Rootable depth controls height growth of *Pinus halepensis* Mill. in gypsiferous and non-gypsiferous soils[1]

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Abstract

Pinus halepensis is generally considered a species adapted to soils with gypsum but there is hardly any data available to support such statement nor to assess the degree to which soil gypsum may constrain tree development. We studied fifty five 200 m^2-plots in a *P. halepensis* plantation in NE Spain including both plots on soils with gypsum and plots on soils without gypsum. Trees were measured to estimate site index at age 40 years (SI40). A soil pit was described in each plot to a depth of 1 m or to a root-limiting layer, and samples of the various horizons analysed for pH, organic carbon (C), total nitrogen, Olsen phosphorus (P), exchangeable potassium, calcium carbonate, and gypsum concentration, and texture. We studied root development in the soil horizons of 15 of these plots by counting root numbers per surface area at depths of 0-30 cm, 30-55 cm, and 55-80 cm in three 100 cm^2-squares per depth. Penetration resistance and bulk density were also measured in these horizons. Soils with gypsum were frequently less than 25 cm deep, and had negligible concentrations of Olsen phosphorus. Values of SI40, with a maximum of 15.5 m, were primarily determined by a positive effect of soil rootable depth, and to a lesser extent by the negative effect of the C/P ration and rock fragment content in the upper 30 cm of soil. Density of fine and very fine

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roots decreased in deeper soil horizons from a maximum value of 97 roots.dm^{-2} in the surface horizon, but also as penetration resistance and gypsum concentration increased. Soil gypsum does not have a direct influence on growth but constrains the volume of soil that may be explored by roots, which is mainly limited by penetration resistance.

Keywords: gypsum; land evaluation; phosphorus; roots; soil rootable depth.

1. Introduction

Soils with gypsum occur in some 100 million ha over the world but are particularly widespread in northern Africa and western Asia (Verheye and Boyadgiev, 1997). These soils provide specific conditions for plant development and the resulting plant communities are considered a conservation priority in the European Union. Such conditions include poor water availability (Herrero, 1991; Poch et al., 1998), worsened root penetration (Poch and Verplancke, 1997; Poch et al., 1998), and decreased phosphorus availability (Kordlaghari and Rowell, 2006). Nevertheless, Drohan and Merkler (2009) suggest that it is not gypsum by itself the factor determining the distribution of so-called gypsophile plant species, but the plant requirements in these conditions (e.g., water, nutrients) may be fulfilled by other soil and/or site conditions.

Extensive areas with soils developed from gypsiferous materials were deforested in ancient periods, and the landscape has not fully recovered due to a combination of factors including human disturbance and the very slow development of soils in these conditions (Peña et al., 1996; Dana and Mota, 2006). Various forest species used in afforestation projects in semiarid areas have shown diminished growth with increasing gypsum concentration in soils (Olarieta et al., 2009, 2012; Pascual et al., 2012). *Pinus halepensis* Mill. has been proposed as a species that can adapt to high gypsum contents in soil (Navarro, 1996; Verheye and Boyadgiev, 1997), but previous studies suggested, on the basis of a very limited number of sampling plots, a negative effect of soil gypsum on its growth (Olarieta et al., 2000).

Soil rootable depth, also termed ‘effective soil depth’ by Murtha (1988), ‘root restricting depth’ (SSS, 1993), ‘effective root depth’ (Fitzpatrick, 1996), or ‘potential rooting depth’ (Shepherd et al., 2008), is the depth of soil to which plant roots can penetrate and provide a significant uptake of water and nutrients, and is therefore related to the presence of fine (1-2 mm in diameter) and very fine roots (less than 1 mm in diameter) (FVFR herafter), which are the main water and nutrient absorption surfaces of plants (Block et al., 2006). It is widely suggested as a significant soil property to be assessed in field surveys, indicating the soil available water holding capacity (Fitzpatrick, 1996; Fernández et al., 2000; Shepherd et al., 2008), and has been shown to be one of the main soil variables controlling the distribution and growth of various forest species in semiarid areas (Olarieta et al., 2000; Rodríguez-Ochoa et al., 2014) and also in more humid climates (Ares and Marlats, 1995; Kooijman et al., 2005; Olarieta et al., 2006; Mirschel et al., 2011).

The distribution of roots throughout the soil profile provides an assessment of the volume of soil, and therefore of water and nutrients, that roots have access to (Bengough, 2012). Soil rootable depth may then be defined in the field in terms of the presence of a minimum number of FVFR (more than 10 per dm^2; Murtha, 1988; Fitzpatrick, 1996) or through soil indicators of restriction to root development (SSS, 1993; Shepherd et al., 2008). These indicators include (SSS, 1993) cemented horizons of any thickness; horizons more than 10 cm thick with a massive, platy, or weak structure of any type that are very firm when very moist or wet or have a large penetration resistance (over 2 MPa if very moist); presence of a water table; abrupt textural changes; salinity; sodicity; or aluminium toxicity. Ares and Peinemann (1992) found, in the temperate subhumid region of Buenos Aires (Argentina), that root density of *Pinus halepensis* was positively correlated with organic matter content in horizons down to a depth of 50 cm, but negatively correlated with clay content and bulk density of these horizons.

