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Relationship among soil parameters, tree nutrition and site index of *Pinus radiata* D. Don in Asturias, NW Spain

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Abstract

The relationships among soil parameters, tree nutrition and site index were examined in *Pinus radiata* D. Don stands in a climatically homogeneous area of NW Spain. Thirty-eight even-aged stands, ranging from 10 to 54 years, were sampled. In each stand, a representative plot of 0.1 ha was selected and different stand variables and parent material were considered. The soils in the study area are strongly acidic, with high proportions of organic matter, high C/N ratios, and low exchangeable base cation and available P concentration extracted by Mehlich 3 method (PM3). Although foliar N was sufficient in every stand studied, widespread deficiencies of K, P and, to a lesser extent, Mg and Ca were diagnosed. The foliar concentrations of P were positively correlated with PM3 and effective cation exchange capacity. The SI values ranged between 9.5 and 28.8 m and were positively correlated with foliar P and extractable K in soil. In the stands developed on quartzite and sandstone lithologies, the SI was negatively correlated with slope and foliar N respectively. The results suggest the importance of site selection and fertilizer treatment in reforestation programmes.

Key words: age-height relationship, needle analysis, Pinus insignis, soil analysis.

Resumen

Influencia de los factores edáficos en el índice de sitio y estado nutricional de *Pinus radiata* D. Don en Asturias, noroeste de España

Se estudia en 38 parcelas de 0,1 ha cada una las propiedades del suelo que más influyen en el índice de sitio (IS) de plantaciones de *Pinus radiata* D. Don de 10 a 54 años de edad y en su estado nutricional en Asturias, considerando diferentes variables de masa y distinto material parental. Los suelos estudiados presentaron un carácter fuertemente ácido, alto contenido de materia orgánica, relación C/N elevada, bajo contenido en bases y P disponible extraído por el método de Mehlich 3 (PM3). Las deficiencias más extendidas fueron en K y P, observándose en algunas parcelas deficiencias en Mg y Ca. Sin embargo, las concentraciones en N fueron siempre superiores al nivel crítico. El P foliar se correlacionó positivamente con la capacidad de intercambio catiónico efectiva y con PM3. El IS osciló entre 9,5 y 28,8 m y estuvo positivamente correlacionado con la concentración de P en acículas y con el K intercambiable en el suelo en todas las parcelas y negativamente con la pendiente y el N foliar en las parcelas desarrolladas sobre cuarcitas y areniscas respectivamente. Los resultados revelan la importancia de la elección del sitio y la necesidad de fertilización en los programas de reforestación.

Palabras clave: análisis de acículas, análisis de suelo, pino insigne, relación altura-edad.

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Introduction

Radiata pine is one of the most important species in terms of wood production in the Spanish forest sector. In Asturias (NW Spain), radiata pine plantations occupy a total surface area of 18,020 ha (less than 20% between 25 and 30 years of age), mainly distributed in the central zone and the west of the region, according to the data from the Third National Inventory of Spanish Forests (DGCN, 2006). In reforestation programmes (EU regulation 2080/92), particularly those involving abandoned agricultural land, this species is currently being planted at a rate of 1,000 ha per year (Canga and Cámara, 2004), which gives an idea of the growing importance that the species will have in the Asturian forest sector in the future. Nevertheless, production varies greatly among plantations and appears to be related to the nutrient status of the forest, which in turn is related to the type of soil and the site preparation techniques used (Zas, 2003). The success of sustainable silviculture is dependent on the efficient recycling of nutrients, which in turn is determined by the characteristics of the organic matter including its mineralization dynamics, pH, texture and the effective soil depth (Canga, 2007).

In Spain during the second half of the 20th century, radiata pine has been planted in more than 300,000 ha in old fields, in a wide range of soils and climatic condition (Atlantic and Mediterranean areas). Optimum growth of radiata pine occurs at between a mean minimum temperature of 5°C and mean maximum temperature of 20°C, with an optimum mean temperature of 13.2 and 15.5°C for Atlantic and Mediterranean plantations respectively (Romanyà and Vallejo, 2004). The species can grow well in fertile soils, even at moderately low rainfall regimes, with between 750 and 950 mm of mean annual rainfall (Romanyà and Vallejo, 2004). For example, the Spanish foresters from the Mediterranean area sometimes refer to radiata pine as the «dry land poplar» because it can give yields almost as high as *Populus* sp. in drier soils. The impact of environmental factors on tree growth varies greatly with tree species, but it may not be relevant within a narrow range or when the environmental factors fall in the optimum conditions for a species (Klinka and Carter, 1990; Wang and Klinka, 1996).

