Foliar nutrient status and nutritional relationships of young Pinus radiata D. Don plantations in northwest Spain

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Abstract

Fifty-four plots of young *Pinus radiata* D. Don plantations on abandoned agricultural land in Galicia (northwest Spain) were selected for nutritional diagnosis. Nutritional status was assessed by foliar analysis using the critical levels method. The relationships between foliar nutrient concentrations and the plantation's growth and survival and the topsoil physical and chemical properties were also analyzed. The most common deficiencies among plots were P and Mg. Foliar N concentrations were relatively high and generally they were above the critical level. Foliar N:P, N:K and N:Mg ratios were significantly unbalanced in 31, 44 and 17 out of 54 studied plots. Foliar P levels were significantly higher on sites with previous herbaceous land use and on soils with a finer texture, whereas foliar Mg levels were higher at low altitudes. Foliar nutrient levels were not significantly correlated with their respective soil levels except in the case of K. Foliar Ca and Mg concentrations correlated positively with topsoil pH. Growth correlated positively with foliar K and Mg concentrations and negatively with foliar N:P, N:K and N:Mg ratios. Percentage of dead and poor state plants were negatively correlated with foliar P, K and Ca levels and positively correlated with foliar N:P and N:Mg ratios. These results suggested that nitrogen may be in excess and may condition the uptake of other nutrients. Foliar N level was considered as an unfavorable parameter whereas foliar P, K, Ca and Mg concentrations were considered as favorable parameters for *P. radiata* establishment in Galicia.

Key words

Nutritional status, Soil analysis, Foliar analysis, Deficiency diagnosis, *Pinus radiata*

Introduction

Pinus radiata D Don. is the most important exotic conifer planted in Spain, where the total surface area is approximately 270.000 ha, distributed mainly in the Basque Country (northeast Spain). The surface area planted with this species in Galicia (northwest Spain) is around 60.000 ha (Dans et al., 1999). Regulation EEC No. 2080/92 is an accompaniment measure of the Community Agricultural Policy (CAP) reform that instituted a European aid scheme to promote afforestation as an alternative use of agricultural land. The application of this Regulation has led to a noteworthy increase of the radiata pine forest area in Galicia. The area planted with this species in Galicia during the first five years of the application of this Regulation was over 10.000 ha (Xunta de Galicia, unpublished data). These plantations were installed on agricultural land with a wide ranging degree of abandonment. Some sites had just been cultivated the previous year whereas in others agricultural use had been abandoned several decades before.

Pinus radiata nutritional problems are widespread in Australia and New Zealand where this species covers more than 2 Mha, and fertilizers are a major factor contributing to high growth rates (Stone, 1982; Turner and Lambert, 1986). There are several techniques for managing fertility and optimizing the response to fertilization treatments. The most commonly used is foliar analysis followed by the critical levels method (Lambert et al., 1984; Bonneau, 1988). This technique compares foliar concentrations with critical levels defined as the concentration at which the species produces 90% of its maximum (Needham et al., 1990). Soil analysis may also be used as an aid for evaluating forest nutritional status. However, the interpretations of the many methods for determining soil nutrient availability and its relationship to tree nutrient status have been met with limited success (Ballard et al., 1971). Therefore, no attempt is made to offer an explicit listing of critical and/or optimum soil nutrient levels. Thus, soil analysis may be of less value than foliar analysis for diagnosing the existence and severity of a nutritional problem. However, the use of soil analysis may be an interesting practice to correct a nutrient deficiency detected previously by foliar analysis (Ballard and Carter, 1986).

Despite the prevalence of P. radiata in Spain, no fertilization plans have been developed to date. However, previous studies have detected important nutritional disorders in radiata pine plantations in northeast Spain. Phosphorus and magnesium deficiencies were the most common (Mesanza et al., 1993; Romanya and Vallejo, 1996). Therefore, important benefits can be expected through adequate fertilization treatments. Galician soils are typically coarse-textured, acidic, with high levels of organic matter and low nutrient levels (Macias et al., 1982). Comparing with northeast Spain, nutritional problems in Galicia can be expected to be much more severe.

The aim of this work is to evaluate the nutritional status of young Pinus radiata plantations in Galicia. In addition, nutritional status was related to soil and physiographical parameters and plantation growth and survival with the aim to study the factors that may contribute to the nutritional disorders found.