Information on the degree of limitation of soil gypsum on root development is lacking. Data from different countries collected by Mousli (1981), mostly from agricultural crops, suggests that plant roots do not penetrate horizons with a gypsum concentration over 250 $mg.g^{-1}$, and that horizons with 100-250 $mg.g^{-1}$ of gypsum provide a limitation to root development, whereas this author states that pines and eucalyptus cannot penetrate soil horizons with more than 600 $mg.g^{-1}$ of gypsum.

The objective of this paper is to clarify the effect of soil gypsum on *P.halepensis*, and, particularly, whether increasing concentrations of gypsum in soils are a specific limiting factor for root development and growth of this species.

2. Materials and methods

2.1 Sites and soils

The study area is located in Castillonroy (Huesca, northeast Spain, 41º52’N, 0º33’E, altitude: 320-450 m) and comprises 227 ha afforested with *Pinus halepensis* in 1956-60. This is a semiarid area, with a mean annual rainfall of 414 mm and a potential evapotranspiration (Turc method) of 764-1098 mm. More details about it may be found in Olarieta et al. (2000). As the latter study included only four plots on soils with gypsum, we aimed our sampling at this type of soils, and studied another twenty five plots, which included nineteen on gypsiferous soils and six on soils without gypsum. In these plots, 200 m^2 in size, the number of trees with a diameter at breast height greater than 5 cm (dbh) were counted, their height and dbh were measured, and their age determined from cores extracted at ground level. Dominant height was calculated from these data, and site index at age 40 years (SI40) was estimated following Gómez et al. (1997).

Aspect and degree of slope were also measured in each plot with a compass and a clinometer, respectively, and a soil pit was described to a depth of 100 cm or to underlying rock or strongly-cemented horizon following the SINEDARES criteria (CBDSA, 1983). Rootable depth was estimated following Fitzpatrick (1996).

Samples of the various soil horizons were dried at 40ºC and sieved to 2 mm, and analysed for pH (1:2.5 in water), organic carbon (Walkley-Black method considering a recovery factor of 1.58 (De Vos et al., 2007)), total nitrogen (N) (Kjeldahl method), Olsen phosphorus (P), exchangeable potassium (K) (determined by atomic absorption spectrophotometry after extraction with 1N NH_4OAc at pH 7), calcium carbonate equivalent (volumetric calcimeter method), texture (pipette method), and gypsum (thermogravimetric method; Artieda et al. (2006)). Plant-available water holding capacity of soils (AWHC) was estimated from rootable depth, and coarse-fragment content and texture of horizons within the rootable depth (NEH, 1997). Organic carbon to total N (C/N) and organic carbon to Olsen P (C/P) ratios were estimated from these analyses. Soils were classified according to Soil Taxonomy (SSS, 1999), considering the soil moisture regime to be aridic when AWHC was less than 50 mm and xeric if this value was greater than 50 mm. A simple soil moisture budget was estimated for each plot following Olarieta et al. (2000) on the basis of the climatic data from the Alfarràs station, located less than 5 km away from the study area, and mean annual actual evapotranspiration and accumulated moisture deficit calculated.

Root density

A specific study of root density was conducted on 15 plots covering the range of SI40 values in the area. On the wall of the soil pit nearest to a tree, always at a distance of 1-1.5 m, we counted the number of live FVFR in three 10 cm x 10 cm squares per depth (sampling unit of 3 dm^2 per depth) at depths of 0-30 cm (RDa), 30-55 cm (RDb), and 55-80 cm (RDc), or to the depth of the soil pit if shallower. The squares were placed within each depth so as to fit within a single soil horizon. A total of 38 soil horizons were therefore sampled.

At each horizon we measured penetration resistance horizontally five times with an Ejkelkamp hand penetrometer (model IB) with a 0.25 cm^2 surface-area cone and a compression spring of 220 N, except in 3 horizons because of their high content of rock fragments (n=35). Volumetric moisture content was measured at each horizon with a dielectric soil moisture sensor (10HS, Decagon Devices). Three undisturbed samples were taken from each horizon with steel cylinders (50 mm long and 60 mm inside diameter) to determine bulk density after drying at 40ºC, except in 13 in which the cylinders could not be properly filled up (n=25).

