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Land requirements for *Pinus halepensis* Mill. growth in a plantation in Huesca, Spain

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Abstract. Land requirements for *Pinus halepensis* Mill. growth were studied in thirty plots of a 40 year-old plantation in the semiarid Lower Ebro valley, northeast Spain, by comparing site index values to land characteristics. Site index at 40 years ranges from 4.1 m to 12.3 m. Moisture availability is the basic requirement for growth while nutrient availability has only a minor influence. Changes in moisture availability in the area are controlled by changes in soil rootable depth, with a minor effect of aspect. Soils developed on Tertiary gypsum rock are not suitable for afforestation with this species. Geomorphic and soil information may be combined, at various degrees of detail, to provide reliable estimates of Aleppo pine growth.

Keywords: Afforestation, land evaluation, Pinus halepensis, soil water, water availability, semiarid zones, Spain

INTRODUCTION

Aleppo pine (*Pinus halepensis* Mill.) is an important tree species around the Mediterranean Basin covering about 6.8×10^6 ha, of mainly calcareous soils, together with *P. brutia*, both species being very similar ecologically and genetically (Barbéro *et al.* 1998). Managed forests of Aleppo pine occupy more than 100 000 ha in Tunisia (Soulères 1975). In Israel, more than 35 000 ha have been planted with this species since 1926 (Schiller 1982), and in southeast France it covers about 180 000 ha (Abbas 1986). It is also the most widely used species for afforestation of semiarid and arid areas in Spain. Natural forests occupy some 800 000 ha, while another 450 000 ha were planted to this species between 1940 and 1980, mainly along the Mediterranean coast and the Ebro valley (Gil *et al.* 1996). Soil and water conservation was the general objective of these plantations.

Land evaluation (FAO 1976) is the process of estimating the performance of homogeneous land units for specific land utilization types. The definition of such land units is also a basic requirement for adequate forest management (Kimmins 1992). This assessment is based on the comparison between the requirements of the land use and the qualities of the land. Work on the requirements of Aleppo pine for successful development has been limited, even though this kind of information, and its application in soil surveys, is very useful for afforestation projects (Laatsch 1966; Dent & Murtland 1990).

Studies on the land requirements of Aleppo pine have been conducted at a national scale in Spain (Gandullo *et al.* 1972), Tunisia (Soulères 1975), and France (Abbas 1986). Work at a local scale has also been conducted in areas of Israel (Schiller 1982), and sparsely in Spain (Laatsch 1966; Zöttl & Velasco 1966; Klop *et al.* 1986). This paper is an attempt to improve information on the land requirements for the growth of Aleppo pine in semiarid regions.

MATERIALS AND METHODS

We studied an area in Castillonroy (Huesca, northeast Spain, 41°52′N, 0°33′E, altitude from 320 m to 450 m) where 227 ha were planted with bare-root seedlings of *P. halepensis* in 1956–60, after site preparation with ox-ploughs. The plantation has not been managed subsequently, although some compartments have been thinned.

Sampling was stratified on the basis of aspect, i.e. north, south, east, and west, geomorphic position, i.e. river terrace, slopes, plateau (Milne *et al.* 1995), and presence or absence of Tertiary gypsum rock. As a result, thirty 200 m^2 plots were studied. In each plot the number of trees with a diameter at breast height (dbh) greater than 5 cm were counted, and their height, diameter at breast height, and crown diameter in two perpendicular directions measured. Age of trees was determined from cores extracted from the trunks at ground level. Leaf area index was estimated from the relations suggested by López-Serrano *et al.* (1997). Dominant height, i.e. the mean height of the 100 largest trees per hectare, was calculated, and site index at age 40 years (SI40) was estimated from the growth curves of Gómez *et al.* (1997) and used as the criterion to evaluate pine growth. Site index is considered the stand parameter least affected by management and thus the commonly accepted measure of site productivity (Hägglund 1981). On the basis of the same growth curves, we also defined the site index class (SIC) for each plot as a qualitative criterion of growth, so that each site index class encompasses a SI40 range of two metres, e.g. a plot with a site index class 4 has a SI40 between 3 and 5 m. Aleppo pine development on soils developed on gypsum rock is patchy, so plots on this parent material were located within these patches.

