Soil Use and Management, Sepbember 2006, **22**, 238–244 doi: 10.1111/j.1475-2743.2006.00038.x

Land evaluation for forestry: a study of the land requirements for growing *Pinus radiata* D. Don in the Basque Country, northern Spain

J. R. Olarieta[1], G. Besga[2], R. Rodríguez-Ochoa[1], A. Aizpurua[2] & A. Usón[3]
[1]*Departament de Medi Ambient i Ciències del Sòl, Universitat de Lleida, Rovira Roure, 177, Lleida 25198, Spain,* [2]*Departamento de Agrosistemas y Producción Animal, NEIKER, Berreaga, 1, Derio 48160, Bizkaia, Spain, and* [3]*Departamento de Agricultura y Economía Agraria, Escuela Politécnica Superior de Huesca, Universidad de Zaragoza, Carretera de Cuarte s/n, Huesca 22071, Spain*

Abstract

Land requirements for the growth of *Pinus radiata* D. Don were studied in 112 plots by comparing site index (SI) values with land characteristics. The SI at the reference age of 20 years ranged from 10.4 to 32.7 m. The growth of Radiata pine increased as soil rootable depth increased, with a mean depth of about 50 cm in plots with an SI higher than 29 m. The results show that soil physical properties had a major influence on growth rates with soils of a loamy texture resulting in higher rates than clay rich soils. Soil nitrogen and phosphorus availability had significant effects on growth on soils developed on non-volcanic parent material whilst potassium availability was significant in soils on volcanic parent material. There were strong interactions among the land characteristics of each land unit so that the magnitude of the specific effect of a given variable was highly dependent on the values of the others. Results are discussed in relation to land use planning.

Keywords: Andisols, land characteristics, land use planning, forest soils

Introduction

Radiata pine (*Pinus radiata* D. Don) is one of the most widely used species for intensive plantation forestry, covering over 4×10^6 ha around the world, mainly in New Zealand, Chile, Australia, Spain and South Africa (Lavery & Mead, 1998). In Spain, it occupies about 300 000 ha and more than 50% of the total forest area in the Basque Country (northern Spain). Knowledge about the land characteristics that influence the performance of *P. radiata* plantations is a basic requirement for planning. It can help to identify the suitability of plots for this use, homogeneous management units in established plantations and specific management practices needed to improve yield or to avoid soil degradation (Valentine, 1986; Kimmins, 1992).

The influence of land characteristics on the growth of Radiata pine and on plantation management has been studied: for example, in Chile (Francke *et al*., 1988), New Zealand (Hunter & Gibson, 1984) and Australia (Hollingsworth *et al*., 1996) where a specific 'Soil Classification for *Pinus radiata*' has been developed (Turvey *et al*., 1986, 1990). In Spain, a study at a country-wide scale was conducted by Gandullo *et al*. (1975) and recent work has concentrated, with limited sets of data, on acid soils in Galiza (north-west Spain) (Sánchez-Rodríguez *et al*., 2002) as well as in both Mediterranean and Atlantic areas (Romanyà & Vallejo, 2004). But differences in the spatial scales of the studies and in land characteristics of each area led to different conclusions in relation to the effect of these characteristics on the growth of Radiata pine. The objective of this paper is to study at a detailed spatial scale the effect of land characteristics and soil type on the growth of Radiata pine.

Materials and methods

The Lea-Artibai region, which covers 22 500 ha and where Radiata pine plantations represent about 80% of the forest area, was chosen within the Basque Country because of its

Correspondence: J. R. Olarieta.
E-mail: jramon.olarieta@macs.udl.es
Received November 2005; accepted after revision April 2006

soil variability and because its plantations are considered to be well managed for wood production (Figure 1). These plantations are commonly found at altitudes between sea level and about 700 m.

The region has a temperate humid climate. Mean annual temperature varies between 11.0 and 14.6 °C whilst the mean temperature in the coldest month is 4.6 °C and 20.8 °C in the hottest. Mean annual rainfall varies from 1000 to 1600 mm, monthly summer rainfall (May–September) between 75 and 98 mm, and estimated mean annual potential evapotranspiration (Turc) from 800 to 1060 mm. Soil parent materials are mainly sedimentary rocks (mudstone, marl, limestone and sandstone), volcanic rocks and Quaternary fluvial deposits.