Data analysis

Statistical analyses were performed in R (R Development Core Team, 2009). We used data from both the 25 plots studied in this paper and the 30 plots studied by Olarieta et al. (2000) in the same plantation to analyse the influence of soil and site variables on site index (n=55). We analysed the variation in SI40 among Soil Taxonomy subgroups with mixed models in the “nlme” package (Pinheiro et al., 2015), introducing plot as a random factor nested within subgroups. Significance of differences among subgroups was determined with the Tukey test in the “multcomp” package (Hothorn et al., 2008). The influence of specific soil and site variables on SI40 was analysed by means of multiple linear regression models with the backward selection procedure. Soil variables determined in the laboratory and in the field were introduced as weighted means of the values for the mineral horizons in the upper 30 cm of soil. Aspect was included after linearization with the function: Linear_aspect = 180 - |aspect – 180|. As a result, values near 0 correspond with northerly aspects whereas values close to 180 correspond with southerly aspects. Other site variables included as explanatory variables were degree of slope and heat load (Warren II, 2008), and mean annual actual evapotranspiration and mean annual accumulated moisture deficit for each site, estimated from the soil moisture budget, were included as climatic variables. Specific linear regression models were built for the whole set of plots (n=55), for soils with gypsum (n=23), for soils without gypsum (n=32), and for soils without gypsum and with a rootable depth over 100 cm (n=13) as the actual value of this depth could not be described in the field. Variables were transformed when necessary to comply with the basic statistical assumptions. Models that did not fulfil these assumptions or which showed *P* values higher than 0.05 or which included explanatory variables with individual *P* values higher than 0.05 were rejected. Regression trees were used with the “rpart” package (Therneau et al., 2015) to define the threshold values for the variables explaining site index and were pruned using the cross-validation criterion.

Root density variability among the three soil depths sampled was also analysed by mixed models with plot as a nested random variable. Multiple linear regressions were applied for each soil depth to explain root density using gypsum, organic carbon, calcium carbonate, and rock fragment content, and penetration resistance and bulk density as explanatory variables. Penetration resistance and bulk density were introduced as means of the samples or measurements taken. We used logistic regressions to define, from the whole set of root densities, which of those variables had a significant influence in producing root-limiting horizons (i.e., horizons with less than 10 FVFR.dm^{-2}) or horizons not limiting root development (i.e., those with more than 10 FVFR.dm^{-2}). Classification trees were used with the “rpart” package to establish the threshold values of those variables that define root-limiting horizons.

Results

Site index of Pinus halepensis

Values of SI40 ranged from 0.7 m to 15.5 m and varied significantly among the various Soil Taxonomy subgroups defined (Table 1). Soils with an aridic moisture regime (i.e., an AWHC smaller than 50 mm), and particularly Lithic-Xeric Torriorthents, showed the lowest SI40. The latter were all developed from gypsum rock and had a gypsum concentration in the upper 30 cm of the mineral soil of 190-920 mg.g^{-1}. On the other hand, 67% of the Gypsic Haploxerepts defined had negligible concentrations of gypsum in the surface mineral horizon (less than 3 mg.kg^{-1}) but gypsic horizons deeper in these soils had concentrations of 320-970 mg.g^{-1}. Soils with gypsum (Lithic-Xeric Torriorthents, Lithic Haplogypsids, and Gypsic Haploxerepts) had lower concentrations of P and K (mean values of K smaller than 45 mg.kg^{-1}, and a maximum of 93 mg.kg^{-1}) in the upper 30 cm of mineral soil than soils without gypsum (mean values of K higher than 97 mg.kg^{-1} , and a maximum of 229 mg.kg^{-1}). Organic carbon concentration in the surface mineral horizon was always smaller than 40 mg.g^{-1}, and did not reach 15 mg.g^{-1} in Typic Xerofluvents (Table 1).

The best multiple linear regression model explaining SI40 for the whole set of plots included, as explanatory variables, rootable depth, with a positive effect, and CP ratio and rock fragment content (which varied from 0% to 90% in volume) in the upper 30 cm of soil with a negative effect (Table 2). A similar model was obtained by substituting gypsum concentration for CP ratio in the regression, as these two variables were significantly correlated (r=0.65; P<0.001; n=55).

The regression tree analysis for these plots (mean SI40=7.6 m; root deviance=576; n=55) provides a model (R^2=0.62) with a first split between soils with a gypsum concentration in the surface mineral horizon of more than 110 mg.g^{-1} (mean SI40=4.4 m; deviance=103; n=18) and those with a smaller concentration (mean SI40=9.2 m; deviance=188; n=37), and a second split for the latter between those with a rootable depth of more than 74 cm (mean SI40=11.0 m; deviance=64; n=14) and those with less than 74 cm (mean SI40=8.1 m; deviance=54; n=23).