A soil pit was described in each plot to a depth of 1 m or to a root-limiting layer. Samples of the various soil horizons were

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analysed for pH (1 : 2.5 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 pH7), calcium carbonate-equivalent content, and texture (pipette method). Plant-available water holding capacity (CRAD) was estimated from rootable depth, texture-related available water, i.e. water retained between suctions of 0.05 and 15 bar (Hall *et al.* 1977), and coarse- fragment content. Soils were classified at the family level of Soil Taxonomy (Soil Survey Staff 1994). Following the common criteria used for the agricultural soils in the area, the soil moisture regime was considered to be xeric when the CRAD value was greater than 50 mm, and aridic if less than 50 mm (Herrero *et al.* 1993).

Basic climatic data were obtained from the nearby Alfarrás station. The area has a semiarid climate, with a mean annual rainfall of 414 mm, a mean monthly temperature between 4 °C and 24 °C, a mean minimum temperature of the coldest month, January, of 0 °C, and an estimated mean annual reference evapotranspiration of 1200 mm. We estimated effective rainfall as 85% of total rainfall (Schiller & Cohen 1998). Mean monthly temperatures were adjusted for aspect following Montero de Burgos (1982). Mean monthly values of radiation and Turc's potential evapotranspiration (ETPm) were calculated for each plot with the ECOSIM package (Gracia 1991), which accounts for the effects of geographical location, aspect, slope, and topographic shading. Water balances were calculated for each site assuming an exponential depletion of soil water, whereby soil available water at the end of a dry month (AW) was obtained from:

$$\mathrm{AW} = \mathrm{CRAD}.\exp\left(\frac{-AMD}{CRAD}\right)$$

where AMD is the accumulated moisture deficit, i.e. potential evapotranspiraton minus rainfall accumulated for each month.

Values of mean annual actual evapotranspiration (ETR) were obtained from these water balances. As transpiration from Aleppo pine is much reduced during the dry period (Schiller & Cohen 1998), we also calculated a moist-period evapotranspiration parameter (ETI) for each site as the accumulated potential evapotranspiration for the November–March period plus the residual soil moisture at the end of March. For both the water balance and the moist-period parameter three different base temperatures were used (0 °C, 5 °C, and 7.5 °C).

Statistical analyses were performed with the SAS package (SAS Institute 1989). The soil chemical fertility measurements were introduced in the analysis as averages for 0–30 cm depth.

RESULTS AND DISCUSSION

Soils of the study plots have developed on mainly coarse alluvium and Tertiary rocks. Eleven subgroups and twenty-five families of Soil Taxonomy were defined (Table 1). Soils on the undulating plateau dominating the area have all devel-

Table 1. Geomorphic and soil characteristics of study plots.

