Invest. Agrar.: Sist. Recur. For. (2003) 12 (1), 75-85

Foliar nutrient status and tree growth response of young *Pseudotsuga menziesii* Mirb. (Franco) to nitrogen, phosphorus and potassium fertilization in Galicia (Northwest Spain)

R. Zas*

Lourizán Forestry Research Center. Forest Production Department. Apdo. 127. 36080 Pontevedra. Spain

Abstract

The nutritional status of 14 young *Pseudotsuga menziesii* plantations on abandoned agricultural land in Galicia (Northwest Spain) was studied and related to growth response to N, P and K fertilization. Nutritional status was assessed using macronutrient foliar analysis followed by the critical levels method and foliar nutrient ratios interpretation. Douglas fir showed high N levels in control foliage samples. Foliar N:P and N:K ratios were greatly unbalanced in many sites. Foliar Mg concentrations were below the satisfactory levels in all cases and P, K and Ca were deficient in several cases. Height growth of untreated plants correlated positively with foliar P, K and Ca concentrations and negatively with total soil N in the surface soil. Thus, P, K and Ca were classified as favorable parameters for Douglas fir growth, whereas N was classified as an unfavorable parameter. According to this, the application of urea significantly reduced the Douglas fir growth in several trials. However, there was a lack of consistence between the foliar diagnosis and the growth response to superphosphate and potassium sulphate applications at the end of the first growing season following fertilization. This response was much lower than expected after the foliar diagnosis. The low fertilization rates used, the short time passed between fertilization and response measurements or other factors such as Mg nutrition and other nutrient interactions, could be the cause. In conclusion, N fertilization is not recommended in young *P. menziesii* plantations on abandoned agricultural land in Galicia whereas further research is needed to generate a fertilization recommendation for the other nutrients.

Keywords: *Pseudotsuga menziesii,* fertilization, foliar analysis, deficiency diagnosis, Galicia, Spain.

Resumen

Estado nutricional y respuesta en crecimiento a la fertilización con nitrógeno, fósforo y potasio en plantaciones jóvenes de *Pseudotsuga menziesii* Mirb. (Franco) en Galicia

Se estudió el estado nutricional de 14 plantaciones jóvenes de *Pseudotsuga menziesii* en tierras agrarias en Galicia y se relacionó éste con la respuesta en crecimiento a la fertilización con N, P y K. El estado nutricional se evaluó mediante analítica foliar aplicando el método de los niveles críticos e interpretando las relaciones entre pares de nutrientes. Los niveles foliares de N en las plantas control fueron muy altos y las relaciones N:P y N:K resultaron altamente descompensadas en la mayoría de las parcelas. Las concentraciones foliares de Mg fueron inferiores a los niveles satisfactorios en todos los casos, mientras que las de P, K y Ca resultaron deficientes sólo en determinadas ocasiones. El crecimiento en altura de las plantas control se correlacionó positivamente con los niveles foliares de P, K y Ca y negativamente con el N total del horizonte superficial del suelo. De esta manera, se consideró al P, K y Ca como parámetros favorables para el crecimiento del abeto Douglas y al N como parámetro desfavorable. Concordando con esto, la aplicación de urea provocó una disminución significativa del crecimiento en varios ensayos. Sin embargo, la respuesta a la fertilización con superfosfato y sulfato potásico no resultó congruente con el diagnóstico foliar previo, siendo esta respuesta mucho menor de la esperada. Las bajas dosis de fertilizantes, el escaso tiempo transcurrido entre la fertilización y la evaluación de la respuesta u otros factores como la nutrición en Mg y otras interacciones entre nutrientes podrían ser la causa. En conclusión, la fertilización nitrogenada no es una práctica recomendable en las plantaciones jóvenes de *P. menziesii* en tierras agrarias abandonadas en Galicia. Es necesario profundizar más en la investigación para poder ofrecer unas recomendaciones prácticas respecto a la fertilización con el resto de elementos.

Palabras claves: *Pseudotsuga menziesii*, fertilización, análisis foliar, diagnóstico de deficiencias, Galicia.

* Corresponding author: rzas@sfp.cifl.cesga.es
Received: 08-02-02; Accepted: 27-09-02.