In the case of soils without gypsum, the value of SI40 was explained by a linear model including a positive effect of soil rootable depth, a negative effect of soil organic carbon and linearized slope aspect, and a minor positive effect of soil Olsen phosphorus (Table 2). The regression tree for these plots (mean SI40=9.2 m; root deviance=172; n=32) only provided a split (R^2=0.47) between soils with over 75 cm of rootable depth (mean SI40=11.0 m; deviance=64; n=14) and those with a smaller rootable depth (mean SI40=7.8 m; deviance=27; n=18).

For those of these plots with soils with a rootable depth over 100 cm, site index was explained by linear regression with a positive effect of the estimated soil AWHC and Olsen P concentration and a negative effect of organic carbon concentration in the upper 30 cm of mineral soil (Table 2). The regression tree analysis did not provide any significant models.

For soils with gypsum, SI40 was explained by a linear regression model (Table 2) showing a positive effect of soil rootable depth and a negative effect of the CP ratio and rock fragment fraction in the upper 30 cm of mineral soil. Introducing gypsum concentration in the upper mineral horizon in the equation substitutes for CP ratio and rock fragments but provides a poorer model. The regression tree model (mean SI40= 5.5 m; root deviance=221; n=23) showed only one split (R^2=0.59) that separated those soils with a rootable depth smaller than 26 cm (mean SI40= 2.8 m; root deviance=20; n=10) from those with a depth bigger than 26 cm (mean SI40= 7.6 m; root deviance=72; n=13).

Root density

Mean root density values were significantly different among the three soil depths ($P<0.003$). The mean value of RDa (65±22 roots.dm^{-2}, with a maximum of 97 roots.dm^{-2})

was significantly higher than that of RDb (31±21 roots.dm^{-2}, and a maximum of 67 roots.dm^{-2}), and the latter significantly higher than that of RDc (15±14 roots.dm^{-2}, and a maximum of 39 roots.dm^{-2}). Soil moisture content at the time of sampling varied between 150 g.kg^{-1} and 210 g.kg^{-1} and was not significantly correlated with penetration resistance (P=0.18).

No root-limiting horizons were described at the 0-30 cm depth, and linear regression analysis for RDa showed gypsum to be the only significant explanatory variable, whereas variability in root density at a depth of 30-55 cm was explained by a negative effect of increased penetration resistance and a positive effect of increased organic carbon concentration (Table 3). In the deeper horizons, RDc was explained by a negative effect of increased penetration resistance.

The results obtained with the logistic regression analysis showed penetration resistance to be the main variable producing root-limiting horizons, and gypsum having a minor effect (Table 4). According to this model, root-limiting horizons appear, for example, with penetration resistance values of 5 MPa and gypsum concentrations of 736 mg.g^{-1} or with values of 7.0 MPa and 203 mg.g^{-1}, respectively. Penetration resistance was the only significant variable appearing in the classification tree analysis, which, with an overall internal prediction error of 11%, classified horizons with a penetration resistance over 6.2 MPa as root-limiting (67% correct predictions), and those with lower penetration resistance values were classified as non-limiting (97% correct predictions) (Figure 1). Nevertheless, gypsum concentration sets a maximum value of RD at any depth (Figure 2), so that concentrations over 400 mg.g^{-1} produce horizons with less than about 60 FVF roots.dm^{-2}, and horizons with concentrations over 700 mg.g^{-1} have root densities of less than 20 FVF roots.dm^{-2}.

Neither the root density in the upper 30 cm of soil (RDa) (P=0.24) nor the sum of the RD values throughout the soil profile (P=0.12) were significantly correlated with SI40.

Discussion

Site index

The SI40 values obtained in our plots were much smaller than those reported by Ares and Marlats (1995), which ranged from 6 m to 24 m at the age of 25 years in a much more humid region (mean annual rainfall of 690-920 mm) with similar values of mean monthly temperature. But in both cases rootable depth was the most significant variable explaining site index of *Pinus halepensis* as was also the case in the previous study conducted in our study area (Olarieta et al., 2000).

The negative effect on SI40 of the rock fragment content in the surface mineral horizon appeared for all types of soils studied, even for the deepest ones without gypsum (Table 2), reflecting the smaller AWHC of soils with a large content of rock fragments, and is consistent with the results obtained by other authors for this species (Ares and Marlats, 1995). Nevertheless, AWHC, estimated from rootable depth, content of rock fragments, and texture, was a poorer predictor of SI40 than rootable depth. The reason for this may be related to the calculation method not being suited to the studied soils, e.g., it may overestimate the negative effect of rock fragments on AWHC, as they have been shown to provide some water to plants during dry periods (Tetegan et al., 2015). But it may also be the case that the individual variables used to estimate AWHC provide relevant information in relation to soil properties other than water holding capacity. Rock fragments, for example, decrease AWHC but produce smaller values of soil bulk density, which is an important factor for root development of *Pinus halepensis* (Ares and Peinemann, 1992). AWHC only becomes a significant variable on deep soils without gypsum, in which rootable depth could not be estimated and the variability in rock fragment content and texture provides a wide range of particle-size families of the profiles (from sandy-skeletal to fine-loamy) (SSS, 1979) and textural classes in the surface mineral horizons (from clay to sandy loam).