Material and methods

Fifty-four sample plots were selected from reforestations made on marginal agricultural land during the application of the EEC 2080/92 regulation within the CAP reformation in 1995 and 1996. In these selected plantations one rectangular sample plot of 50 forested plants was established. Sample plot size was variable depending on the plantation density, with a minimum area of 300 m^2. Plots were sampled between April and December 1997 when plantations were around 1-1.5 years old.

On each site topographic position, altitude and slope were determined. The previous land use of each plantation was determined in relation to the vegetation community at the time of planting. Four types of previous land use were considered: herbaceous (H), herbaceous with shrubs invasion (HS), shrubs (S) and shrubs with tree natural regeneration (ST). These four classes can be interpreted as an index of the time passed since agricultural use was abandoned. The parent material of each site was also determined. Five different substrate groups were considered (Macias et al., 1982): granites (Gr), schists (Sc), slates (Sl), sedimentary rocks (Sed) and basic and ultrabasic rocks (B).

In each plot 5 superficial soil samples (upper 20 cm, 8 cm diameter) were collected in the 4 corners and center of the plot. These samples were mixed, homogenized and considered as a composite sample per plot. Soil samples were air-dried and sieved with a 2 mm screen before analysis. These composite samples were analyzed for total Kjeldahl nitrogen (Benton et al., 1991), available Bray-II phosphorus (Bray and Kurtz, 1945), exchangeable K, Ca and Mg, pH and organic matter. Exchangeable cations were extracted with ammonium acetate 1N and analyzed by atomic absorption spectophotometry (Benton et al., 1991). The pH was measured in distilled water (1:2.5 dw soil:vol). The organic carbon was determined by the Walkley and Black (1934) method; organic matter was read as C and then multiplied by 1.72 (Douchaufour, 1987). Sand, silt and clay percentage were determined using the pipette method (Piper, 1950) and texture classification was obtained using the U.S.D.A. (1951) texture categories in five classes. Average soil depth for each plot was obtained from depth measurements with a helicoidal-bore in the same five points where soil samples were taken.

One-year-old foliar samples were collected from ten plants (20% of the total number of plants) in each plot following Ballard and Carter (1986). All samples were bulked to obtain one sample of green needles per plot. Samples were lyophilised, ground and digested at 400 ºC with concentrated HNO_3 and $HClO_4$. Ca, Mg, Fe, Cu, Zn and Mn were determined by atomic absorption spectophotometry and K by emission spectophotometry (Perkin Elmer Spectophotometer). N was analyzed by the Kjeldalh method (Benton et al., 1991) and P was evaluated by Bray-II colorimeter method (Bray and Kurtz, 1945) (UV-VIS Beckman). The plot variation in foliar nutrient concentration was determined in three random plots. The coefficient of variation, calculated through three composites samples of four plant each per plot, averaged 3.6, 12.3, 12.5, 15.6 and 14.8 for N, P, K, Ca and Mg respectively.

Total height and basal diameter were measured in all plants of each plot. The percentage of dead and poor state plants (clorosis or defoliation symptoms) was determined.

The plantation's nutritional status was evaluated using the foliar critical levels reported by Will (1985). This author recommend sampling in early autumn when nutrient concentrations are relatively stable and maximum stress is produced. We sampled between April and December but, as Will (1985) indicated, severe nutrient deficiencies can usually be recognized in samples taken at any time of the year. Foliar concentration ratios were also used to determine the balance between nutrients. A foliar N/P ratio above 10 and above 16 was interpreted as a marginal or critical excess of N relative to foliar P concentration. A foliar N/P ratio below 12.5 indicated an optimal P nutrition (Raupach et al., 1969). In the same way, a foliar K/N ratio below 0.65 and 0.5 was considered to be related with marginal and critical K nutrition respectively (Ingestad, 1979) and a foliar N/Mg ratio above 17.5 indicated critical Mg nutrition in relation to nitrogen nutrition (Bonneau, 1988). In addition, foliar K/Ca ratios were calculated as a measure of cation balance. A foliar K/Ca ratio below 0.5 was related with problems in the K nutrition (Ballard and Carter, 1986).