Introduction

Pseudotsuga menziesii (Mirb.) Franco plantations cover approximately 30,000 ha in Spain, distributed mainly in the Basque Country (Vega *et al.*, 1998). In Galicia, *Pseudotsuga menziesii* is not a widespread species but, in the last five years, the European Program for afforestation of agricultural land has increased notably the area planted with this species. Douglas fir has become the fourth most important species planted in Galicia under the application of the Regulation EU 2080/92 which institutes an European aid scheme to promote afforestation as an alternative use of agricultural land. In fact, the Galicia Forest Plan has recommended the plantation of this species in more than 70,000 ha (Xunta de Galicia, 1992).

In a previous study we found important nutritional disorders in *P. menziesii* plantations on abandoned agricultural land in Galicia (Zas and Serrada, submitted). In that study, N appeared as an excessive nutrient that may thwart the uptake of other nutrients such P and K. These nutrients were diagnosed as deficient elements in most of the plantations studied. Two different diagnostic methods were used: the critical levels method (Lambert *et al.*, 1984) and the DRIS system (Diagnosis and Recommendation Integrated System). The DRIS system, proposed by Beaufils (1973) for agricultural crops, has become an alternative to the critical levels method for forest nutrition management and fertilization research (Truman and Lambert, 1980; Svenson and Kimberley, 1988; Shumway and Chappell, 1995; Romanya and Vallejo, 1996; Wadt *et al.*, 1998; Zas, in press). Conceptually, DRIS differs from other methods for interpreting nutrient status in its focus on nutrient ratios and balance rather than critical concentrations (Needham *et al.*, 1990).

In Zas and Serrada (submitted) report, it was observed that the DRIS system applied to soil nutrient data (Shumway and Chappell, 1995) and the critical level method applied to foliar nutrient data (Ballard and Carter, 1986) agreed in the N and P diagnosis but not in the diagnosis of Ca and K. There was a lack of consistence between both diagnostic methods. Some authors have remarked that DRIS norms and critical levels can vary among geographical regions, genotypes and other factors (Needham *et al.*, 1990; Turner and Lambert, 1986). As Turner and Lambert (1986) and Walworth and Sumner (1987) pointed out, testing of the DRIS norms and the critical levels before using them is very important.

In this study we assess the foliar nutrient status of 14 young *Pseudotsuga menziesii* plantations on abandoned agricultural land in Galicia and we analyze the growth response to N, P and K fertilization in these sites. The main objectives of this paper are to verify the nutritional disorders previously found in Galician Douglas fir plantations, and to propose an establishment fertilization prescription for new plantations on similar sites.

Material and Methods

Sites description

Fourteen sites of young *Pseudotsuga menziesii* plantations on abandoned agricultural land were selected for nutritional diagnosis and fertilization response evaluations. The stands, distributed throughout the Galician territory (NW Spain) (Fig. 1), ranged in age from 2 to 4 years old at the time of fertilization. All sites were planted under the application of Regulation EU 2080/92 on abandoned agricultural land. Spacing was 3×3 m in all sites. Site and stand characteristics of each site are provided in Table 1. Elevations ranged from 250 to 1098 m. Slopes were generally low. Climate is characterized by high annual rainfall levels with relative and variable dry summers, and warm

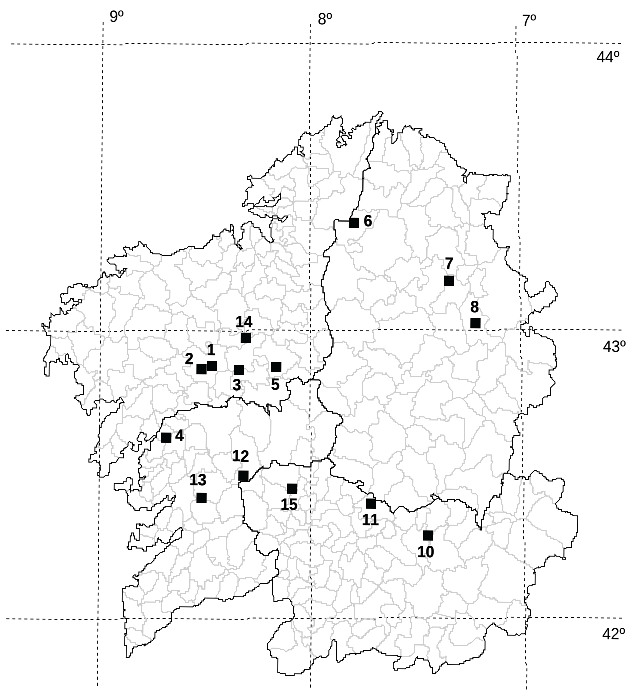

Figure 1. Location in Galicia of study sites.