The commanding influence of rootable depth on SI40 extends through all types of soils, confirming the proposals of Verheye and Boyadgiev (1997) in the sense that rootable depth is the most significant variable for the evaluation of gypsiferous soils and that soils in which this depth is smaller than 50 cm (e.g., Lithic-Xeric Torriorthents) present severe limitations for the growth of *Pinus halepensis*. Afforestation of these soils with this species may not be advisable.

The significant influence of the CP ration, or the Olsen phosphorus and organic carbon concentration in the upper mineral horizon, in all the types of soil studied suggests that phosphorus availability is a relevant factor in the growth of *P. halepensis*, and that such availability is intimately related to soil organic carbon. Phosphorus is a nutrient particularly scarce in soils with gypsum (Kordlaghari and Rowell, 2006) and has proved to be a significant factor for the growth of other forest species such as *Quercus ilex* in similar environments (Pascual et al., 2012). Furthermore, P fertilization produced significant increases in basal area and height of *P. halepensis* saplings in calcareous soils (Sardans et a., 2004).

Litter from *P. halepensis* has a high proportion of recalcitrant compounds (Rovira and Vallejo, 2002) which coupled with a semiarid climate produces a very slow decay rate and decreased nitrogen mineralization of this litter in plantations (Grünzweig et al., 2007; Gelfand et al., 2012). But the negative effect we found of organic carbon concentration in the surface mineral horizon on SI40 contrasts with the positive relation reported by Rodríguez-Ochoa et al. (2008) in natural forests of this species in another semiarid area in northeast Spain. We therefore suggest that soil phosphorus may be immobilized by the build-up of organic carbon in our plantations, which may have not yet reached a mature state due to the slow incorporation of litter into the soil (Ruiz-Navarro et al., 2009). While other studies have emphasised the slowing of nitrogen mineralization (Grünzweig et al., 2007; Gelfand et al., 2012), our results only showed a weak correlation between SI40 and CN ratio for the whole set of plots ($r = -0.34$; $P = 0.03$) and a non-significant correlation for plots with gypsiferous soils ($r = -0.52$; $P = 0.10$).

The explanatory power of the regression models of site index improves when substituting CP ratio for gypsum concentration in the surface mineral horizon in both the model for all plots and that for soils with gypsum. In this respect we agree with the suggestion by Drohan and Merkler (2009) that soil gypsum does not have a direct specific effect on the species requirements for growth, but soils with gypsum in the study area have a set of characteristics (i.e., small rootable depth, low concentrations of available phosphorus) that constrain such growth.

Root density

The maximum RD obtained, just under 100 FVFR.dm^{-2}, is significantly smaller than the maximum of over 200 FVFR.dm^{-2} suggested by Fitzpatrick (1996) as a general guide for non-limiting soil conditions, but is higher that the densities recorded by Sternberg et al. (1996) for chaparral vegetation in southern California.

Although the response of a given plant species to contrasting soil conditions in terms of root proliferation may be very complex (Hodge, 2004), a clear pattern emerges in which root density decreases deeper in the soil. Ares and Peinemann (1992) found a similar general pattern for *Pinus halepensis* but with exceptions according to changing soil horizons. While they did not measure penetration resistance, their results showed a negative influence of increasing clay concentration and bulk density on fine-root density. In our case, penetration resistance, and gypsum concentration to a minor extent, were the significant factors explaining root density, but both cases point to mechanical impedance as the major limitation (Bengough, 2012). Elongation of *Pinus radiata* roots was shown to decrease with increasing penetration resistance from 0 to 3 MPa with a soil matric potential of -0.01 MPa (Zou et al., 2000). No roots were recorded by Sinnett et al. (2008) in soils at field capacity with penetration resistance values above 6 MPa and over 90% of the roots were described in horizons with penetration resistance values of less than 3 MPa. Increasing penetration resistance in the surface mineral horizon to values over 7.0 MPa also decreased height of *Quercus ilex* trees to 40% of the height of trees growing in soils with values under 5 MPa (Olarieta et al., 2012).