Relationships between foliar nutrient concentration, soil levels and plantation growth and survival were studied by correlation analysis. Percentage variables were transformed previously by angular transformation (Sabin and Stafford, 1993). Significant differences between substrates, previous land use and topsoil texture classification were tested by analysis of variance and LSD means comparison test. Principal component analysis was also carried out to classify foliar, growth and survival parameters. All analyses were carried out using the SAS statistical package (SAS, 1989).

Results and discussion

Survival and growth

The frequency distribution of the percentage of dead and poor state plants in the 54 studied plots is presented in Fig. 1. Most of the plots showed low values of these parameters. However, percentage of dead plants rises to more than 40% in 3 cases, and percentage of poor state plants was over 40% in nearly 20% of the cases. These values are much more higher than those expected for the study area, a favorable region for P. radiata introduction (Dans et al., 1999).

Height and diameter growth was very variable among the studied plots. Mean height of the 54 plots averaged 84.5 cm, ranging from 21.3 to 193.3 cm. Mean diameter averaged 16.7 mm, ranging from 4.6 to 42.1 mm. Both variables were significantly correlated ($r^2 = 0.84$; $p \leq 0.001$).

Foliar nutrient diagnosis

The results obtained in the analyses of the foliar samples are summarized in Table 1. Mean P and Mg foliar nutrient concentrations are below the marginal level reported by Will (1985). The variation between plots is quite high for all nutrients especially for Ca and Mn. The least variable nutrient is nitrogen.

On the basis of critical levels (Will, 1985) we observed that more than 80% of the plantations studied showed a severe deficiency. The most common deficiency was P and Mg (Fig. 2). Forty-one and 25 out of the 54 plots studied showed critical P and Mg foliar levels. We also observed critical Ca, K and N foliar concentrations in 10, 2 and 2 cases respectively.

Phosphorus deficiencies are the most widespread in P. radiata plantations around the world (Turner and Lambert, 1986). Several authors have also found P disorders in the Spanish P.

radiata plantations (Mesanza et al., 1993; Romanya and Vallejo, 1996). As it was reported by Mesanza et al. (1993), we observed a premature fall of the 2-yr-old needles and an abnormally short needle length in many plots, symptoms associated with P deficiencies (Will, 1985; Hunter et al., 1991). It must be noted that P deficiencies are more frequent in 6-15-yr-old trees, that is, at the time of greatest nutrient demand (Turner and Lambert, 1986). The low foliar P levels observed in our younger studied plots lead us to expect an increase in P disorders as the plantations get older. P deficiencies have been associated with acidic and sandy soils with low water retention capacity, especially on soil derived from deposited sands, volcanics and sandstones (Turner and Lambert, 1986). No significant differences in P foliar concentrations between different parent material were observed but P foliar levels were greatly influenced by the previous land use (Fig. 4a) and the superficial horizon texture (Fig. 4b). The more recently agricultural land use was abandoned with herbaceous vegetation still being dominant, the higher the pine's foliar P levels. The longer the agricultural abandonment, either shrub or tree vegetation colonized the soil and the pines showed lower P foliar levels. Furthermore, the foliar P concentrations were lower as the superficial horizon texture became coarser. Thus, special attention must be paid to P nutrition on coarse-textured soils with heavy shrub vegetation.

Magnesium deficiencies were also very common (Fig. 2) and more frequent than in other older P. radiata nutritional studies in Spain (Mesanza et al., 1993; Romanya and Vallejo, 1996), possibly due to stand age difference. Turner and Lambert (1986) indicated that Mg disorders in Pinus radiata are more frequent in 3-6-yr old stands. As Mesanza et al. (1993) found in the Basque Country (northeast Spain), Mg foliar concentration was negatively correlated with altitude ($r = -0.29$, $p<0.05$). Furthermore, the Mg soil levels were positively correlated with soil pH ($r = 0.48$, $p<0.001$) and with soil silt percentage ($r = 0.24$, $p<0.05$). So, special attention must be paid to Mg nutrition on mountain sites with acidic and coarse-textured soils. Magnesium nutrition in P. radiata is receiving increasing attention in New Zealand forestry (Payn et al., 1995). Magnesium is a critical component in the carbon fixation and transformation processes in the tree. It has been reported that, contrary to what occurs with N and P deficiencies, the lack of Mg can lead to a decrease in the root:shoot ratio (Ericsson and Kahr, 1995; Payn et al., 1995). Consequently, the tree's root system may be smaller allowing less nutrient uptake by the tree and the decrease in carbon allocation to the roots may provide less substrate for the mycorrhizal symbiosis, which is so important in pines (Payn et al., 1995). Because of this, the Mg deficiencies found in the one-year old plantations studied here prove to be much more dramatic and may condition the tree establishment.