Plot	Parent material	Geom[a]/Slo[b]/Asp[c]	Classification	Rootable Depth cm)
E1	Alluvium	T/1-	Coarse-loamy, mixed, calcareous, mesic Typic Xerofluvent	125
E2	Alluvium	T/1-	Fine-loamy, mixed, calcareous, mesic Typic Xerofluvent	125
E3	Alluvium	T/1-	Loamy-skeletal, mixed, calcareous, mesic Typic Xerofluvent	125
E4	Gypsum rock	Sl/6/N	Loamy, gypsic, mesic Lithic Xerorthent	44
E5	Colluvium	CSl/5/N	Sandy, gypsic, mesic Gypsic Xerochrept	39
E6	Alluvium	Sl/15/N	Coarse-loamy, carbonatic, mesic Petrocalcic Xerochrept	74
E7	Alluvium	Sl/10/S	Loamy-skeletal, mixed, mesic, shallow Xeric Petrocalcid	25
E8	Alluvium	P/5/S	Loamy-skeletal, carbonatic, mesic, shallow Calcic Petrocalcid	45
E9	Alluvium	Sl/17/E	Loamy-skeletal, mixed, mesic, shallow Xeric Petrocalcid	41
E10	Gypsum rock	Sl/25/N	Loamy, gypsic, mesic Lithic Torriorthent	29
E11	Gypsum rock	Sl/10/N	Loamy-skeletal, gypsic, mesic Lithic Torriorthent	28
E12	Alluvium	Sl/25/E	Fragmental, mixed, mesic Calcixerollic Xerochrept	125
E13	Alluvium	Sl/18/W	Loamy-skeletal, carbonatic, mesic Calcixerollic Xerochrept	125
E14	Alluvium	Sl/15/N	Coarse-loamy, carbonatic, mesic Calcixerollic Xerochrept	125
E15	Alluvium	Sl/10/W	Loamy-skeletal, mixed, mesic, shallow Petrocalcidic Palexeroll	35
E16	Alluvium	P/1/-	Coarse-loamy, carbonatic, mesic Petrocalcic Palexeroll	57
E17	Alluvium	P/1/-	Loamy-skeletal, mixed, mesic, shallow Xeric Petrocalcid	23
E18	Alluvium	P/1/-	Loamy-skeletal, carbonatic, mesic Petrocalcic Palexeroll	51
E19	Alluvium	Sl/18/N	Coarse-loamy, carbonatic, mesic Petrocalcic Xerochrept	55
E20	Alluvium	Sl/32/E	Loamy-skeletal, carbonatic, mesic Calcixerollic Xerochrept	125
E21	Alluvium	Sl/23/S	Sandy-skeletal, carbonatic, mesic Calcixerollic Xerochrept	125
E22	Colluvium + sandstone	Sl/24/S	Coarse-loamy, mixed, calcareous, mesic Typic Xerorthent	75
E23	Alluvium	Sl/18/E	Loamy-skeletal, carbonatic, mesic Petrocalcic Xerochrept	55
E24	Alluvium	Sl/18/S	Loamy, mixed, calcareous, mesic, shallow Typic Xerorthent	49
E25	Alluvium	Sl/15/N	Loamy-skeletal, carbonatic, mesic, shallow Petrocalcic Xerochrept	45
E26	Alluvium	Sl/19/N	Coarse-loamy, carbonatic, mesic Petrocalcic Xerochrept	58
E27	Alluvium	Sl/18/W	Loamy-skeletal, carbonatic, mesic Xeric Petrocalcid	64
E28	Alluvium	Sl/15/E	Loamy, mixed, calcareous, mesic, shallow Petrocalcic Xerochrept	34
E29	Alluvium	Sl/18/W	Loamy, mixed, calcareous, mesic, shallow Xeric Petrocalcid	32
E30	Alluvium	Sl/24/W	Loamy, mixed, calcareous, mesic, shallow Petrocalcic Xerochrept	49

[a] Geom: geomorphic position; T: terrace; CSl: slope concave in contour and profile; P: plateau. [b] Slo: slope (%). [c] Asp: aspect; N: north; S: south; E: east; W: west.

oped petrocalcic horizons above 60 cm depth, and in some cases, when this horizon is below 50 cm, a mollic surface horizon has also developed. On the most recent terrace developed by the small river running along the north of the area, soils have not developed diagnostic horizons, apart from ochric epipedons, and are classified as Typic Xerofluvents. On the slopes between these two geomorphic units the soil types are very variable. Tertiary gypsum always appears as a lithic contact, i.e. a hard coherent rock (Soil Survey Staff 1994), above 50 cm depth, while gypsic horizons developed on gypsiferous colluvium were observed to behave as root-limiting layers for Aleppo pine. Calcic and petrocalcic horizons appear in soils developed on colluvium/alluvium on these slopes. All soils are non-saline.