In northern Spain, mainly in the Basque Country and in Galicia, forestry researchers have a good knowledge of radiata pine production in relation to silvicultural practices (Sánchez *et al*., 2003; Castedo, 2004). Studies of the ecological factors that influence the productivity of radiata pine have also been carried out (Sánchez *et al*., 2002). In Galicia nutrient deficiencies have been diagnosed in young plantations (Zas, 2003; Zas and Serrada, 2003), and the impact of soil preparation techniques have been related to the fertility and the nutritional status of repopulated stands (Merino and Edeso, 1999). In each of these studies, physical and chemical characteristics of the soil were considered to be the most important factors determining the productivity of the species. However, there is a lack of intensive studies on soil fertility and plantation nutrition in radiata plantations in Asturias.

Forest sites are specific areas that sustain tree growth and include a multitude of interconnected environmental factors that affect vegetation development. The site index (SI) is commonly used to evaluate site quality, because it is easy to interpret, it is of high productive significance and also of practical use in the correct application of production tables (Bravo and Montero, 2001; Sánchez, 2001; Diéguez-Aranda *et al*., 2006). The relationships between site index (SI) and specific site characteristics or forest nutrient status may provide useful information for the planning involved in sustainable forest management (Sánchez, 2001). The use of these relationships, obtained from predictive or explanatory models (Sánchez *et al*., 2003; Diéguez-Aranda *et al.,* 2005; Skovsgaard and Vanclay, 2008), allows the selection of the most suitable species and the prediction of forest growth.

Numerous regional Spanish studies have been carried out under fairly homogeneous climatic conditions to estimate the effect of soil properties on site productivity to aid forest planning. Studies show that foliar analysis is a very useful tool for relating soil characteristics to the nutrient status of the trees (Brañas *et al*., 2000; Zas, 2003; Zas and Serrada, 2003). The interest with these types of studies lies in differentiating between variables that determine site productivity. Gerding and Schlatter (1995) found that in radiata pine stands established on sandy soils in Chile, the extractable potassium (K) was highly correlated with SI, although the foliar concentrations of K were sufficient. Some studies in NW Spain have shown important nutritional problems in mature stands of radiata pine on typically acid forest soils. Phosphorus (P) deficiencies were the most frequent (Brañas *et al*., 2000; Romanyà and Vallejo, 2000; Sánchez *et al*., 2002; Zas and Serrada, 2003), while nitrogen (N) is rarely deficient and it sometimes occurred in excess in stands with a balanced nutrition (Palacios *et al*., 1995; Zas and Serrada, 2003). The amounts of P are usually decisive in determining the variation in productivity of radiata pine in highly geochemically altered acidic leached soils (McLaughlin, 1996). Surface soil acidity can serve as an indicator of soil fertility and may indicate indirectly the quantity of available P. Effective soil depth is another variable used to evaluate site quality, and is related to the exploitable soil volume for the roots and, consequently to the available water and nutrition (Pyatt *et al*., 2001). Louw (1991) observed that in radiata pine stands in South Africa, the foliar nutrient concentration and the volume of soil available for roots were highly correlated, as was site index. Other studies in young plantations have revealed nutrient deficiencies (especially K), which were attributed to fixation of elements by clay minerals, and low foliar levels of P, Ca and/or Mg as important factors limiting growth (Merino and Edeso, 1999).

Different systems have been used to interpret foliar analysis: the critical levels of nutrients (Binns *et al*., 1980); ratios between nutrients (Ballard and Carter, 1986) and the Diagnosis and Recommendation Integrated System «DRIS» (Schultz and De Villiers, 1988). In radiata pine, the values of critical levels reported by Will (1985), deduced from numerous studies in New Zealand, are frequently employed as reference values for the nutritional status of the species (Sánchez *et al*., 2003; Zas, 2003).

There is very little information available on the nutrient status of Spanish forests and the corresponding relationships with soil properties and productivity. In the particular case of Asturias (NW Spain), no such information is available. The objective of this study was to examine how the productive capacity of radiata pine in Asturias is related to nutrient status and soil properties. The results of the study may help decision making about species choice and management practices in forest plantations.

Material and methods

The study was carried out in the province of Asturias (NW Spain). The climate of the area is Atlantic (European). The altitude of most sites is moderate, ranging between 300 and 700 m. The average annual precipitation and potential evaporation/transpiration (PET) varied from 1,080 to 1,352 mm and of 635 to 710 mm, respectively. The average annual temperature varied from 11.9 to 13.3°C (Table 1), and the terrain is hilly with slope gradients often exceeding 18%. The soil moisture regime is Udic, with adequate soil moisture for most of the growing season except for a 1 month period of drought in summer (IGME, 2001).