Nitrogen foliar concentrations were over the critical levels in most cases (Fig. 2). Nitrogen deficiencies are not frequent in P. radiata stands (Stone, 1982; Hunter et al., 1991). Problems associated with high N are more common (Turner and Lambert, 1986). High N levels in the foliage of field-grown trees increased both number and size of lateral shoots, and the trees with lower nitrogen had much better stem form (Turner and Lambert, 1986). Some authors have indicated that in many cases it may be desirable to maintain lower N levels in trees in young stands (Will, 1971; Knight, 1973). The excess of N may also impede the uptake of other nutrients as P, K and Mg (Lambert and Turner, 1978; Mohren et al., 1986; Binggeli et al., 2000). These problems are frequent in young stands on improved pasture sites where soils have been stripped for exchangeable base cations through acidification reactions (Birk, 1992).

The diagnosis of the studied plantations through the N:P, N:K and N:Mg foliar ratios balance is summarized in Fig. 3. Thirty-one, 44 and 17 out of 54 plots studied showed a strong N:P, N:K and N:Mg imbalance respectively, indicating a clear excess of N in relation to the P, K and Mg nutrition in most of the studied plots. Organic amendment was and still is a widespread practice in Galician agricultural soils (Sánchez, 1995) that could increase the nitrogen soil up to excess levels for pine establishment. We have also observed a relative excess of nitrogen in another study on young Pseudotsuga menziesii plantations in Galicia (Zas and Serrada, submitted). Several authors have found a negative correlation between soil N levels and the site quality index for P. radiata in north-east Spain (Romanya and Vallejo, 2000), Galicia (Sánchez et al., 2000) and north Spain (Gandullo et al., 1974).

As in other nutritional studies in Spain, foliar K levels were satisfactory in most cases (Romanya and Vallejo, 1996; Mesanza et al., 1993). K was the only element where foliar levels were significantly correlated with the superficial soil levels ($r=0.46$, $p<0.01$). As we observed here, Ballard et al. (1971) did not find a significant correlation between foliar Ca and Mg and exchangeable Ca and Mg in the top soil in New Zealand. Merino and Edeso (1999) neither found significant correlation between the foliage contents of K, Ca and Mg and their respective contents in the soil.

We also observed Ca deficiencies in 10 cases. Foliar Ca concentrations were greatly influenced by the parent material (Fig. 5a), as Romanya and Vallejo (1996) observed in north-east Spain. In addition, foliar Ca levels were positively correlated with soil pH ($r = 0.40$, $p<0.01$) and topsoil silt percentage ($r = -0.34$, $p<0.05$) and negatively correlated with sand topsoil percentage ($r = 0.37$, $p<0.05$). The effect of the topsoil texture on the foliar Ca concentrations is presented in Fig. 4b. The most important Ca disorder can be expected to appear on acid and coarse-textured soils on granite rocks. In other countries, Ca deficiencies have been found in specific locations, generally in older stands (> 15 years) on soils derived from acid volcanics or sandstone parent materials (Birk, 1994). Ca deficiency often develops in areas of P deficiency, and hence these deficiencies are corrected simultaneously with superphosphate applications (Will, 1985; Turner and Lambert, 1986). All the plantations studied where foliar Ca was critical showed also critical P levels except in two cases where P was marginal. The application of superphosphate in these plantations seems to be an interesting practice.

Micronutrient levels were over the critical levels in most cases (Fig. 2). One and 3 out of 54 plots showed critical foliar levels for Fe and Zn respectively.

