analyses were performed in R (R Development Core Team 2009). We used ANOVA to study the variation in soil and tree variables among aspect and parent material/land-use classes, introducing plot as a random factor nested within the fixed factors. Canonical correlation analysis (CCA) in the Vegan package of R was used to analyse correlation between tree variables and soil and site variables for the whole set of plots. Multiple linear regression analyses were performed for the whole set of plots with the backward selection procedure using mean and dominant height and diameter as dependent variables and soil and site variables as independent variables. The procedure was also used separately for each groups of plots (LM-SH, GY-SH, and CO-AG) but using the forward selection method. Only models complying with the basic statistical assumptions were accepted. In all cases, relationships were only considered significant if $P<0.05$.

The three groups of variables used in the analyses were: i) site variables, including slope, aspect (north and south; introduced as a dummy variable with values of 0 for south and 1 for north when used in multiple linear regression), parent material/previous land use (LM-SH, GY-SH, and CO-AG), and cover of spontaneous vegetation, ii) tree variables, including number of dead trees, and mean and dominant height and diameter, and iii) soil variables, including both those described in the field and those measured in the laboratory, were introduced in the analyses as weighted means of the values for the horizons in the upper mineral soil horizon (20-30 cm).

Results

Soil characteristics

Soils varied significantly among parent material/previous land-use units (Table 1) but not between slope aspects. Soils in GY-SH plots were classified as Lithic Torriorthent (three plots), Gypsic Haploxerept (two plots), and Lithic Haplogypsid (one plot), and all belong to the gypsic mineralogy class. These soils were mostly shallow (6-26 cm in depth, except in one case that had a depth of 90 cm), with lower pH, amount of rock fragments, and lower P, $CaCO_3$, active lime, organic matter, and N concentration than the plots located in the other parent materials. Their texture was silty-loam to loam according to field determination, and their gypsum content in the surface mineral horizon varied between 660 $g.kg^{-1}$ and 810 $g.kg^{-1}$.

Soils in the LM-SH plots were classified as Petrocalcidic Palexeroll (three plots), Lithic Haploxeroll (two plots), and Petrocalcic Palexeroll (one plot). Two plots belong to the loamy-skeletal particle-size class and four to the carbonatic mineralogy class. Their texture was loamy in most cases. Soils in CO-AG plots were classified as Petrocalcidic Palexeroll (three plots), Petrocalcic Palexeroll (two plots), and Xeric Petrocalcid (one plot). Three plots belong to the loamy-skeletal particle-size class and all of them to the carbonatic mineralogy class. These soils had a loamy to silty-loam texture.

Tree survival and size

The estimated plantation density was 1144-1378 $seedlings.ha^{-1}$, without significant differences among the three plot classes. The number of dead trees and height and diameter of trees varied significantly among parent material/land use units ($P < 0.0001$) (Table 2). Slope aspect and the interaction between parent material and aspect had no significant effect on any of the variables studied.

Trees growing on CO-AG plots had significantly lower mortality and higher diameter and height than trees on GY-SH and LM-SH plots (Table 2). Mortality was very high on GY-SH plots reaching a mean value of 82%. Trees larger than 50 cm dominated on

CO-AG plots and over 30% of trees were more than 150 cm high. On the other hand, trees with a height ranging between 25 and 50 cm were the most frequent in LM-SH and GY-SH plots, while trees smaller than 25 cm represented more than 30% of all trees. A similar pattern appeared in relation to tree diameter, with over 60% of trees on GY-SH and LM-SH plots having a diameter of less than 10 mm, whereas over 40% of trees on CO-AG plots had a diameter of 10-50 mm and 30% had a diameter of more than 50 mm.

Variables explaining height and diameter of trees

The first axis explained 91% of the variability in the data, while the second axis explained less than 2% (Table 3) in the canonical correlation analysis (CCA) for the whole set of plots, and therefore we only interpreted the first axis (CCA1) in this study. This axis was negatively related to tree mortality and positively related to height and diameter. The three main explanatory variables were soil gypsum, that had a negative correlation with CCA1, and soil P concentration and amount of rock fragments, which had a positive correlation with CCA1 (Table 3).