Estimated values of annual actual evapotranspiration showed low variability for a given base temperature. Using 0 °C, ETR ranges from 408 mm to 414 mm; with 5 °C, from 324 mm to 352 mm; and with a base temperature of 7.5 °C, from 309 mm to 352 mm. The moist-period evapotranspiration (ETI) was a more variable parameter than ETR. Its values ranged from 134 mm to 146 mm with a base temperature of 0 °C; from 96 mm to 124 mm with 5 °C; and from 80 mm to 125 mm with 7.5 °C.

Stand characteristics were very variable between plots (Table 2). Ten per cent of the plots had a site index class (SIC) of 4, 20% a SIC of 6, 42% a SIC of 8, 14% a SIC of 10, and 14% a SIC of 12. The mean diameter at breast height of the plots ranged from 7.5 cm to 19.6 cm, and the basal area from 5.1 to 27.6 $m^2 ha^{-1}$. Variability in the latter is in part related to human intervention, as only some of the plots studied have been thinned, while others retain a very high tree density.

Table 2. Stand characteristics.

Plot	Mean height m)	SI40[a] m)	Basal area $m^2 ha^{-1}$)	LAI[b] $m^2 m^{-2}$)
E1	9.6	11.4	17.6	1.19
E2	10.9	12.3	17.4	0.91
E3	9.7	11.5	15.3	0.85
E4	3.9	4.9	9.9	1.58
E5	5.5	7.2	10.7	1.24
E6	6.2	7.3	17.7	1.53
E7	3.4	4.4	7.5	2.00
E8	5.1	6.8	8.4	1.42
E9	6.0	7.6	20.0	2.68
E10	3.4	5.5	5.5	1.50
E11	2.6	4.1	5.1	0.38
E12	7.0	8.0	17.4	1.40
E13	8.8	10.3	21.7	1.61
E14	9.2	11.1	27.6	1.72
E15	6.5	7.4	20.7	1.90
E16	7.2	8.3	16.5	1.45
E17	7.2	8.6	14.6	1.79
E18	6.2	6.9	19.9	2.46
E19	7.8	9.0	19.0	1.43
E20	5.9	7.3	8.8	1.26
E21	6.4	8.6	12.6	2.13
E22	7.8	9.8	13.6	1.30
E23	5.9	6.8	12.5	1.10
E24	7.8	9.1	11.7	1.48
E25	8.5	9.9	12.9	0.96
E26	7.0	8.5	18.2	1.70
E27	6.7	7.8	20.2	2.25
E28	5.8	6.9	14.9	2.26
E29	6.2	6.5	19.9	2.08
E30	7.3	7.5	22.6	1.89

[a] SI40: site index at age 40 years. [b] LAI: leaf area index.

Developing Schiller's work (1982) on the influence of bedrock on Aleppo pine growth, we combined geomorphic and soil information (Table 3) to classify the plots into one of six groups: river terraces; plateau with petrocalcic horizon; slopes with gypsum rock; slopes with fine sediments; slopes with coarse sediments; and slopes with petrocalcic horizons. This classification resulted in a significant explanation ($R^2 = 0.71$; $P<0.01$) of SI40 variability. There was significantly more tree growth on river terraces (mean SI40 = 11.7 m) than on slopes with fine sediments (mean SI40 = 9.3 m), slopes with coarse sediments (mean SI40 = 8.6 m), slopes that have developed petrocalcic horizons (mean SI40 = 7.8 m), and platforms with petrocalcic horizons (mean SI40 = 7.1 m). SI40 values for slopes with Tertiary gypsum rock were significantly lower than for all other situations (mean SI = 4.8 m).