A total of 38 stands of radiata pine were selected throughout Asturias (Fig. 1); the characteristics of the stands are shown in Table 1. The sample was chosen to represent the widest possible range of stand conditions, mainly reflected in the age, quality and densities of the species and the range of different soil moisture and nutrient conditions. Asturian forest soils are characterized by moderate or shallow depth, high organic matter content in the upper horizon, and high or moderate acidity (pH around 4), except in eastern Asturias, where most of the rocks are basic (Guitian *et al*., 1985). The Spanish radiata pine plantations are not fertilized resulting in widespread nutritional deficiencies (Romanyà and Vallejo, 1996; Zas and Serrada, 2003). The soils were classified as Ustorthent, Ustochrept and Dystrochrept (Soil Survey Staff, 1999) developed on whitish quartzite (9 stands), black slate (8), feldspar

Table 1. Summary of some characteristics of the 38 radiata pine stands under study

	Minimum	Maximum	Mean	Std. dev.
Altitude (m)	100.00	725.00	470.85	162.22
Mean annual temperature (°C)	11.90	13.30	13.00	0.51
Mean annual precipitation (mm)	1,080.00	1,352.00	1,130.00	78.73
Potential evapotranspiration (mm)	635.00	710.00	667.00	19.53
Slope (%)	0.00	75.00	44.35	14.32
Soil depth (m)	0.19	0.85	0.34	0.08
SI (m at 20 years age)	9.54	28.80	17.56	3.29
Stand age (years)	10.00	54.00	23.95	11.39
Basal area (m^2 ha^{-1})	4.95	78.20	34.99	18.16
Stocking (stems ha^{-1})	275.00	1,860.00	890.07	325.06

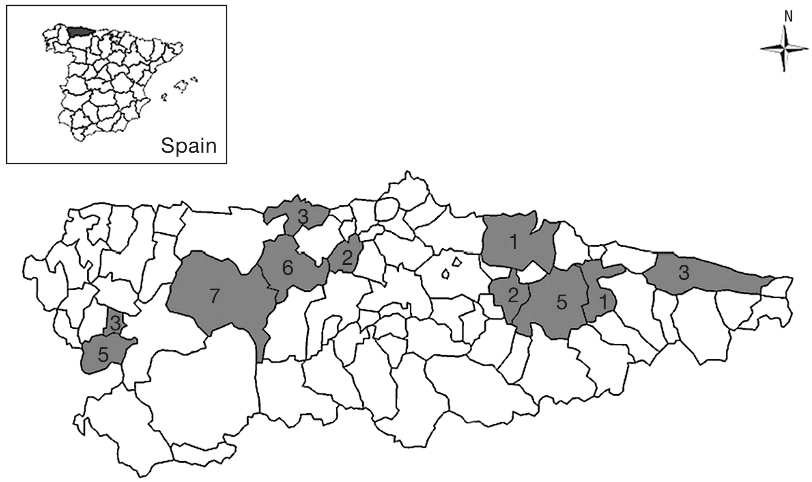

Figure 1. Location of the study area. Number of plots in each region.

sandstone (15), and conglomerate (6) (IGME, 2001). The soils developed from quartzite and sandstone rocks had slightly higher content of silt and coarser texture than the others soils.

Radiata pine is grown on a 30-35 year rotation, and pruning and thinning are common practices. In each stand, a representative plot of 0.1 ha was selected and the diameter at breast height (dbh) was measured on all trees in these plots. The heights of 30 randomly selected trees and 10 dominant trees were measured. In each plot, the SI values were obtained from the site quality system developed by Canga (2007). The system was originally proposed by Krumland and Eng (2005) and was derived on the basis of the Generalizad Algebraic Difference Approach (Cieszewski and Bailey, 2000) by considering two parameters of the original Bertalanffy-Richards model to be site-specific. Concretely, the asymptotic parameter was expressed as an exponential function of X and the shape parameter as a linear function of the inverse of X. The final model after substituting the values of the parameters is expressed as follow:

$$Y = Y_0 \left(\frac{1-\exp\left(-0,05274t\right)}{1-\exp\left(-0,05274t_0\right)} \right)^{-3,161+17,90/X_0} \qquad [1]$$

where:

$$X_0 = \frac{\ln Y_0 + 3,161 L_0 + \sqrt{\left(\ln Y_0 + 3,161 L_0\right)^2 - 71,60 L_0}}{2}$$

and

$$L_0 = \ln\left(1-\exp\left(-0,05274t_0\right)\right)$$

and where Y_0 is the dominant height (meters) at age t_0 (years) and Y is the predicted height (meters) at age t (years).