Multiple linear regression analysis of dominant height across the 18 plots also showed soil P concentration and soil depth to be positively related to that variable, while soil penetration resistance had a marginal negative effect (Table 4).

Multiple linear regression analysis for CO-AG plots showed a positive relationship between mean tree diameter and soil P concentration and a negative relation between mean tree height and soil pH (Table 4). According to these models, a P concentration above 19 $mg.kg^{-1}$ was related to mean diameter values greater than 35 mm, the mean value obtained in these plots. Similarly, soil pH values higher than 8.1 are related to mean height values lower than 112 cm.

On LM-SH plots, active lime was the only variable that significantly explained the variability in dominant diameter and mean height in the multiple linear regression analysis, with a negative effect in both cases (Table 4). Active lime concentrations over 13% were related to dominant diameter and mean height values smaller than 13 mm and 45 cm, respectively. In the case of dominant height, the clay concentration in the soil was the only significant explanatory variable, also with a negative effect, and the model indicated that concentrations over 15% were related to dominant height values of less than 78 cm.

Multiple regression models for height and diameter in GY-SH plots were, in general, not statistically acceptable, and only a model showing a marginal negative effect of gyspum concentration ($mg.g^{-1}$) on mean height (cm) could be obtained:

$$Hm = 65 - 0.04*gypsum \qquad (R^2 = 0.60; P= 0.07)$$

Discussion

The height and diameter values of 15-year old *Quercus ilex* trees in the study plots are smaller than those reported in holm oak plantations in France by Bichard (1982) and Curt and Marsteau (1997). Height and diameter values in the CO-AG plots are similar to those reported by Bocio et al. (2004) in abandoned farmland in southern Spain, but those from GY-SH and LM-SH plots are much smaller. The higher growth reported in Bocio et al. (2004) may be the result of lower moisture deficit in their study area mainly due to lower evapotranspiration as their plots were located at higher altitude than our plots (900 vs. 350-500 m).

The lack of significant differences in height and diameter of *Q. ilex* trees obtained in the present study between the two contrasting slope aspects, north and south, is particularly striking as the low rooting depth of the studied soils (Table 1) was expected to amplify the higher water deficit in south-facing slopes. North-facing slopes usually have lower temperature and higher soil moisture conditions than south-facing slopes in the northern hemisphere (Bolstad et al. 1998; Griffiths et al. 2009). Evergreen plants are particularly exposed to the combination of high air temperatures and low soil moisture in the summer and low temperatures with relatively higher radiation in the winter. This combination of stressful environmental conditions controls the distribution of this type of species (Warren II 2008). Nevertheless, no significant differences were found among different slope aspects in terms of the site index of *Pinus halepensis* plantations in semi-arid north-eastern Spain (Olarieta et al. 2000). Al Omary (2011) did not find differences in the height of trees of this species between north- and south-facing slopes in Jordan either, but tree height in west-facing slopes was significantly higher as a result of their position in relation to moisture coming from the Mediterranean.

On the other hand, the significant positive relation between soil rootable depth and tree growth in the multiple linear regression model for the whole set of plots (Table 4) confirms previous results in the literature (Bichard 1982; Cartan-Son et al. 1992; Rodà et al. 1999; Curt and Marsteau 1997).

Rock fragment abundance in soils appears as a significant variable in the CCA with a positive relation with tree size (Table 3). But this variable does not show any effect in any of the multiple linear regression analyses separately performed for each group of plots. We therefore suggest that the variable 'rock fragments' is just an indicator of the more general differences between the three groups of plots (Table 1), and may not point to a specific effect on plant growth.

