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

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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, 23 on soils with gypsum and 32 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 (extracted with NH_4OAc), calcium carbonate (calcimeter method), and gypsum concentration (Artieda method), and texture. We studied root development in the soil horizons of 15 of these plots by counting root numbers 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, in all types of soils, by a positive effect of soil rootable depth, indicating the dominant influence of water availability, and to a lesser extent by the negative effect of the C/P ratio and rock fragment content in the upper 30 cm of soil. Density of fine and very fine roots decreased in deeper soil horizons from a maximum value of 97 roots·dm^{-2} in the surface horizons. Mechanical impedance by increased penetration resistance was the main limitation for root development. Soil gypsum does not have a direct influence on growth but constrains the volume of soil that may be explored by roots.

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 gypsum by itself is not the factor determining the distribution of the so-called gypsophile plant species, and that 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). *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 poor growth of this species on shallow soils (i.e., Lithic-Xeric Torriorthents) developed from gypsum rock (Olarieta et al., 2000).

Soil rootable depth, also termed ‘effective soil depth’ (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 hereafter), which are the main water and nutrient absorption surfaces of plants (Block et al., 2006). Soil rootable depth 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). It is 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).

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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 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 (SSS, 1993; Fisher and Binkley, 2000). Root density of *P. 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 in the temperate subhumid region of Buenos Aires (Argentina) (Ares and Peinemann, 1992).

Information on the degree of limitation of soil gypsum on root development is very scarce. 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 $mg \cdot g^{-1}$, whereas this author states that pines and *eucalyptus* cannot penetrate soil horizons with more than 600 $mg \cdot g^{-1}$ 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, 41°52′N, 0°33′E, altitude: 320–450 m) and comprises 227 ha afforested with *P. 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). The textural class of each soil horizon was determined in the field following Porta et al. (1986). Rootable depth was estimated following Fitzpatrick (1996).

Samples of the various soil horizons were dried at 40 °C 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 1 N NH_4OAc at pH 7), calcium carbonate equivalent (volumetric calcimeter method; Porta et al., 1986), and gypsum (thermogravimetric method; Artieda et al. (2006)). Texture (pipette method) was only determined for horizons with gypsum concentration smaller than 50 $mg \cdot g^{-1}$. 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 phosphorus (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.

2.2. Root density

A specific study of root density was conducted on 15 of the plots covering the range of SI40 values. 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 × 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 only those that the depth of soil allowed. 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 Eijkelkamp hand penetrometer (model IB) with a 0.25 cm^2 surface-area cone and a compression spring of 220 N, except in 3 horizons with a 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 40 °C, except in 13 horizons in which the cylinders could not be properly filled up ($n = 25$).

2.3. 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: $\text{Linear\_aspect} = 180 - |\text{aspect} - 180|$. As a result, values varied between 0 (northerly aspects) and 180 (southerly aspects). Other site variables included as explanatory variables were degree of slope and heat load (Warren, 2008). 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 properly described in the field. Variables were transformed when necessary to comply with the basic statistical assumptions. We rejected models that did not fulfil these assumptions (linearity, homocedasticity, independence and normality of residuals) or which showed P values higher than 0.05 or which included explanatory variables with individual P values higher than 0.05. Correlated soil and site variables, if they finally appeared significant, were introduced alternatively in the models. Otherwise, the models proposed were those with the highest R^2 and lowest Akaike Information Criterion (AIC) values. Regression trees were used with the "rpart" package (Therneau et al., 2015) to define the threshold