The previous dynamic equation enables dominant height Y (meters) at any age t (years) to by obtained from any other dominant height Y_0 (meters) at any other age t_0 (years). Therefore, to estimate the dominant height Y for some desired age t given site index SI (meters) and its associated base age t_{SI} (years), simply substitute Y_0 with SI and t_0 with t_{SI} in equation [1]. Similarly, to estimate SI at some chosen base age t_{SI}, given dominant height Y_0 at age t_0, simply substitute SI for Y and t_{SI} for t in equation [1].

In each plot, soil depth was determined at a minimum of three randomly selected points, using a Dutch auger. With the same auger 5 soil samples not fertilized were taken to make a bulk of soil horizons between 0-20 cm depth. The samples were air-dried, crumbled, finely crushed and sieved with a 2 mm screen, before analysis, in duplicate. Particle-size distribution was determined by the pipette method, and sodium hexametaphosphate and Na_2CO_3 were used to disperse the samples (Gee and Bauder, 1996). The pH was measured in H_2O with a glass electrode in a suspension of soil and water (1:2.5) and the electrical conductivity measured in the same extract (diluted 1:5). Organic matter was determined by the ignition method. Total N was determined by a Kjeldahl digest (Klute, 1996). Available P was determined colorimetrically with Mehlich 3 reagent (Mehlich, 1985), considered to be the most appropriate extractant for a wide range of non-calcareous soils (Monterroso *et al*., 1999; Afif and Oliveira, 2006). Exchangeable cations (K, Mg, Na and Ca) extracted with 1 M NH_4Cl, and exchangeable aluminium extracted with 1 M KCl, were determined by atomic absorption/emission spectrophotometry; the effective cation exchange capacity (ECEC) was calculated as the sum of the values of the latter two measurements (sum of exchangeable cations and exchangeable Al).

Needle samples of current-year's growth, were collected in September from the upper third of the crowns of two dominant trees and from another two well-formed radiata pine trees chosen at random in each stand (Will, 1985). The samples were mixed to provide a composite sample for each stand. The composite samples were cleaned with distilled water, oven-dried at 70°C for 48 hours, milled and sieved with a 0.5 mm screen, before analysis, in duplicate. The concentrations of P and boron (B) were determined by colorimetric analysis following combustion for 4 h in a muffle furnace at 450°C, and dissolution of the ashes with 6 N HCl. The Ca, Mg and K were analyzed by atomic spectrophotometry in the same extract (Jones *et al*., 1991). Nitrogen (organic and ammonia) was determined by Kjeldahl digestion.

Independence of the residuals was tested by the Durbin-Watson test, normality of the residuals by the Shapiro-Wilk (W) test, and the homogeneity of residual variances by Levene's test (SPSS, 2005).

Using the Simultaneous (Enter method in SPSS) multiple regression method, SI was regressed on the linear combination of nutrient concentrations in needles and soil parameters. Multivariate relationships between foliar nutrients, soil nutrients and SI were explored by principal component analysis, with a correlation matrix derived from the significant characters (SPSS, 2005).

Results and discussion

Descriptive statistics for the soil properties studied in the selected plantations, and classified according to soil parent material, are shown in Table 2. The SI values ranged between 9.5 and 28.8 m, indicating a large variation in productivity among the different sites. The range of SI values for the studied stands was similar to that reported for another region in northern Spain (Sánchez *et al*., 2002). The intensively managed radiata pine plantations of south Australia and the reduced water stress of New Zealand plantations have higher site index than the Spanish plantations studied (Hunter and Gibson, 1984; Hollingsworth *et al*., 1996). Unexpectedly, the lowest productivity of the plantation studied in northern Spain coincided with the area with highest rainfall. Radiata pine appears to be particularly intolerant to soil waterlogging (Boomsma and Hunter, 1990), but the steep slopes of the rainy sites under study make it difficult to attribute the low productivity of these sites to this process. In any case, the most humid

Table 2. Mean values for SI and soil properties in the 38 radiata pine stands, grouped according to soil parent material