The significant relation between height and soil P found in this study (Tables 3 and

4) may be related to both changes in P availability and to the effect of the high content of carbonates and active lime on P solubility and uptake. P is a limiting factor in the growth of holm oak in calcareous soils with low levels of Olsen phosphorus (5 $mg.kg^{-1}$) (Sardans et al. 2004), but Mayor and Rodà (1992) concluded that primary production of *Q. ilex* stands was not limited by nutrients in slightly acidic soils, which may be the result of the high P solubility at this range of soil pH. Similarly, P fertilisation had little effect on holm oak growth in neutral pH soils (Rodà et al. 1999). In contrast, Sardans et al. (2006) obtained a higher growth and an increase in Mg, S, Fe, and K tissue concentration of *Q. ilex* after P fertilisation of soils with high calcium carbonate and active lime concentration. On the other hand, the relatively high levels of soil P in the CO-AG plots are likely the result of past agricultural practices, as they are very rarely found in shrublands.

The size of *Q. ilex* trees also shows a negative relation with active lime on LM-SH plots and with soil pH on CO-AG plots (Table 4). These two soil variables influence the availability of soil phosphorus (Kordlaghari and Rowell 2006), and therefore, high levels of soil calcium are related to low levels of P in *Q. ilex* leaves (Rapp et al. 1999) and to lower height of trees (Curt and Marsteau 1997).

Soil penetration resistance showed a marginal negative effect on tree growth (Table 4), in agreement with the proposals of Curt and Marsteau (1997) and Cubera et al (2009). Cascales (2005) obtained a much stronger relation in soils with resistance values from 4 to 9 MPa. But in our case values were lower, with 50% of the plots having a resistance of less than 4 MPa and only one reaching 6 MPa (Table 1). This suggests a critical soil penetration resistance of 4-5 MPa below which there is no major limitation for *Q. ilex* growth.

Soil P concentration was particularly low in the GY-SH plots (Table 1). This very limited P availability, as well as that of other nutrients, is very frequent in gypsum soils

(Oyonarte et al. 1996; Kordlaghari and Rowell 2006) and plays a significant role in determining the composition of plant communities that grow on these soils (Castillejo et al. 2011). The small size of *Q.ilex* trees in GY-SH plots, compared to those in other plots (Table 2), is consistent with results obtained for other species, such as *Pinus halepensis* and *Q. faginea*, in the area (Olarieta et al. 2000 and 2009). The high content of gypsum in the upper mineral horizons of these soils, over 660 $g.kg^{-1}$, suggests that another possible reason for the poor development of holm oak trees could be low water availability, as in those conditions the packing of gypsum crystals prevents root development (Poch et al. 1998).

The high variability in tree mortality obtained in the whole set of plots studied is consistent with survival data in published literature (del Campo et al. 2010). But we have not pursued this issue any further because the lack of data on initial plantation densities provides a weak basis for such analysis. Nevertheless, both water and nutrient availability, namely P and K, have been shown to influence the survival of holm oak seedlings (Gómez-Aparicio et al. 2005, 2008; del Campo et al. 2010)

The lower mortality and higher growth in CO-AG plots in relation to GY-SH and LM-SH plots can be explained, at least in part, by differences in soil characteristics. But differences in competition with spontaneous vegetation may have also played a significant role (Valdecantos et al. 2009). Some of the species present in plots in former shrubland, such as *Brachypodium retusum* in both GY-SH and LM-SH plots, have been shown to hinder survival and growth of holm oak seedlings (Prévosto et al. 2011). *Aphyllantes monspeliensis*, which appeared frequently in LM-SH plots, grows in thick tussocks with large amounts of fine roots in the upper 10 cm of soil (Burylo et al. 2011), and may have strongly competed for water and nutrients with *Q. ilex* seedlings.

Conclusions

Height and diameter of 15-year old *Q. ilex* trees growing on shallow calcareous and gypsiferous soils are related to the availability of soil phosphorus and negatively affected by the content of active lime and gypsum in the soil.

In general, survival and growth of trees are satisfactory on former agricultural plots with soils developed on stony colluvium. On former shrublands, development of these plantations is poor on soils developed on limestone, and very problematic on soils developed on gyspum.