Sampling was stratified on the basis of altitude (below 200 m, between 200 and 400 m and above 400 m) and soil parent material as these were the only available land information about the region. Sample plots of 200 m^2 were distributed throughout Lea-Artibai and established approximately at the centre of larger stands. In some cases, the plots were smaller so as to keep them homogeneous in terms of plantation characteristics, geomorphology and soil type. The plantation owner was interviewed to confirm management practices and history of the stand. Management involves hand weeding for the first three years, three intermediate thinnings between years 8 and 20, pruning up to a height of 2 m and clear-felling after 30–40 years. In none of the study plots had mechanical site preparation techniques been used before plantation.

In each plot, we counted the number of trees, and for each tree, we measured diameter at breast height and total height. From these data, dominant height (i.e. the mean height of the 100 largest trees per hectare) was calculated, and the site index (SI, i.e. the dominant height extrapolated for the reference age of 20 years) was estimated for each plot based on growth curves (Madrigal, 1975). The SI is considered the stand parameter least affected by management and thus the most commonly used measure of site productivity (Hägglund, 1981; Valentine, 1986). Site class (SC) of each plot was also defined according to the following classification: I (SI ≥ 29.0 m), II (25.0 ≤ SI < 29.0 m), III (20.0 ≤ SI < 25.0 m), IV (15.0 ≤ SI < 20.0 m), V (SI < 15.0 m).

For each plot, site conditions and a soil profile down to a depth of 1 m or to geological material were described. Rootable depth was defined as the depth to a layer with less than 10 roots of less than 2 mm diameter per 100 cm^2 in plantations older than 15 years of age, or in younger plantations as the depth to rock, or to a lithic or paralithic contact, or to a layer more than 10-cm thick that has a weak structure and a large penetration resistance (Soil Survey Division Staff, 1993; Webb & Wilson, 1995; Fitzpatrick, 1996). Soil horizons were sampled from the soil pit, and surface horizons down to 30 cm were sampled from five subsamples taken at random within the plot. At these five points, we also determined the soil rootable depth in plots on limestone or marl, where the short-range spatial variability of this characteristic was high.

Soil samples were air-dried, sieved to 2 mm, and analysed for pH (in water and in potassium chloride), organic matter (Walkley–Black method), total nitrogen (Kjeldahl method), available phosphorus (Olsen method), cation exchange capacity (1 N NH_4OAc at pH 7 extraction method), exchangeable aluminium (extraction with 1.2 M $BaCl_2$ and titration with NaOH), texture (USDA fractions) (pipette method). The number of samples analysed for each variable is shown in Table 1. For statistical analysis, the mean values from samples collected from 0 to 30 cm were used. Other soil and site characteristics used were geomorphic position (valley bottom, slopes with north, east, south, or west aspect and interfluve), 'topex value' (sum of the angles of inclination of the skyline at the eight major directions of the compass) as a proxy for exposure, and soil parent material. Soil drainage class was also assessed according to the following morphological criteria: 'well drained' (without redox mottling within 100 cm, or up to 2% between 60 and 100 cm); 'moderately well drained' (2–20% mottling between 60 and 100 cm, or up to 2% in the upper 20 cm); 'imperfectly drained' (mottling between the lower limit of the A horizon and a depth of 60 cm, or more than 2% mottling in the upper 20 cm); 'poorly drained' (mottling with chroma less than 2 in the upper 60 cm).

Undisturbed samples of the surface mineral horizon were taken using four metal cores (53 mm long and 61 mm inside diameter) per plot in 31 plots for the determination of bulk density after drying at 40 °C and estimation of total porosity and packing density following Webb & Wilson (1995). Undisturbed samples were then saturated and placed in a pressure plate extractor at 33 kPa to determine the water content at this potential. Aeration porosity was determined

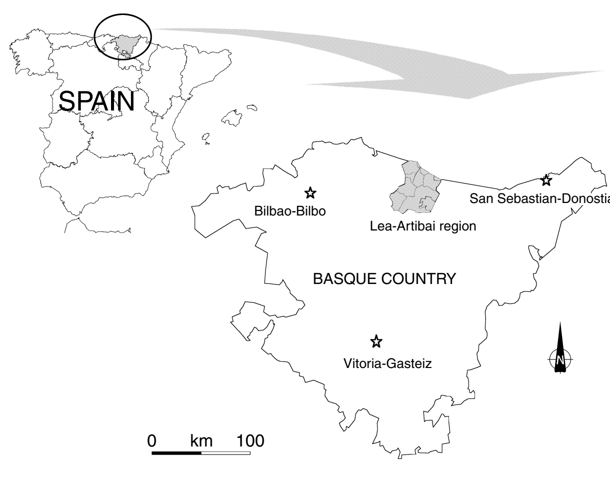

Figure 1 Location of the study area.