In general, the development of the plantation had produced a good vegetation cover of the soil, thus fulfilling its objective of soil and water conservation. But in the areas overlying gypsum rock, trees had not only grown slowly but also patchily, with many bare areas where trees had died providing minimal soil cover. The reason for this failure is the poor water availability of these soils, which contain 60–80% gypsum (Herrero 1991). Available water capacity is inversely proportional to their gypsum content, and recrystallization of gypsum around roots also limits their capability to take water from the soil (Eswaran & Zi-Tong 1991). Other strategies, rather than afforestation with Aleppo pine, should thus be examined for soil and water conservation in these conditions, which are common in other arid and semiarid environments (van Alphen & de los Ríos 1971). Complete avoidance of disturbance or revegetation with species adapted to gypsiferous soils may be considered (Guerrero 1998).

To study the effect of aspect, plots on river terraces and

Table 3. Variability of site index at age 40 (SI40) years between geomorphic-soil units.

Units	SI40 (m)* mean ± s.d.	SI40 (m) min.–max.	*n*
River terraces	11.7 ± 0.5 a	11.4–12.3	3
Slopes/Fine sediments	9.3 ± 1.6 b	7.2–11.1	4
Slopes/Coarse sediments	8.6 ± 1.3 bc	7.3–10.3	4
Slopes/Petrocalcic horizon	7.8 ± 1.1 bc	6.5–9.9	10
Plateau/Petrocalcic horizon	7.0 ± 1.7 c	4.4–8.6	6
Slope/Gypsum rock	4.8 ± 0.7 d	4.1–5.5	3
	$R^2 = 0.71$		

* significant ($P<0.05$); means with the same letter are not significantly different ($P<0.05$); n = number of plots.

Table 4. Effect of aspect on site index at age 40 years (SI40).

Aspect	SI40 (m) n.s. mean ± s.d.	SI40 (m) min.–max.	*n*
North	8.8 ± 1.5	7.2–11.1	6
West	7.9 ± 1.4	6.5–10.3	5
South	7.7 ± 2.2	4.4–9.8	5
East	7.3 ± 0.5	6.8–8.0	5

N.S.: not significant ($P<0.1$); n = number of plots.

Table 5. Variability of site index at age 40 years (SI40) between soil taxonomic units.

Soil subgroups	SI40 (m)* mean ± s.d.	*n*
Typic Xerofluvent	11.7 ± 0.5 a	3
Typic Xerorthent	9.5 ± 0.5abc	2
Calcixerollic Xerochrept	9.1 ± 1.7abc	5
Petrocalcic Xerochrept	8.0 ± 1.2bcd	7
Petrocalcic Palexeroll	7.6 ± 1.0 bcd	2
Petrocalcidic Palexeroll	7.4 bcd	1
Gypsic Xerochrept	7.2 bcd	1
Xeric Petrocalcid	7.0 ± 1.6 bcd	5
Calcic Petrocalcid	6.8 cd	1
Lithic Xerorthent	4.9 d	1
Lithic Torriorthent	4.8 ± 1.0 d	2

* significant ($P<0.05$); means with the same letter are not significantly different ($P<0.05$); *n* = number of plots.

Table 6. Correlation coefficients between stand and land characteristics.

	SI40[e]	Mean height	Basal area
Rootable depth	0.68**	0.64**	0.32*
CRAD[a]	0.67**	0.64**	0.31*
K[b]	N.S.	0.35[†]	N.S.
ETR 7[c]	0.43*	0.44*	N.S.
ETI 7[d]	0.44*	0.44*	N.S.

N.S.: not significant ($P<0.10$). [†] significant at $P<0.10$. * significant at $P<0.05$. ** significant at $P<0.01$. [a] CRAD: profile available water capacity. [b] K: mean exchangeable potassium for 0–30 cm depth. [c] ETR 7: mean annual actual evapotranspiration with a base temperature of 7.5°C. [d] ETI 7: moist-period evapotranspiration with a base temperature of 7.5°C. [e] SI40: site index at age 40 years.

plots on the plateau with slopes less than 5% were excluded from the analysis. Plots on slopes with Tertiary gypsum rock were also excluded because of their severe limitation on tree growth. Aspect did not have a statistically significant effect on SI40 (Table 4). There was a tendency, though, for more growth on north-facing slopes than on other aspects.