Soil parent material and former land-use can provide a useful preliminary guide to assess the suitability of *Quercus ilex* plantations, but significant variability in the performance of this species occurs within classes of those variables. Therefore, further detailed analysis of soil characteristics is required to evaluate land suitability for these plantations.

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Table 1 Soil characteristics of the three groups of plots (GY-SH: shrubland on gypsum rock; LM-SH: shrubland on limestone; CO-AG: former agricultural plots on colluvium) (means and standard deviations). For each group n=6.

	GY-SH	LM-SH	CO-AG
Soil rootable depth (cm)	30 (31) a	17 (5) a	28 (11) a
Rock fragments (% v/v)	7 (9) b	30 (19) a	42 (17) a
Penetration resistance (MPa)	4.6 (0.8) a	3.3 (1.4) a	4.0 (1.3) a
pH	7.8 (0.1) b	8.2 (0.1) a	8.1 (0.2) a
$CaCO_3$ ($mg.g^{-1}$)	210 (80) b	540 (40) a	470 (80) a
Active lime ($mg.g^{-1}$)	20 (20) c	130 (50) b	190 (40) a
Olsen P ($mg.kg^{-1}$)	6 (5) b	10 (4) b	19 (7) a
Exchangeable K ($mg.kg^{-1}$)	135 (143) a	125 (37) a	173 (51) a
Clay ($mg.g^{-1}$)	(*)	160 (30) b	200 (40) a
Organic matter ($mg.g^{-1}$)	2.6 (0.5) b	5.1 (1.2) a	4.7 (0.8) a
Total nitrogen ($mg.g^{-1}$)	1.0 (0.2) b	2.3 (0.6) a	1.9 (0.3) a

(*) Particle size analysis was not performed on soil samples from GY-SH plots. Means followed by the same letter are not significantly different at P=0.05. ns: not significant.

Table 2 Estimated number of dead trees, height, and diameter of holm oak trees in the three groups of plots (GY-SH: shrubland on gypsum rock; LM-SH: shrubland on limestone; CO-AG: former agricultural plots on colluvium) (least squares means and standard errors). For each group n=6.

	GY-SH	LM-SH	CO-AG	Standard errors
Dead trees.ha^{-1}	1133	440	103	73
Mean height (cm)	35	45	112	8
Dominant height (cm)	48	76	204	15
Mean diameter (mm)	7	13	35	3
Dominant diameter (mm)	11	25	77	5

Table 3 Results of the canonical correlation analysis between tree variables and soil and site variables for the whole set of plots (n=18).

	CCA1
Eigenvalue	0.284
Proportion of variance explained	0.91
Scores for tree variables	
Dead trees.ha^{-1}	- 0.89
Mean diameter	0.32
Dominant height	0.32
Scores for site and soil variables	
Slope aspect	0.05
Exchangeble K	0.33
Olsen P	0.75
Penetration resistance	- 0.09
Soil rootable depth	0.16
Rock fragments	0.63
Soil gypsum	- 0.85

CCA1: first axis of the analysis

Table 4 Summary of the results of the multiple linear regression analyses.

Sample plots	Dependent variable	Independent variables	Parameter estimate	Variable P value	Model P value	Model R^2
All (n=18)	Dominant height (cm)	Olsen P ($mg.kg^{-1}$)	7.97	0.0001	0.0008	0.68
		Rootable depth (cm)	1.54	0.04		
		Penetr. Resistance (MPa)	-16.60	0.12		
CO-AG (n=6)	Mean diameter (mm)	Olsen P ($mg.kg^{-1}$)	1.4	-	0.02	0.76
	Mean height (cm)	pH	-155.71	-	0.03	0.72
LM-SH (n=6)	Mean diameter (mm)	Active lime ($mg.g^{-1}$)	-0.12	-	0.006	0.88
	Mean height (cm)	Active lime ($mg.g^{-1}$)	-0.25	-	0.005	0.89
	Dominant height (cm)	Clay ($mg.g^{-1}$)	-0.37	-	0.05	0.64