Table 1 Minimum, mean and maximum values for some chemical and physical properties of topsoils

	Dpth	pH	OM	Nt	OP	Ca	K	Al	Als	Cl	Sn	BD	PD
Minimum	10	3.6	11	1	0	0	23	0.00	0	7	4	0.75	1.0
Mean	41	4.8	40	2	4	0.3	87	0.04	35	34	27	1.31	1.5
Maximum	> 100	7.5	153	9	69	4.1	576	0.12	90	60	91	1.70	1.9

Dpth, soil rootable depth (cm); pH, pH in water; OM, organic matter (g kg^{-1}); Nt, total nitrogen (g kg^{-1}); OP, Olsen phosphorus ($\mu g\ g^{-1}$); Ca, exchangeable calcium ($cmol_c\ kg^{-1}$); K, exchangeable potassium ($\mu g\ g^{-1}$); Al, exchangeable aluminium ($cmol_c\ kg^{-1}$); Als, aluminium saturation of the exchange complex (%); Cl, percentage clay; Sn, percentage sand; BD, bulk density (t m^{-3}); PD, packing density (t m^{-3}). $n = 112$ for Dpth, pH, OM, P, K; $n = 85$ for Nt; $n = 82$ for Cl, Sn; $n = 37$ for Al, Als; $n = 36$ for Ca; $n = 31$ for BD, PD.

as the difference between total porosity and water content at 33 kPa.

Three climatic variables were estimated for each plot on the basis of data from local meteorological stations and according to the age of the plantations (mean values obtained from the data for the years when the plantation had actually been growing), altitude and distance from the sea. These variables were mean monthly temperature, mean monthly rainfall during the May–September period (monthly summer rainfall), and mean monthly rainfall (monthly rainfall).

Statistical analyses were done with the SAS package, using the correlation procedure to obtain Pearson correlation coefficients, the generalized linear models procedure with separation of the means by Duncan's test, and the stepwise regression procedure for linear regressions. All regressions were tested for normality, linearity, homocedasticity and independence of explanatory variables.

Results

General characteristics of the sample plots

Soils of the sample plots were classified as Udorthents, Udifluvents, Epiaquents, Dystrochrepts, Eutrochrepts, Haplumbrepts, Hapludalfs, Paleudalfs, Hapludults, Haplohumults, Hapludands and Hapludolls. The variation of some soil characteristics down to 30 cm depth are shown in Table 1. Thirty-six plantations were the first rotation on former agricultural plots while the others were second or third rotations on former bracken dominated (*Pteridium aquilinum*) fields. The age of the stands varied between 9 and 41 years, stand density between 167 and 1730 trees ha^{-1}, basal area between 1.3 and 80.9 $m^2\ ha^{-1}$, and SI between 10.4 and 32.7 m.

Growth of Radiata pine at a regional scale

For all plots, mean altitude was higher for the worst SCs (Table 2). All plots of SC-I were below 450 m in altitude and all other SCs occurred up to 600 m. All SCs could be found below 100 m altitude, except SC-V which only appeared above 250 m altitude. This negative effect of altitude on the growth of Radiata pine may be related to a decrease in temperature but also to an increase in exchangeable aluminium, as altitude was positively correlated with this variable ($R = 0.56$, $P < 0.01$).

The SI varied across geomorphic positions, and mean values were higher on valley bottoms (mean SI of 27.6 m), and lower on interfluves and north-facing slopes (mean SI of 20.5–20.7 m), all other positions not differing much among themselves.