Correlation and principal component analysis

The correlation coefficients between foliar nutrient concentration, percentage of dead and poor state plants and mean total height and basal diameter are shown in Table 2. As Mesanza et al. (1993) found in the Basque Country, all significant correlations between foliar nutrients were positive. Despite the apparent nitrogen excess indicated by the great foliar imbalance N:P, N:K and N:Mg (Fig. 3), foliar P and K levels were positively correlated with foliar N levels. It seems that the N uptake increases as the P and K availability does. Mesanza et al. (1993) found similar results for 1-yr-old needles but no for current-year needles. Some other works showed negative correlations between foliar nutrients, especially for K, Ca and Mg (Ballard et al., 1971). P-Ca and Ca-Mg correlations are especially noteworthy, as already observed by Turner and Lambert (1986) and Mesanza et al. (1993).

The percentage of dead and poor state plants correlated negatively with mean height and diameter indicating that the plantations with better survival showed the highest growth. The higher foliar P and Ca levels, the lower percentage of dead plants was observed, and the higher foliar K concentrations, the lower was the percentage of poor state plants found. Foliar K and Ca levels were positively correlated with plantation growth. Furthermore, N:P, N:K and N:Mg foliar ratios were negatively correlated with growth, N:P ratio was positively correlated with percentage of dead plants and the N:Mg ratio was positively correlated with percentage of poor state plants. These results suggest that foliar P, K, Ca and Mg appear as favorable parameters for the establishment of Pinus radiata in Galicia and the excess of N, that generated a great nutritional imbalance, appears as an unfavorable parameter.

The results of the principal components analysis (PCA) were consistent with this assumption (Fig. 6). The first principal component (eigenvalue = 3.93, percentage of variance explanation = 33 %) can be interpreted as an evaluation of the plantations results. The height and diameter growth are situated at the positive end of this axis while the percentage of dead and poor state plants are situated at the negative end. The foliar P, K, Ca and Mg levels appear at the positive side of this first component whereas the N:P, N:K and N:Mg foliar ratios and N foliar concentrations appears on the left hand side of the graph. The favorable parameters appear at high levels of this axis and unfavorable parameters appear at low levels. These results are almost the same as those found by Mesanza et al. (1993) in older Pinus radiata plantations in northeast Spain.

The correlation coefficients between the physical and topsoil parameters and the values of the first principal component are shown in Table 3. The first component is positively correlated with topsoil pH, percentage of silt and exchangeable K, and negatively correlated with altitude. As this first axis represents an evaluation of the plantations favorable results, it can be concluded that the best establishment results for Pinus radiata in Galicia were found at low altitudes on loamy soils with high levels of exchangeable K and pH. In other studies, Pinus radiata quality site is often correlated with parameters that regulate the water disposability. The soil water capacity (Zwolinski et al., 1998), the soil depth and effective soil depth (f.e. Turvey et al., 1986), the soil texture, drainage and permeability (f.e. Gerding and Schlatter, 1995), and the annual precipitation (f.e. Grey and Taylor, 1983) have been shown to be related to Pinus radiata growth. The correlation found here between the first principal component and the topsoil sand and silt percentage indicate the importance of soil water retention disposability for the establishment of P. radiata in Galicia. Soil nutrient availability had also been related to P. radiata quality sites, especially in those regions where soil fertility is generally low. P and Ca are the nutrients most often positively correlated with pine growth

(Ballard, 1971; Truman et al., 1983; Hunter and Gibson, 1984; Turner and Lambert, 1987; Zwolinski et al., 1998). We did not observe significant correlations between the soil levels of these nutrients and the first principal component. However, it must be noted that foliar P and Ca concentrations were negatively correlated with the percentage of dead plants, indicating the importance of these nutrients in the establishment of Pinus radiata in Galicia. Nevertheless, the exchangeable K levels were correlated with both the first principal component and growth and survival. K was the only element where foliar levels were significantly correlated with the superficial soil levels. All P, K, Ca and Mg nutrients seem to be essential in pine establishment in Galicia, however only the soil K levels have a direct influence on the establishment result. The uptake of P, Ca and Mg seems to be influenced by other factors rather than the respective soil nutrient levels. The nitrogen excess could be one of these factors.

Conclusions

The most common deficiencies in the studied plantations were P and Mg. Foliar N levels were high and possibly excessive as N:P, N:K and N:Mg foliar ratios were greatly unbalanced in most of the studied plots.