Soil taxonomic units at the subgroup level gave a good explanation of SI40 variability ($R^2 = 0.75$; $P<0.01$), although the number of samples in some units is too low (Table 5). At one extreme, Typic Xerofluvents showed the largest mean site index with 11.7 m, and at the other extreme, Lithic Xerorthents and Lithic Torriorthents had the smallest, with less than 5 m. The latter two subgroups correspond to soils developed on Tertiary gypsum rock, which shows again the deleterious effect of this parent material on Aleppo pine growth in this area. Soils with an aridic moisture regime had smaller values of SI40, in general, than those with a xeric moisture regime. We thus believe that the criterion developed for the flat agricultural areas of this region of 50 mm available water capacity to separate aridic from xeric moisture regimes is also reliable as a general rule for these hilly areas.

Site index, mean height, and to a lesser extent basal area, showed a significant positive correlation with rootable depth and available water capacity (Table 6). Soil depth has also been shown to have a determinant role on tree growth in Aleppo pine forests in France (Abbas 1986).

Mean annual actual evapotranspiration (ETR) and moist-period evapotranspiration (ETI), both with a base temperature of 7.5 °C, showed a positive correlation with site index and mean tree height. This confirms that Aleppo pine requires relatively mild winters for adequate growth, as had been suggested by Gandullo *et al.* (1972).

Chemical fertility characteristics, averaged for 0–30 cm depth, did not show any correlation with pine growth, except for potassium which was positively related to mean height. Laatsch (1966), and Zöttl & Velasco (1966) found very good correlations between potassium concentration in Aleppo pine needles and tree height.

Similar results were obtained when we related soil characteristics to site index class. Plots with a site index class 12 had a significantly greater rooting depth and available water capacity than plots on all other site index classes (Table 7). But there were no statistically significant relationships between site index class and total nitrogen, organic carbon, Olsen phosphorus, or exchangeable potassium.

CONCLUSION

Much of the variability in growth of Aleppo pine in the study area was related to soil variability. Moisture supply appeared to be the most important factor limiting growth and it was determined, in turn, by soil rootable depth. Aspect had only a minor influence. Nutrient availability, at the levels found in the area, had no significant effect on growth, except for a weak positive correlation with potassium. There was a specific deleterious effect of gypsum resulting in soils developed on gypsum rock in this area being unsuitable for afforestation

Table 7. Variability of soil characteristics between site index classes (mean and s.d.).

Site index class	Rootable depth cm)*	CRAD mm)*	N (%) n.s.	O.C. (%) n.s.	P ppm) n.s.	K (ppm) n.s.	*n*
SIC12	125 ± 0 a	166 ± 61 a	0.08 ± 0.10	1.1 ± 0.7	3.3 ± 1.5	131 ± 42	4
SIC10	74 ± 37 b	67 ± 19 b	0.18 ± 0.10	2.3 ± 0.7	5.8 ± 3.6	171 ± 50	4
SIC8	67 ± 36 b	72 ± 27 b	0.16 ± 0.07	2.1 ± 0.4	3.9 ± 1.2	136 ± 44	13
SIC6	41 ± 11 b	51 ± 6 b	0.13 ± 0.08	2.0 ± 0.8	3.8 ± 2.7	113 ± 38	6
SIC4	32 ± 10 b	38 ± 15 b	0.10 ± 0.10	1.7 ± 0.9	5.7 ± 6.0	124 ± 98	3

CRAD: profile available water capacity. N: mean total nitrogen for 0–30 cm depth. O.C.: mean organic carbon for 0–30 cm depth. P: mean Olsen phosphorus for 0–30 cm depth. K: mean exchangeable potassium for 0–30 cm depth; *n* = number of plots. * significant at $P<0.05$; N.S.: not significant ($P<0.10$); means with the same letter are not significantly different ($P<0.05$).

with Aleppo pine.

These requirements may be used to obtain suitability assessments of *P. halepensis* growth at local scales in semiarid areas with calcareous and non-saline soils.

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