	All stands[a]	Quartzite	Slate	Sandstone	Conglomerate
SI (m)	17.56 (3.29)	17.72 a	16.65 a	18.53 a	16.11 a
Soil depth (m)	0.34 (0.08)	0.37 a	0.34 a	0.33 a	0.34 a
Slope (%)	44.35 (14.32)	44.50 a	35.91 a	45.04 a	53.67 a
Clay (%)	15.76 (8.67)	14.58 ab	19.54 b	17.74 ab	7.57 a
Sand (%)	69.03 (16.11)	72.19 ab	61.90 a	64.59 a	84.87 b
Organic matter (%)	19.73 (7.31)	16.52 a	23.03 a	21.90 a	14.71 a
pH (water 1:1)	3.78 (0.33)	3.73 a	3.64 a	3.75 a	4.01 a
Total N (%)	0.38 (0.17)	0.36 a	0.30 a	0.48 a	0.29 a
C/N	33.61 (14.22)	31.51 a	48.17 b	28.31 a	30.60 a
Extractable P (mg kg^{-1})	6.04 (4.60)	4.17 a	4.97 a	8.44 a	4.25 a
Extractable K ($cmol_c$ kg^{-1})	0.23 (0.16)	0.27 a	0.17 a	0.25 a	0.17 a
Extractable Ca ($cmol_c$ kg^{-1})	1.30 (0.67)	1.36 a	1.29 a	1.35 a	1.12 a
Extractable Mg ($cmol_c$ kg^{-1})	0.42 (0.23)	0.35 a	0.45 a	0.48 a	0.31 a
Extractable Al ($cmol_c$ kg^{-1})	7.71 (5.01)	6.82 ab	5.65 ab	10.96 b	3.65 a
ECEC ($cmol_c$ kg^{-1})	10.56 (5.28)	9.84 ab	8.23 ab	13.99 b	6.13 a

[a] Standard deviations are shown in brackets and significant differences between means are indicated with different letters, a < b (Tukey test, $P < 0.05$).

locations are also the coldest, and therefore the least productive. Other authors have also noted the higher sensitivity of radiata pine to soil resources such as water storage and nutrients than to climate (Nambiar, 1991). Analysis of variance did not reveal any significant effects of parent material on SI. Similarly Sánchez *et al*. (2002) have studied a 47 set plot of radiata pine plantations in northwest Spain and have not found significant impact of parent material on SI. The importance of parent material in forestry has been pointed out elsewhere and has often been used for classifying site quality in specific areas (Turvey and Poutsma, 1980; Turner and Holmes, 1985; Romanyà and Vallejo, 2004).

The soils in the study area are strongly acidic, with high contents of organic matter and high C/N ratios, low effective depth, and low contents of exchangeable base cations and of Mehlich 3 available P (Table 2), in accordance with the properties usually displayed by very acid forest soils in cold, humid areas (Sánchez *et al*., 2002; Afif and Oliveira, 2006). The soils developed from conglomerate had slightly lower organic matter, clay, and extractable Ca and Mg concentrations than other soils, giving rise to a lower effective cation exchange capacity (ECEC) (although the differences were not significant).

In the correlation matrix for the basic soil properties, there were good positive correlations between ECEC and exchangeable Al, Mg and K, with correlation coefficients of 0.978^{***}, 0.547^{**} and 0.477^{*} respectively, and with the clay content and total N ($r = 0.504^{**}$ and 0.587^{**}, respectively). There were good positive correlations between exchangeable Ca and both organic matter content and N, with correlation coefficients of 0.417^{**} and 0.323^{*} respectively, and also a good correlation between the latter two variables ($r = 0.405^{*}$). The available P extracted with Mehlich 3 reagent was positively correlated with Kjeldahl N ($r = 0.389^{*}$) and negatively correlated with effective soil depth ($r = -0.418^{**}$). The least fertile soils with low levels of available P generally had a shallow soil depth. Similar deficiencies, particularly in P and extractable bases have been observed in acid forest soils under radiata pine plantations in Spain (Romanyà and Vallejo, 1996; Zas, 2003; Zas and Serrada, 2003). Romanyà and Vallejo (2004) showed that Atlantic radiata pine plantations grow in soils rich in organic matter and N and in shallow soils with low pH, low available P and general low fertility. These plantations are thus not likely to be limited by the lack of N but by the lack of P. On the other hand, Mediterranean radiate pine plantations grow in a large variety of site conditions ranging from low to neutral pH, from shallow to deeper soils and from low to high nutrient (NPK) availability (Boardman, 1988; Grey, 1989).

The mean concentrations of 7 nutrients in radiata pine needle samples from the 38 plots under study and grouped according to parent material are shown in Table 3, along with the critical and marginal levels reported for New Zealand (Will, 1985). Relative to the New Zealand reference levels, the stands in this study were clearly deficient in P and Mg, although the P deficiency was more important and consistent with the results reported for radiata pine in other Spanish peninsular regions (Romanyà and Vallejo, 1996; Zas and Serrada, 2003). Visual symptoms of deficiencies of these nutrients were also observed in several plots. The concentrations of K in needles in all of the plots studied were below the critical level, and the highest values corresponded to those plots with high contents of exchangeable Al in the soil. Huang and Bachelard (1993) showed that in hydroponic culture, the absorption

Table 3. Concentration in mg g^{-1} of nutrient elements in the needles of *P. radiata* in plantations on different soil parent materials[a]