Verheye and Boyadgiev (1997) proposed that the rootable depth in gypsiferous soils is only limited by a petrogypsic horizon or hard gypsum rock, whereas our results suggest that cementation is not a requisite for root restriction. Increased gypsum concentration in soil horizons provided a gradual increase in the limitation on root development (Figure 2) rather than a threshold effect at a certain concentration, such as that produced by penetration resistance (Figure 1). Our results show the presence of up to 60 FVFR.dm^{-2} in horizons with gypsum contents over 600 mg.g^{-1}, which was proposed by Mousli (1981) as a limit for pine root penetration. Similarly to the data reported by Poch and Verplancke (1997) and Olarieta et al. (2012), gypsiferous horizons very rarely reached penetration resistance values of 8.0 MPa. Our results support the proposal of Poch and Verplancke (1997) that penetration resistance does not provide a full explanation of the reduced root development in these horizons, and that the discontinuous pores produced by the growth of gypsum crystals may provide the missing link.

Contradictory results have been obtained in the literature relating the root system to tree growth. For example, Al Afas et al. (2008) also showed the absence of a significant correlation between various fine root variables and above-ground biomass of different

Populus clones, but Ares and Peinemann (1992) showed significantly greater root densities (measured as root length per unit volume of soil) in low-growth stands of *Pinus halepensis* than in high-growth stands. Neither root density at any of the three depths nor the sum of the root densities in the soil profile were significantly correlated to site index in our plots. Nevertheless, root density was a good indicator of rootable depth, and as far as this variable provided the best explanatory power of tree growth we propose it as an important variable to be described in the field when the vegetation has had the time to develop its root system. For crops or young vegetation, soil indicators, such as penetration resistance and gypsum content may be useful to assess rootable depth.

Our results also support the need for detailed field-soil analysis to understand constraints on plant species distribution and growth (Drohan and Merkler, 2009) but always considering the full depth of soils. The all too frequent recourse to laboratory analysis of some, usually chemical, variables of surface samples of soils completely misses whole-profile variables that are much more significant for plants (e.g., rootable depth, drainage class) (McAuliffe, 1994; Hamerlynck and McAuliffe, 2008; Walthert et al., 2013), and therefore provides a very incomplete picture of soil behaviour. Furthermore, the gypsiferous, or otherwise, character of soils cannot be defined from the chemical analysis of surface samples. Surface soil horizons may contain no significant amounts of gypsum but horizons at depths of less than 50 cm may show concentrations of up to 970 mg.g^{-1}.

Conclusions

Water availability and phosphorus availability to a lesser extent are the main factors explaining the growth of *Pinus halepensis* in soils with and without gypsum in this semiarid environment. Soil rootable depth and rock fragment content in the upper mineral horizon are the relevant indicators of water availability, and organic carbon and Olsen phosphorus concentration in the surface mineral horizon are those relevant for phosphorus availability.

Soil gypsum does not have a direct influence on growth but constrains the volume of soil that may be explored by roots, which is mainly limited by penetration resistance. Soils require to be fully studied as a whole profile to properly understand their influence on plant development.

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Table 1.- Site index of *Pinus halepensis* at age 40 years and main characteristics of the soils studied according to their classification at the subgroup level of Soil Taxonomy

Soil Subgroup	SI40[1] (m)	Rootable depth[2] (cm)	Organic Carbon[3] ($mg.g^{-1}$)	AWHC[4] (mm)	Olsen Phosphorus[3] ($mg.kg^{-1}$)	n
Typic Xerofluvent	12.3 a (11.6-13.5)	100 (100-100)	10 (6-13)	124 (49-171)	3 (1-5)	4
Typic Calcixerept	10.6 ab (7.4-15.5)	97 (71-100)	21 (8-33)	104 (31-175)	4 (1-10)	9
Typic Xerorthent	9.2 abc (8.4-10.0)	59 (49-75)	22 (14-31)	84 (58-124)	3 (3-4)	3
Gypsic Haploxerept	9.0 bc (7.2-12.6)	46 (27-61)	20 (11-29)	77 (45-104)	1 (0-3)	6
Petrocalcic Calcixerept	8.3 bc (6.9-10.1)	55 (41-74)	29 (20-39)	60 (36-106)	5 (4-11)	6
Petrocalcidic Palexeroll	7.9 bc (7.4-8.4)	46 (35-57)	28 (27-28)	52 (29-75)	3 (3-4)	2
Typic Calcixeroll	7.6 bc (7.0-8.1)	75 (51-100)	26 (24-27)	41 (32-50)	4 (2-6)	2
Xeric Petrocalcid	7.0 c (4.5-8.7)	39 (23-64)	30 (22-35)	29 (14-53)	5 (4-8)	7
Lithic Haplogypsid	6.3 cd (3.6-9.0)	25 (20-30)	28 (14-41)	24 (21-27)	1 (0-2)	2
Lithic-Xeric Torriorthent	3.6 d (0.7-7.1)	22 (6-33)	19 (6-35)	33 (8-64)	0 (0-1)	14

[1] SI40: site index of *Pinus halepensis* at 40 years.

[2] Values of 100 cm correspond with soils in which the rootable depth extended below the 100 cm-depth of the soil pit.

[3] Values for OC and Olsen P are those of the upper 30 cm of the mineral soil.