Exposure was significantly less in plots of SC-I than in those of classes II, III and IV, but was significantly higher in plots of class V than in all other plots. This positive effect of exposure could be the result of improved protection against the wind, but part of the explanation may also be because of differences in soil chemistry as the 'topex value' was negatively and

Table 2 Means and standard deviations for some land characteristics for the various site classes for *Pinus radiata* in the study plots

Site class	n	Altitude*** (m)	Topex*** (°)	Dpth** (cm)	pH*	T*** (°C)
I	14	179 (120) b	110 (25) a	52 (25) a	5.0 (0.6) a	13.1 (0.7) a
II	28	267 (162) b	87 (24) b	46 (22) ab	5.0 (0.8) a	12.7 (0.8) ab
III	45	265 (151) b	89 (35) b	38 (16) bc	5.0 (0.9) a	12.9 (0.9) a
IV	14	394 (167) a	77 (18) b	37 (11) bc	4.4 (0.6) b	12.3 (1.0) bc
V	11	471 (122) a	54 (27) c	34 (12) c	4.4 (0.7) b	11.9 (0.9) c

n, number of plots; Dpth, soil rootable depth; T, mean monthly temperature. Significant at *$P < 0.10$, **$P < 0.05$, ***$P < 0.01$. In each column, means followed by the same letter are not significantly different ($P < 0.10$).

Table 3 Means and standard deviations of the site index (SI) at age 20 years for *Pinus radiata* in relation to soil rootable depth, drainage and topsoil pH

Dpth (cm)	SI (m)	*n*	Drainage	SI (m)	*n*	pH	SI (m)	*n*
≥80	28.7(2.0)	6	Moder.	23.8(5.0)	13	4.5 ≤ pH ≤ 5.0	24.9(4.6)	23
50 ≤ Dpth < 80	24.1(3.8)	29	Good	23.7(4.6)	75	5.0 < pH ≤ 6.0	24.9(4.7)	31
30 ≤ Dpth < 50	22.3(5.8)	51	Imperf.	20.5(6.1)	23	> 6.0	23.5(3.5)	12
< 30	21.9(4.6)	26	Poor	16.8	1	4.0 < pH < 4.5	20.7(4.9)	28
						≤4.0	20.6(5.6)	18

n, number of plots; Dpth, soil rootable depth; Moder., moderately well drained; Imperf., imperfectly drained.

weakly correlated with aluminium saturation of the exchange complex ($R = -0.47$; $P < 0.01$).

Mean rootable depth, pH and estimated annual temperature were greater in plots with better SC (Tables 2 and 3). Plots of SC-I and -II could have a rootable depth of only 10 cm and pH value as low as 4.0, but SC-V did not contain any soils with rootable depth > 50 cm. Stands of class I occurred in areas with mean temperatures between 12 and 14 °C, but all other classes occurred where mean annual temperatures were less than 12 °C.

Although some drainage classes were not well represented in the sample plots, there was a tendency for soils with poorer drainage classes to have lower site indices, except for moderately well-drained soils, which had similar indices to those on well-drained soils (Table 3).

The interaction of soil parent material and altitude class was significantly related ($R^2 = 0.60$; $P < 0.05$) to the SI of plots, although in some cases, this was based on a small number of sample plots (Table 4). A striking result was the similarity in site indices over all altitude classes on volcanic parent material, with the mean SI in every class always within 25–26 m. On volcanic parent materials, the SC only varied between I and III, even though the sampled plots ranged in altitude from 150 to 600 m.

To identify the specific effect of the various land characteristics on the growth of Radiata pine, we analysed separately the plots on volcanic parent material from those on non-volcanic parent material and within the latter, we performed the analysis for each group of plots representing a different combination of altitude class and soil parent material.

Growth of Radiata pine on non-volcanic soil parent material

The SI for these plots was significantly explained by a multiple linear regression (equation 1) ($R^2 = 0.77$; $P < 0.01$; $n = 24$) that shows a significant positive effect ($P < 0.01$) of rootable depth (Dpth) and Olsen phosphorus (OP), a significant negative effect of total nitrogen ($P < 0.01$) (Nt), and a non-significant effect ($P = 0.14$) of aluminium saturation (Als).

$$\mathrm{SI} = 27.7 + (0.12 \times \mathrm{Dpth}) - (4.8 \times \mathrm{Nt}) + (1.0 \times \mathrm{OP}) - (0.03 \times \mathrm{Als}) \quad (1)$$

In these plots, rootable depth varied from 10 to 100 cm, total nitrogen between 1 and 5 g kg^{-1}, phosphorus from 0 to 69 μg g^{-1} and aluminium saturation between 0 and 90% (pH between 3.6 and 7.5).