Foliar P, K, Ca and Mg levels appeared to be related to the better growth and survival of pines and were considered as favorable parameters for Pinus radiata establishment in Galicia. On the contrary, foliar N was considered as an unfavorable parameter. High values of this parameter were related to low rates of tree growth, low survival and nutritional imbalance. Nitrogen establishment fertilization is then a practice not to be recommended in Galicia Pinus radiata plantations, especially on low pH, coarse-textured soils with low soil K levels and in high altitudes.

The best establishment results (highest growth and survival) were found at low altitudes, on loamy-textured soils with high pH and high levels of exchangeable potassium and when previous agricultural land use was abandoned recently.

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Table 1. Mean and coefficient of variation of the foliar nutrient levels in the 54 Pinus radiata plots.

Foliar nutrient	MEAN	CV
N ($g \cdot kg^{-1}$)	16,9	19,4
P ($g \cdot kg^{-1}$)	1,1	47,0
K ($g \cdot kg^{-1}$)	6,2	40,3
Ca ($g \cdot kg^{-1}$)	2,1	81,5
Mg ($g \cdot kg^{-1}$)	0,8	50,6
Fe ($mg \cdot kg^{-1}$)	71,3	39,8
Cu ($mg \cdot kg^{-1}$)	8,4	40,4
Zn ($mg \cdot kg^{-1}$)	30,1	47,9
Mn ($mg \cdot kg^{-1}$)	189,2	80,3

Table 2. Pearson correlation coefficients significant at $p<0.05$ between foliar nutrient concentrations, percentage of dead and poor state plants and mean height and diameter in each plot.

	Foliar nutrients								Plantation results			
	N	P	K	Ca	Mg	N:P	N:K	N:Mg	% dead	% poor state	H	D
N	1.00	0.27	0.28			0.37		0.57				
P		1.00		0.75	0.55	-0.63			-0.32			
K			1.00				-0.81			-0.35	0.35	0.30
Ca				1.00	0.69	-0.45		-0.33	-0.29			
Mg					1.00	-0.46		-0.66			0.28	
N:P						1.00		0.56	0.32		-0.28	-0.29
N:K							1.00			0.40	-0.36	-0.38
N:Mg								1.00			-0.28	-0.28
% dead									1.00	0.35	-0.33	-0.35
% poor state										1.00	-0.34	-0.37
Heigth											1.00	0.91
Diameter												1.00

Table 3. Pearson correlation coefficients and significant levels between physical and topsoil parameters and the first principal component of the ACP. **, $p<0.01$; *, $p<0.05$. Only significantly parameters are presented.

Source	r	P<F
Altitude	-0.42	**
Sand	-0.42	**
Silt	0.41	**
pH	0.33	*
Exchangeable K	0.32	*

Fig. 1. Frequency histogram of the percentage of dead plants and poor state plants among the 54 studied plots.

Fig. 2. Percentage of sampled plots in relation to foliar diagnosis by the critical levels method (Will, 1985).

Fig. 3. Percentage of P. radiata plots in relation to foliar concentration balance.

Fig. 4. Mean and standard error of P foliar concentration in the P. radiata studied plots grouped by (a) the previous land use and (b) the superficial horizon texture. Previous land use: H, herbaceous; HS, Herbaceous with shrub invasion; S, Shrub; ST, Shrub with natural tree regeneration. Superficial horizon texture (USDA, 1951): MF, moderately fine-texture; Med, medium texture; MC, moderately coarse texture; C, coarse texture. Different letters denote LSD significant differences between groups at $p<0.05$ level. Dotted horizontal lines show critical and marginal P levels (Will, 1985).

Fig. 5. Mean and standard error of foliar Ca concentrations in the P. radiata studied plots groupe by (a) different parent materials and (b) topsoil texture. Dotted horizontal line show critical level for P. radiata (Will, 1985). Different letters denote LSD significant differences among substrates ($p<0.05$). B, basic rocks; Sc, schist; Gr, granite; Sl, slate; Se, sediments. Topsoil texture: See explanation in Fig. 4(b).

Fig. 6. Distribution of foliar N, P, K, Ca and Mg concentrations, foliar N:P, N:K and N:Mg ratios and plantation results (percentage of dead (%Dead) and poor (%Poor) state plants and height (H) and diameter (D) growth) trough the two principal components of the PCA.