[4] Soil available water holding capacity.

Table 2.- Multiple linear regression models of site index at age 40 years of *Pinus halepensis* (SI40)

Plots	Models		Estimate	Std. error	P-value
All plots	R^2=0.74 P<0.0001 n=55	Intercept	-2.52	2.23	0.3
		ln(rootable depth) (cm)	3.06	0.52	<0.001
		gypsum (mg.g^{-1})	-0.03	0.01	0.002
		rock fragments (dm^3.m^{-3})	-0.003	0.001	0.05
All plots	R^2=0.75 P<0.0001 n=55	Intercept	-4.21	1.73	0.02
		ln(rootable depth) (cm)	3.52	0.42	<0.001
		C/P ratio	-0.007	0.003	0.009
		rock fragments (dm^3.m^{-3})	-0.003	0.012	0.009
Soils with gypsum	R^2=0.73 P<0.0001 AIC=95 n=23	Intercept	-2.52	3.35	0.46
		ln(rootable depth) (cm)	3.10	0.85	0.002
		gypsum (mg.g^{-1})	-0.04	0.01	0.01
Soil with gypsum	R^2=0.85 P<0.0001 AIC=69 n=23	Intercept	-2.23	2.54	0.39
		ln(rootable depth) (cm)	3.11	0.66	<0.001
		C/P ratio	-0.007	0.002	0.02
		rock fragments (dm^3.m^{-3})	-0.08	0.03	0.01
Soils without gypsum	R^2=0.63 P<0.0001 n=32	Intercept	2.40	4.07	0.56
		ln(rootable depth) (cm)	2.31	0.78	0.007
		organic carbon (mg.g^{-1})	-0.13	0.04	0.008
		linear_aspect	-0.01	0.01	0.04
		Olsen phosphorus (mg.kg^{-1})	0.28	0.14	0.05
Soils without gypsum with > 100 cm rootable depth	R^2=0.71 P<0.0001 n=13	Intercept	8.64	1.63	<0.001
		Soil AWHC (mm)	0.03	0.01	0.02
		Olsen phosphorus (mg.kg^{-1})	0.57	0.20	0.02
		Organic carbon (mg.kg^{-1})	-1.37	0.53	0.03

C/P ratio: organic carbon to Olsen phosphorus ratio in the upper 30 cm of mineral soil.
AWHC: available water holding capacity.

Table 3.- Multiple linear regression analysis for fine and very fine root density at three soil depths

RD (root density) (roots.dm^{-2})	R^2	Model	Estimate	Std. error	P-value
RDa 0-30 cm depth	R^2=0.38 n=15	Intercept	72.1	5.5	<0.001
		gypsum (mg.g^{-1})	-0.6	0.2	0.01
RDb 30-55 cm depth	R^2=0.80 P=0.007 n=11	Intercept	52.4	18.6	0.03
		penetration resistance (MPa)	-8.5	2.6	0.02
		organic carbon (mg.g^{-1})	2.7	0.9	0.02
RDc 55-80 cm depth	R^2=0.74 n=9	Intercept	60.7	12.2	0.003
		penetration resistance (MPa)	-7.7	1.9	0.006

Table 4.- Logistic models for root-limiting soil horizons

Variables	Parameter estimate	Pr>|z|	AIC	Null deviance	Residual deviance
Intercept	-11.8	0.005	24	35	20
Penetration resistance	1.7	0.008			
Intercept	-12.4	0.017	20	35	14
Penetration resistance	1.6	0.035			
Gypsum	0.006	0.069			