The growth of Radiata pine was affected by soil texture in plots on mudstone below 200 m, where SI variability was

Table 4 Mean and standard deviations of the site index (SI) for *Pinus radiata* at age 20 years (SI) according to altitude and soil parent material class

	Altitude					
	< 200 m		200–400 m		> 400 m	
Parent material	SI (m)	*n*	SI (m)	*n*	SI (m)	*n*
Marly limestone	30.7 (1.5)	6	25.2 (2.8)	9	18.4 (7.1)	6
Colluvium	29.0 (4.0)	3	24.8	1	18.5 (3.2)	3
Alluvium	26.7 (3.2)	8	–	–	–	–
Volcanic rocks	25.5 (3.6)	3	25.9 (3.4)	3	25.0 (1.7)	10
Marl	25.1 (1.8)	4	–	–	–	–
Mudstone	23.6 (3.1)	14	21.9 (5.1)	16	17.8 (4.0)	10
Limestone	23.5 (2.6)	8	19.2 (2.3)	5	11.0 (0.8)	3

n, number of plots.

explained (equation 2) ($R^2 = 0.85$; $P < 0.01$; $n = 6$) by the sand content (Sn) in the surface horizon, which varied in these plots between 5 and 24%, while clay content was high, between 33 and 43%.

$$SI = 17.6 + (0.38 \times Sn) \quad (2)$$

Similarly, in plots on marly limestone between 400 and 600 m, there was also a significant positive effect of sand content in the surface soil horizon (equation 3) ($R^2 = 0.81$; $P < 0.10$; n = 4), which varied in these plots between 6 and 18% while clay varied between 39 and 51%.

$$SI = 4.1 + (1.4 \times Sn) \quad (3)$$

Variation in the SI in plots on mudstone between 400 and 600 m was best described by equation (4) ($R^2 = 0.94$; $P < 0.05$; $n = 6$), which includes the significant and positive effect of pH ($P < 0.01$), which varied between 3.8 and 4.5, and total nitrogen ($P < 0.05$), which varied between 2 and 4 g kg^{-1}.

$$SI = -45.3 + (11.3 \times pH) + (5.5 \times Nt) \quad (4)$$

Growth of Radiata pine on volcanic soil parent material

On this parent material, growth was best described by equation (5) ($R^2 = 0.68$; $P < 0.01$; $n = 16$), with a significant positive effect ($P < 0.01$) of rootable depth, mean monthly temperature (T), and mean monthly summer rainfall (R), which varied between 12 and 90 cm, 11.0 and 13.1 °C and 89 and 97 mm respectively.

$$SI = -80.3 + (0.05 \times Dpth) + (3.2T) + (0.7 \times R) \quad (5)$$

In this set of plots, there were statistically non-significant higher concentrations of phosphorus, calcium and magnesium in soils of plantations of poorer quality (SC-III) (mean values of 11 $\mu g\ g^{-1}$ of phosphorus, 1.71 $mol_c\ kg^{-1}$ of calcium and 0.45 $mol_c\ kg^{-1}$ of magnesium) than in soils of plantations of better quality (SC-I) (3 $\mu g\ g^{-1}$ of phosphorus, 0.05 $mol_c\ kg^{-1}$ of calcium and 0.01 $mol_c\ kg^{-1}$ of magnesium). To investigate these relationships in greater detail, we divided this set of plots into two according to soil profile descriptions and the limited data on bulk density and packing density. In one of them, termed 'andic', soil structure in the surface horizons of soils down to 30 cm depth was strong, fine and granular. In the other subset, labelled 'volcanic', soil structure was moderate to strong, subangular blocky.