Nutrients	All stands	Quartzite	Slate	Sandstone	Conglomerate	C.L.[b]	M.L.[b]
N	24.73 (3.7)	24.81 a	23.10 a	25.45 a	25.02 a	12.0	15.0
P	0.96 (0.56)	1.03 a	0.70 a	1.05 a	0.98 a	1.10	1.4
K	2.83 (0.28)	2.80 a	2.64 a	2.88 a	2.98 a	3.0	5.0
Ca	1.02 (0.30)	1.08 ab	0.84 a	0.97 ab	1.28 b	1.0	1.0
Mg	0.74 (0.22)	0.77 a	0.81 a	0.71 a	0.65 a	0.7	1.0
Fe	21.05 (6.89)	23.33 a	18.75 a	22.67 a	16.67 a	—	—
B	19.91 (7.09)	16.53 a	19.60 a	22.06 a	20.06 a	—	—

[a] The values are means of mixed sampled in each stand, and standard deviations are shown in brackets. Significant differents between means are indicated with differente letters, a < b (Tukey test, $P < 0.05$). [b] Critical (C.L.) and marginal (M.L.) level reported by Weill (1985).

of K increased with increasing amounts of Al provided in the nutrient solution, whereas absorption of Ca and Mg decreased. It is therefore possible that the highly acidic nature of the Asturian soils is affecting the amount of absorbed K. This also occurs in other acid tolerant forest species such as *Tsuga heterophylla*, *Pseudotsuga menziesii* and *Picea sitchensis* (Ryan *et al*., 1986). The levels of Ca in plots established on slate and sandstone were below the critical level and the concentrations of N in needles was higher than the critical or marginal levels in all studied plots. The N:P ratio was not below 10 in any of the plots, clearly indicating an imbalance between these nutrients (Raupach *et al*., 1969).

In stands of radiata pine in Spain (Mesanza *et al*., 1993; Palacios *et al*., 1995; Zas and Serrada, 2003; Zas, 2003) and in New Zealand N deficiencies are not common (Hunter *et al*., 1991), and problems associated with excess amounts of this nutrient are much more important and may determine the absorption of other nutrients (Olykan and Adams, 1995), including P (Zas, 2003). The imbalance between N and P in all plots may be indicative of a negative interaction between the relative excess of N and P nutrition. This negative interaction is due to competition between NH_4^+ and orthophosphate ion for adsorption sites in root systems (Fangmeier *et al*., 1994). On the other hand, there were no significant differences between the main classes of rock in terms of the mean concentrations of nutrients in needles (Table 3). Despite this, lower mean concentrations of P, K and Ca were observed in soils developed from slate, and therefore the indirect effect of the nature of the rock on the nutritional status of radiata pine stands in Asturias may be observed in terms of soil texture or the changes in and release of nutrients to the soil solution (Sánchez, 2001). In the correlation matrix for the 7 nutrients considered in needles, the only good correlations were between Ca and the contents of K and N, with Pearson's correlation coefficients of 0.451** and 0.418** respectively.

The relationships between the concentrations of nutrients in needles and the soil chemical variables are shown in Table 4. The positive correlations between the levels of foliar P and the available P in the soil and the ECEC suggest that an extra input of this element would improve the development of radiata pine, although other factors such as pH, availability of P at depth, mycorrhizal activity and high levels of N may also affect absorption of this element by plants. Despite this, foliar levels of P can by satisfactorily predicted from the concentration of available P in the soil, as has been pointed out in previous studies (Hunter and Gibson, 1984; Louw, 1991), even when the lowest foliar concentrations coincide with low levels of available P in strongly acidic soils. The pH of the soils in the study area was around 4 influencing in the ECEC, whereas Hunter and Gibson (1984) reported an optimum soil pH of 6 for radiata pine. Zas (2003) observed a good correlation between foliar P and soil pH in a nutritional study of radiata pine in Galicia, indicating that under acidic conditions, P assimilation increased with increasing pH that in turn increases the cation exchange capacity. Similar relationships between foliar P, pH and the variables describing the mineral soil fertility such as ECEC were found in intensively managed radiata pine plantation of Australia (Saunder *et al*., 1984). The negative correlations between the concentration of Ca in needles and both the organic matter content of the soil and the C/N ratio suggest that accumulation of humus in the surface layers of acid soils, as a result of slow mineralization, largely due to the formation of stable complexes with Fe and Al sesquioxides (González-Prieto *et al*., 1996), suppresses uptake, resulting in lower foliar concentrations of nutrients, in particular a decrease in the Ca content in needles. Similar results were found in Galicia, where the decrease in the foliar concentration of Ca was attributed to the decline of mature stands of radiata pine (Sánchez, 2001).