Table 1. Site and stand characteristics for the 14 *Pseudotsuga menziesii* studied plantations

Trial	Elevation (m)	Slope (%)	Aspect	Parent material	Annual rainfall (mm)	Mean temp. (°C)	Age (yrs)	Total H (cm)[a]	GLD (mm)[a]
1	360	0	—	Ultrabasic	1860	13.1	2	72.6±5.3	17.1±1.2
2	350	3	SE	Ultrabasic	1769	13.3	4	97.2±7.9	18.4±1.2
3	275	4	NE	Schist	1658	13.6	4	130.6±7.9	27.9±2.2
4	230	27	NE	Granite	2039	13.9	3	55.5±2.7	15.8±0.9
5	275	10	N	Schist	1721	13.6	3	185.4±10	30.1±1.4
6	470	14	W	Sediments	1605	12.5	3	86.8±3.6	19.3±1
7	540	7	W	Slate	1176	11.7	4	153.6±9.9	29.3±2.3
8	908	10	N	Slate	1219	10.5	4	99.4±7	13.3±1
9	1098	28	NW	Granite	1648	10.1	3	73.6±4.2	10.0±0.5
10	705	16	N	Granite	1228	11.1	2	56.6±4.2	8.2±0.4
11	760	21	W	Granite	2420	10.8	4	57.3±3.5	10.5±0.5
12	460	19	NW	Granite	2290	12.5	4	50.1±2.2	10.5±0.6
13	250	7	S	Schist	1599	13.4	4	192.7±9.2	36.1±1.7
14	500	8	S	Granite	1452	12.5	2	114.4±16	21.5±3.3

[a] Mean and standard error of total height (Total H) and groundline diameter (GLD) at the time of fertilization.

mean annual temperatures. Low height and diameter growth rates can be noted. Some 4-year-old stands had a mean total height below 100 cm and less than 2 cm for basal diameter. The absence of an adequate grass and shrub control or the existence of important nutritional disorders could be the cause.

Surface soil (0-20 cm) characteristics of the studied plots are presented in Table 2. The soils have high levels of organic matter and total N, low pH and relative low levels of nutrients. The coefficients of variation of available P and exchangeable Ca are notably high.

Design and treatments

At each site, one fertilization trial was established. Each fertilization trial consisted in 80 samplings grouped

Table 2. Topsoil (0-20 cm) characteristics for the 14 *Pseudotsuga menziesii* studied plantations

Plot	Organic matter (%)	C:N	pH	Total N (g kg^{-1})	Available P (mg kg^{-1})	Exchangeable cations (mg kg^{-1})		
						K	Ca	Mg
1	15.6	71.6	5.2	1.3	4.4	5.2	676.0	73.5
2	17.6	13.9	4.8	7.4	4.6	107.2	39.1	15.6
3	5.0	13.7	5.2	2.1	50.4	240.7	235.5	40.6
4	18.6	14.1	4.2	7.6	7.6	50.9	23.3	10.6
5	10.4	14.8	5.0	4.1	8.3	129.4	68.4	37.4
6	10.4	16.0	5.4	3.8	4.4	79.6	453.7	62.9
7	10.9	12.8	5.4	4.9	23.9	96.8	904.9	32.3
8	8.5	14.5	4.8	3.4	2.3	100.3	388.8	12.5
9	9.6	10.5	4.8	5.3	9.1	64.4	74.9	25.3
10	5.4	12.3	4.7	2.5	43.1	93.7	112.0	33.6
11	16.8	18.7	4.6	5.2	2.9	156.3	125.7	87.6
12	16.7	13.6	4.4	7.1	5.8	69.9	19.1	19.1
13	10.4	13.0	5.0	4.6	7.5	96.4	43.9	30.0
14	3.2	12.4	6.1	1.5	363.3	209.0	771.8	81.6
Mean	11.4	18.0	5.0	4.3	38.4	107.1	281.3	40.2
C.V.	43.9	86.4	9.6	48.0	246.7	57.4	108.9	64.4

[a] Mean and standard error of total height (Total H) and groundline diameter (GLD) at the time of fertilization.

into 5 blocks. Blocks were divided in four experimental units with four plants each. Fertilizer treatments were randomly assigned to the experimental units within each block. In each block, one experimental unit remained untreated, serving as a control, one was treated with urea at 35 g N per plant, one was treated with superphosphate at 55 g P_2O_5 per plant and the fourth one was treated with potassium sulphate at 65 g K_2O per plant. Fertilizers were applied in April 2000. Grass and shrub vegetation were previously removed on a one meter diameter circle around each plant and fertilizers were spread by hand on this weeded out area. Fertilizers were then slightly covered with a thin layer of soil.