In the 'volcanic' subset, the SI had a surprising strong positive correlation with aluminium saturation ($R = 0.97$; $P < 0.05$; $n = 4$) which varied between 2 and 73%, but the small number of plots prevented further analysis. For the 'andic' subset, no significant relationship was established between aluminium saturation and SI, even though the range of values was similar to that of the 'volcanic' subset. Variation in site indices for the 'andic' group was explained by a model ($R^2 = 0.65$; $P < 0.05$; $n = 10$) (equation 6) including a positive effect ($P < 0.05$) of both rootable depth (which varied between 12 and 90 cm) ($P < 0.10$) and potassium (K) (which varied between 61 and 576 $\mu g\ g^{-1}$).

$$SI = 22.8 + (0.03 \times Dpth) + (0.007 \times K) \quad (6)$$

Discussion

The SI values recorded in our plots are similar to those obtained by Francke *et al.* (1988) in Chile, but slightly lower than those obtained by Hunter & Gibson (1984), and higher than those measured by Sánchez-Rodríguez *et al.* (2002) and Romanyà & Vallejo (2004).

Soil rootable depth is shown to be an important factor in most studies (Turvey *et al.*, 1990; Hollingsworth *et al.*, 1996; Romanyà & Vallejo, 2004), but while a minimum depth of 60 cm has been suggested for optimum growth of Radiata pine in Atlantic areas of Spain (Sánchez-Rodríguez *et al.*, 2002), the mean depth in plots of SC-I in our study area was 52 cm, and soils in plots of this SC frequently had a rootable depth of 30–40 cm. One plot of SC-I had an estimated rootable depth of only 10 cm. No windthrow problems were observed in the plot, which may be due to its low exposure (a high topex value of 88). Moisture availability would be an apparent limitation in this site, but similar productivities have been recorded in Australia in areas with lower annual rainfall (800 mm) and higher annual evapotranspiration (1300–1600 mm) (Nambiar, 1995). Furthermore, phosphorus availability in this site was high (20 ppm) and nitrogen availability as well, with a total nitrogen content of 0.4% and a C/N ratio of 8.3. Fife & Nambiar (1997) have shown that improved nitrogen nutrition lowers summer water stress and increases productivity of *P. radiata*.

Plantations on soils of volcanic parent material needed a deeper rootable depth than plantations on soils of non-volcanic parent material to achieve SC-I (mean of 85 cm in the former when compared with 46 cm in the latter). Rainfall appeared as a significant factor for the growth of Radiata pine on soils of volcanic parent material (equation 5) but not on those of non-volcanic material. This, together with the need for deeper rootable depth to achieve SC-I on the former, suggests that moisture availability was of particular importance on soils developed on volcanic parent material.

The positive effect on the SI of the increase in the content of sand in soils with 33–51% clay in the mineral surface horizon (equations 2 and 3) may reflect the need to increase macroporosity and soil aeration in these conditions. This is supported by the results obtained in plots developed on mudstone at altitudes between 200 and 400 m and also in those developed on volcanic parent material where there was no significant effect of sand, and surface mineral horizons of soils had a clay content of 20–37%. On the other hand, on soils with small clay content (0–15%), Turvey *et al.* (1986) found a negative correlation between sand content and stand production. These results suggest that plantations subject to mechanical site preparation techniques may show a long-term reduction in growth as a result of the degradation of the physical properties of soils produced by these techniques (Olarieta *et al.*, 1997; Merino *et al.*, 1998).

Soil physical properties may again be the reason for the difference in SI values between plots with 'andic' character (mean SI of 26.0 m) and those with 'volcanic' character (mean SI of 23.3 m). In the former, packing density values were within the optimum range (less than 1.35 t m^{-3}) suggested by Webb & Wilson (1995), whereas in the latter they were in the medium to high range (1.4–1.9 t m^{-3}) and in some cases above 1.85 t m^{-3}, considered to be limiting for root development. Similarly, soils in the 'andic' group had high aeration porosity values (0.22–0.43 m^3 m^{-3}) within the optimum range for root development of Radiata pine, whilst those in the 'volcanic' group had very low aeration porosity (0.04–0.06 m^3 m^{-3}) which is highly limiting for root development (Zou *et al.*, 2001). This result stresses the importance of the 'condition of the surface soil' attribute in the 'Soil Technical Classification', and suggests the need to further subdivide the 'structured soil' class for this attribute.