Table 4. Pearson's correlation coefficients for nutrient concentrations in soil and needles

	Foliar concentration			
	P	**Ca**	**Mg**	**Fe**
Organic matter		– 0.394*		
C/N		– 0.422**	0.414**	
Extractable P	0.329*			
Extractable K				0.342*
ECEC	0.344**			

* Significant at $P < 0.005$. ** Significant at $P < 0.01$. *** Significant at $P < 0.001$.

Principal component analysis revealed the relationships between edaphic variables (and slope), and their importance in explaining the variability in the data, as well as contingent clusters of observations. The analysis provided six principal components (only eigenvalues >1), which accounted for 71 % of the total variance (the corresponding eigenvalues are shown in Table 5). It was not possible to separate the stands on the basis of any properties affected by soil parent material, with

Table 5. Component coefficients for the six principal component functions

	Y1	Y2	Y3	Y4	Y5	Y6
Soil depth	0.100	–0.095	–0.130	0.905	–0.015	0.105
Slope	0.006	0.054	–0.024	0.060	–0.035	0.937
Clay	0.606	0.111	0.062	0.059	0.572	–0.325
pH	–0.069	–0.096	–0.128	0.043	0.863	0.030
Organic Matter	0.293	0.854	0.032	–0.199	–0.040	–0.001
Total N	0.504	0.116	0.596	–0.272	–0.220	0.249
C/N	–0.212	0.664	–0.575	0.141	0.132	–0.221
Extractable P	0.312	0.063	–0.100	–0.638	–0.484	0.075
Extractable K	0.150	0.100	0.829	0.024	0.003	–0.155
Extractable Ca	–0.125	0.685	0.398	0.002	–0.177	0.212
Extractable Mg	0.658	0.201	0.084	0.417	–0.210	–0.311
Extractable Al	0.959	–0.059	0.083	–0.080	–0.006	0.055
ECEC	0.937	0.034	0.232	–0.045	–0.032	0.071

the first and the second principal components (Fig. 2), possibly due to a similarity in the properties of the soils developed on different lithologies. In contrast, Sánchez *et al*. (2002) have used the principal component analysis for another set of radiata pine classified according to soil parent material in northwest Spain and found clear separation of the stands according to soil texture and exchangeable Ca and Mg influenced by soil parent material.

The Pearson's correlation coefficients for SI, levels of nutrients in needles and edaphic variables, grouped according to parent material are shown in Table 6. The concentration of P in needles and the content of exchangeable K in the soil are the variables that best explain the site quality for all plots. The negative correlation between SI and foliar N in plots developed on sandstone reflect an indirect effect. The plantations with the highest foliar N concentrations were on soils with limited drainage and larger accumulation of soil organic matter, which suggests that reduced aeration would limit the root growth, coinciding with a higher N availability in the soil (Sánchez *et al*., 2002). A

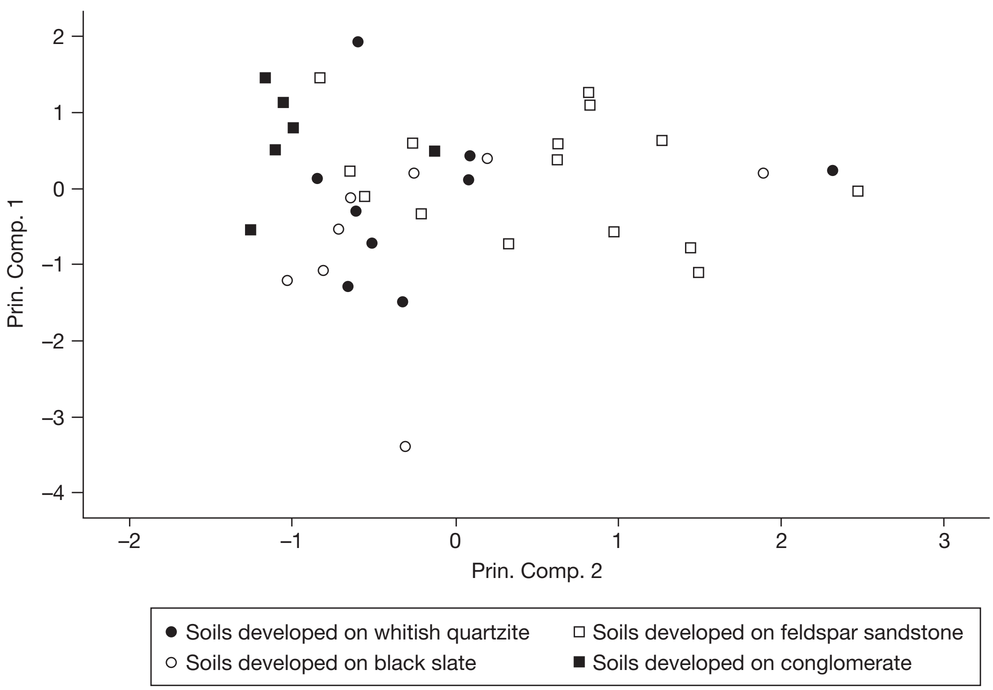

Figure 2. Principal component analysis. The soils wee classified according to soil parent material.