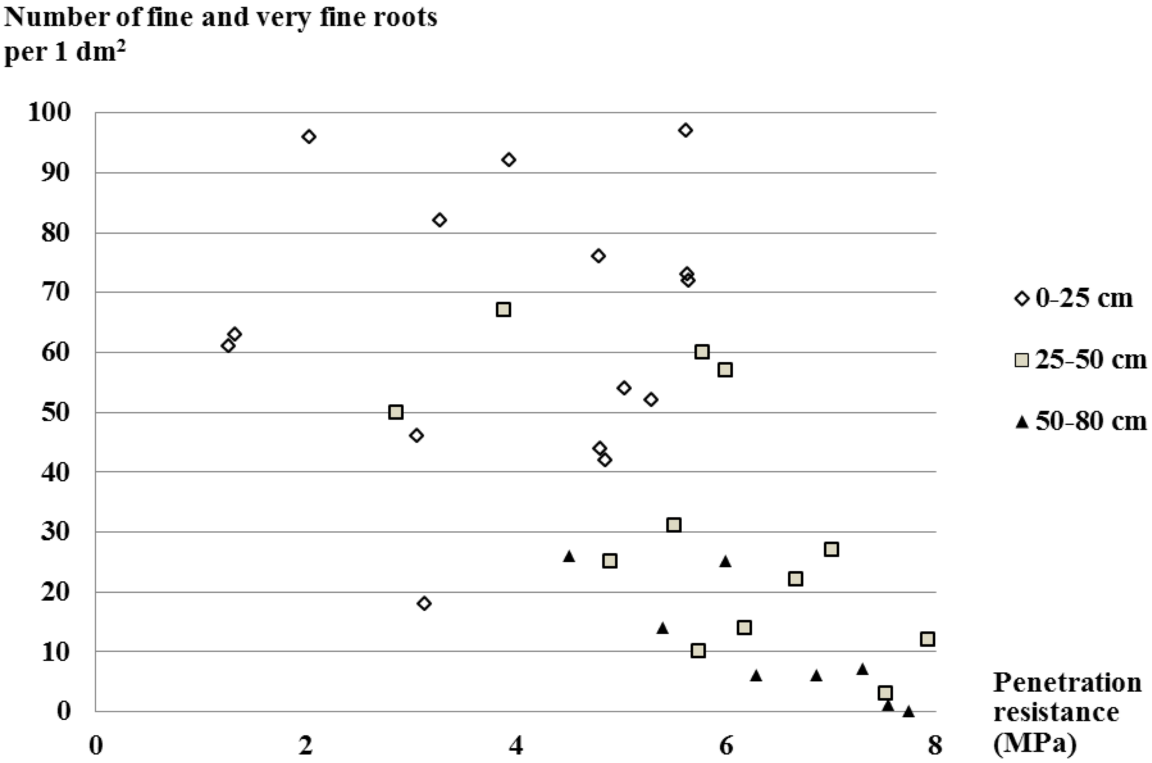

Figure 1.- Fine and very fine root density according to penetration resistance and depth of soil horizon

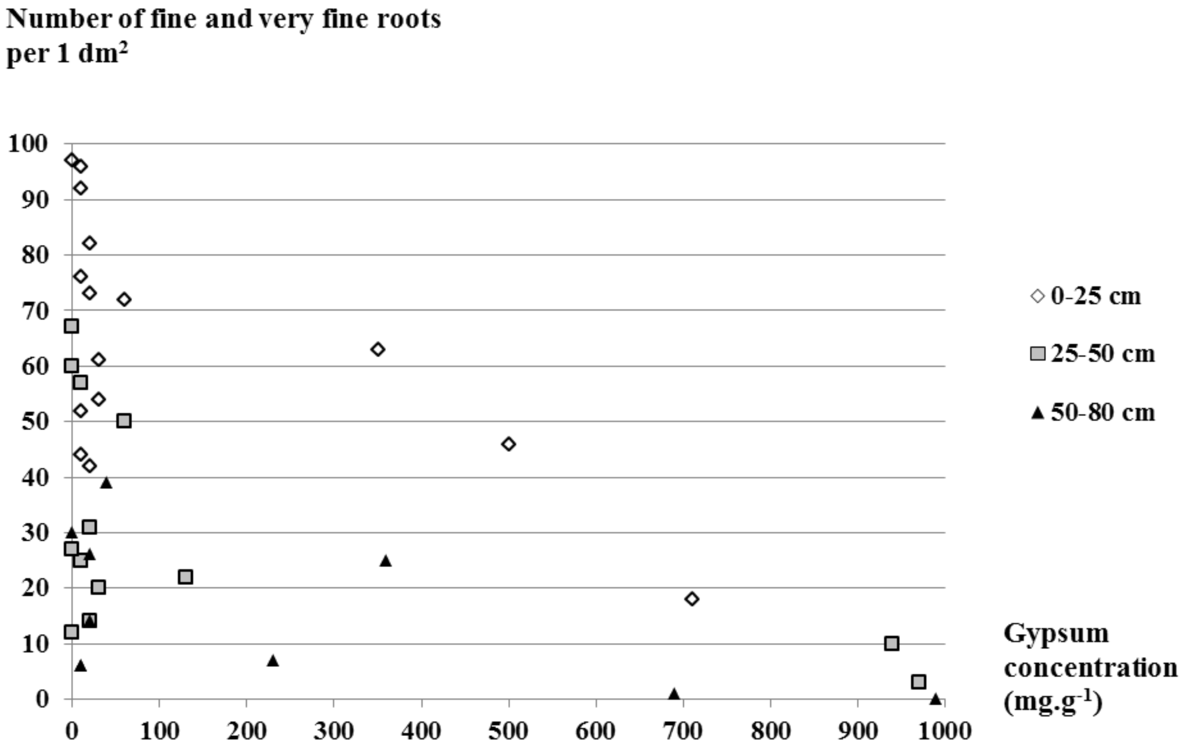

Figure 2.- Fine and very fine root density according to gypsum concentration and depth of soil horizon