The different characteristics and behaviour of these two groups may be related to the previous use of these plots, as most of those in the 'volcanic' group used to be agricultural fields on which organic fertilizers and lime were frequently applied whereas those of the 'andic' group are second-rotation plantations which previously were dominated by bracken. As there were no significant differences between these two groups in terms of texture (both for sand and clay content, $P > 0.20$), we suggest that human intervention on the 'volcanic' group produced a significant degradation of physical properties that masked any improvement in particular chemical properties (higher nutrient concentration and lower aluminium saturation of the exchange complex in these soils in comparison with the 'andic' group).

The results from this study suggest that the optimum pH value for the growth of Radiata pine, although varying according to other land characteristics, was closer to 5 than to 6, the value suggested by Hunter & Gibson (1984) as optimal. The results also indicate that nitrogen is only a potential constraint on non-volcanic parent material (equation 1). In these plots in which pH varies between 3.6 and 7.5, total nitrogen has a negative effect on growth, as suggested also by Gandullo *et al.* (1975), and is positively correlated with the C/N ratio ($R = 0.31$; $P = 0.006$; $n = 83$). This may reflect a lower availability of mineral forms of nitrogen as the total content of this element increased, a hypothesis supported by González-Prieto & Villar (2003) who demonstrated that, in poor quality stands, N has a slow turnover and a big soil pool, whilst in good quality stands there is a quick turnover and a smaller pool.

Table 5 Characteristics of land units in which the site index at 20 years is less than 15 m (each unit must conform to all characteristics in a column)

	Soil parent material		
	Limestone	Mudstone	Marly limestone
Altitude	400–600 m	400–600 m	400–600 m
pH	4.0–6.0	< 4.0	< 6.0
Soil rootable depth	< 20 cm	< 50 cm	< 50 cm
Geomorphic position	North	Crest	Any but south

On the other hand, total nitrogen had a positive effect on the SI for plots on mudstone at 400–600 m (equation 4), where pH varied between 3.8 and 4.5 and had also a positive effect on growth. In this case, the amount of nitrogen available to plant roots may depend on the total amount present, as there is no significant correlation between total nitrogen content and C/N ratio. Lea & Ballard (1982) demonstrated the positive effect of both pH and total nitrogen on the mineralization of nitrogen in soils with a mean pH of 4.7.

At a regional scale, planning objectives include the protection from urban development of land of special quality for forest production, and the diversification of species in the forest area with special emphasis on oak and beech forests. For the latter objective, land of poor quality for *P. radiata* may be targeted for a change to broadleaved forests. Defining what constitutes 'land of special quality' or 'land of poor quality' is necessarily subjective, but the results reported in this paper can assist such assessments. As an example, Table 5 defines land units in which the SI is less than 15.0 m. Land of this class may be defined as land of poor quality for the growth of Radiata pine and targeted for promotion of natural woodland. On the other hand, our work has shown that alluvial soils in the study area generally do not meet the requirements for high-quality land (e.g. SI higher than 29.0 m), because of compaction and pH values over 6.0, thus contradicting regional planning guidelines which indicate that all alluvial soils are of high quality and thus should be protected from urban development. Parent material in itself is thus not a satisfactory surrogate to inform land use planning.

Conclusions

This study has demonstrated that soil physical properties, and aeration in particular, have a marked influence on the growth of *P. radiata*, but in addition, moisture and nitrogen availability and pH in the uppermost 30 cm of soil also have a significant influence. These land qualities do not act independently but the magnitude of the effect of each of them varies according to the values of the others. Further research is required to elucidate in detail the effect of soil physical properties, and to analyse nitrogen availability under different soil conditions and its effect on the growth of Radiata pine.

Acknowledgements

We would like to thank Prof. D.A. Davidson and two anonymous reviewers for their very helpful comments on a previous version of this paper.

References

Fife, D.N. & Nambiar, E.K.S. 1997. Changes in the canopy and growth of *Pinus radiata* in response to nitrogen supply. *Forest Ecology and Management* **93,** 137–152.

Fitzpatrick, R.W. 1996. Morphological indicators of soil health. In: *Indicators of catchment health. A technical perspective* (eds J. Walker & D.J. Reuter), pp. 75–88. CSIRO, Collingwood.

Francke, S., Vergara, N. & Bennewitz, R. 1988. Evaluación preliminar de las principales series y fases de suelo en relación al índice de sitio de plantaciones de *Pinus radiata* D. Don de la X Región. *Ciencia Investigación Forestal* **4,** 1–14.