Table 6. Pearson's correlation coefficients for soil properties, nutrient concentrations in needles and SI[a]

	All stands stands	Quartzite	Sand-stone	Conglo-merate
Slope		– 0.673*		
Extractable K	0.366*		0.717*	
ECEC			0.554*	
Foliar N			– 0.712**	
Foliar P	0.404*		0.588*	
Foliar Fe	0.330*			
Foliar B				– 0.919**

[a] Stands were separated on the basis of soil parent material. [b] Significant at $P < 0.005$. ** Significant at $P < 0.01$. *** Significant at $P < 0.001$.

negative relationship between N and SI has also been observed by Romanyà and Vallejo (2000) in radiata pine plantations in other regions in northern Spain. The predominance of ammonium following mineralization of the organic matter may also cause a decrease in the absorption of some cations (González-Prieto *et al.*, 1996), especially Ca. Moreover, the high negative correlation between foliar B and SI in plots developed on conglomerate may indicate an indirect effect of the relationship between B and other metals, such as Fe and Al. In the plots developed on quartzite, the negative correlation between the SI and slope may be explained by intensive surface runoff and more rapid soil water movement down slope, leading to clogs sites. The reduction in the water availability on steep slopes negatively affects site quality for radiata pine. Sánchez *et al.* (2002) obtained similar results in Galician soils developed on granite, indicating that lateral leaching which removes nutrients from the soil is more extensive on steep slopes. On the other hand, many of the plantations in the study (75%) are growing in soils less than 40 cm deep located on steep slopes. Jackson and Gifford (1974) found the highest productivity of radiata pine in soils of depths between 60 and 80 cm and were attributed to the volume of soil available for root exploration and the availability of water and nutrients (Turvey *et al.*, 1986; Louw, 1991).

Multiple linear regression models did not provide an effective explanation of the variance in SI in terms of the concentrations of nutrients in needles and soil. Much of the data obtained corresponded to plots in which the effective soil depth was low, and therefore soil moisture and other ecological factors may be involved in the variation in productivity. Other multiple regression models obtained in northwest Spain for SI by considering soil properties and foliar nutrient concentrations has found that the SI was influenced by total soil N, soil depth and soil pH. With respect to foliar nutrient concentrations, N, P and Mg had the greatest influence on productivity (Sánchez *et al.*, 2002).

According to the present data, the establishment of highly productive stands of this species should be confined to sites with specific soil characteristics. Other studies in northern Spain have shown that radiata pine productivity decreases with elevation (Gandullo *et al.*, 1974; Romanyà and Vallejo, 2004). In this study, centred in one homogeneous area, no relationship was found between radiata pine productivity and altitude. This may be because of the very small variation in altitude (most were between 400 and 600 m) among the different plantations studied. Although the water demand of radiata pine is high (as high as that of broadleaved forests; Gholz *et al.*, 1990), its productivity appears to be highly dependent on soil quality. This may be so as radiata pine is also a high nutrient demanding species, suggesting that the management of soil fertility may improve the yield. Soil fertility and water supply management may improve site quality in the studied climatic area, where the greatest improvements are to be expected at lower slopes associated with the deeper soils and lower elevations, where the mean annual temperature is higher. In this context, climate change may improve growth conditions for radiata pine in this area, even with the expected moderate decrease in mean annual precipitation. The climate scenario predicted for Asturias over the next 30 years (2011-2040) shown in the worst cases a reduction in average annual rainfall of less than 10% (Anadón and Roqueñí, 2009).

Conclusions

Stands of radiata pine in Asturias (NW Spain) display important nutritional problems that appear to limit growth. These plantations show widespread deficiencies in K and P, but not in N, and the foliar N:P ratio indicates an imbalance between the excess of N and P nutrition, causing reduced productivity. The P nutrition appears to play an important role in the development of radiata pine. In addition, foliar levels of P can by predicted from the concentration of available P in the soil. The plantations studied displayed only slight deficiencies of Mg. Radiata pine site quality is mainly modulated by a soil fertility parameter such as exchangeable K, and the management of soil fertility may improve the yield. The reduction in growth on steep slopes suggests that such topographic features should be avoided for this species.

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