Gandullo, J.M., Gonzalez, S. & Sanchez, O. 1975. *Ecología de los pinares españoles. IV. Pinus radiata* D. Don. Ministerio de Agricultura, Madrid.

González-Prieto, S.J. & Villar, M.C. 2003. Soil organic N dynamics and stand quality in *Pinus radiata* pinewoods of the temperate humid region. *Soil Biology and Biochemistry* **35,** 1395–1404.

Hägglund, B. 1981. Evaluation of forest site productivity. *Forestry Abstracts* **42,** 515–527.

Hollingsworth, I.D., Boardman, R. & Fitzpatrick, R.W. 1996. A soil-site evaluation index of productivity in intensively managed *Pinus radiata* (D. Don) plantations in South Australia. *Environmental Monitoring and Assessment* **39,** 531–541.

Hunter, I.R. & Gibson, A.R. 1984. Predicting *Pinus radiata* site index from environmental variables. *New Zealand Journal of Forest Science* **14,** 53–64.

Kimmins, H. 1992. *Balancing act. Environmental issues in forestry*. UBC Press, Vancouver.

Lavery, P.B. & Mead, D.J. 1998. *Pinus radiata*: a narrow endemic form North America takes on the world. In: *Ecology and biogeography of Pinus* (ed D.M. Richardson), pp. 432–449. Cambridge University Press, Cambridge.

Lea, R. & Ballard, R. 1982. Predicting loblolly pine growth response from N fertilizer, using soil-N availability indices. *Soil Science Society of America Journal* **46,** 1096–1099.

Madrigal, A. 1975. *Tablas de producción, cubicación y tarifas de Pinus radiata* (D. Don) en las provincias vascongadas. Ministerio de Agricultura, Madrid.

Merino, A., Edeso, J.M., Gonzalez, M.J. & Marauri, P. 1998. Soil properties in a hilly area following different harvesting management practices. *Forest Ecology and Management* **103,** 235–246.

Nambiar, E.K.S. 1995. Relationships between water, nutrients and productivity in Australian forests: application to wood production and quality. *Plant and Soil* **168/169,** 427–435.

Olarieta, J.R., Rodriguez, R., Besga, G., Rodriguez, M., Virgel, S. & Domingo, M. 1997. Efecto de las labores mecanizadas de preparación del terreno para plantaciones de pino radiata en algunas propiedades físico-químicas del suelo. In: *I congreso forestal hispano luso* (eds F. Puertas & M. Rivas), pp. 455–459. Gobierno de Navarra, Pamplona.

Romanyà, J. & Vallejo, V.R. 2004. Productivity of *Pinus radiata* plantations in Spain in response to climate and soil. *Forest Ecology and Management* **195,** 177–189.

Sánchez-Rodríguez, F., Rodríguez-Soalleiro, R., Español, E., López, C.A. & Merino, A. 2002. Influence of edaphic factors and tree nutritive status on the productivity of *Pinus radiata* D. Don plantations in northwestern Spain. *Forest Ecology and Management* **171,** 181–189.

Soil Survey Division Staff. 1993. *Soil survey manual*. United States Department of Agriculture, Washington, DC.

Turvey, N.D., Rudra, A.B. & Turner, J. 1986. Characteristics of soil and productivity of *Pinus radiata* (D. Don) in New South Wales. I. Relative importance of soil physical and chemical parameters. *Australian Journal of Soil Research* **24,** 95–102.

Turvey, N.D., Booth, T.H. & Ryan, P.J. 1990. A soil technical classification system for *Pinus radiata* (D. Don) plantations. II. A basis for estimation of crop yield. *Australian Journal of Soil Research* **28,** 797–811.

Valentine, K.W.G. 1986. *Soil resource surveys for forestry*. Clarendon Press, Oxford.

Webb, T.H. & Wilson, A.D. 1995. *A manual of land characteristics for evaluation of rural land*. Landcare research science series no. 10. Manaaki Whenua Press, Lincoln, NE.

Zou, C., Penfold, C., Sands, R., Misra, R.K. & Hudson, I. 2001. Effects of soil air-filled porosity, soil matric potential and soil strength on primary root growth of radiata pine seedlings. *Plant and Soil* **236,** 105–115.