Measurements

Tree measurements for height and groundline diameter were made at the time of plot setup, and at the end of the first growing season following fertilization. All trees were measured. Height and diameter growth (final minus initial height or diameter, respectively) of untreated plants were highly influenced by initial height and diameter, respectively ($r^2 = 0.54$ and $r^2 = 0.60$, $p<0.0001$). Because of this, residuals of these regressions (named RH and RD, respectively) were used as parameters that characterize growth capacity at each site.

Foliar analysis

Current season foliar samples were collected at the end of the growing season one year after fertilization. In each trial (except number 12), all the control plants from the first three blocks were sampled. These twelve samples were bulked to obtain a composite sample of green needles per plot. These samples were used to diagnose the nutritional status of each site.

Foliage samples were collected from three branchends per tree in the top third of the crown (Ballard and Carter, 1986). Samples were placed in plastic bags and stored in ice-cooled containers. Foliage was not washed prior to analysis. Needles were separated from stems and oven-dried at 45ºC. Separate subsamples were oven-dried at 105ºC to know moisture content, and nutrients concentrations were expressed on a dry-weight basis. Nitrogen was determined by a Carloerba CNH-analyzer. Phosphorus, K, Ca and Mg were determined by X-ray fluorescence (Buhrke *et al.*, 1998) using tea leaves as certified reference material.

To determine nutritional status we used the critical and marginal foliar levels for *Pseudotsuga menziesii* proposed by Ballard and Carter (1986). Foliar N:P and N:K ratios were also used to assess the balance between nutrients. A foliar N:P ratio above 12.5 and above 16 was interpreted, respectively, as a marginal or critical excess of N relative to foliar P concentration, whereas a foliar N:P ratio below 12.5 indicated optimal P nutrition (Ballard and Carter, 1986). Ingestad (1979) suggested that for all conifers a foliar N:K ratio above 2 indicates an excess of N in relation to K, while a foliar N:K of 1.5 is optimal.

Statistical analysis

Pearson correlation analysis and principal components analysis (PCA) were used to study the relationships between growth of untreated plants (residuals of the regressions between growth and initial value of height and diameter of the control plants as explained above) and foliar and soil nutrients. Two PCA were carried out: one including foliar and growth parameters and another including soil and growth variables.

The analysis of the growth response to fertilization was carried out by analysis of covariance using the initial height (or diameter) as covariate. Two different kinds of analysis were made: one including all trials together and one independent analysis for each trial. The model for the combined analysis was as follows:

$$Y_{ijk} = \mu + S_i + T_j + B_k(S_i) + S_i{*}T_j + T_j{*}B_k(S_i) + \\ + Y_o + \varepsilon_{l(i,j,k)} \qquad (1)$$

where Y is the height (or diameter) at the end of the first growing season following fertilization; μ is the overall mean; S_i, T_j and $B_k(S_i)$ are the effects of site «*i*» (i = 1, 2, ..., 14), fertilization treatment «*j*» (j = 1, 2, 3, 4) and block «*k*» (k = 1, ..., 5) at site «*j*», respectively; $S_i{*}T_j$ and $T_j{*}B_k(S_i)$ are the effects of site «*i*» x treatment «*j*» interaction and treatment «*j*» x block «*k*» at site «*j*» interaction, respectively, and Y_o is the effect of the covariate initial height (or initial diameter) before fertilization.

The model for independent analysis for each site was as follows:

$$Y_{jk} = \mu + T_j + B_k + T_j{*}B_k + Y_o + \varepsilon_{l(j,k)} \quad (2)$$

Significant differences between fertilization treatments and control were tested analyzing the probabi-

Table 3. Foliar nutrient concentrations in untreated plants of each fertilization trial

Plot	Nutrient concentrations (g kg^{-1})[a]					Nutrient ratios[b]	
	N	P	K	Ca	Mg	N:P	N:K
Critical level	13.0	0.80	4.50	1.00	0.60	>16.0	>2.0
Marginal level	14.5	1.50	8.00	2.50	1.20	12.5-16.0	1.5-2.0
1	19.8	1.59	8.11	4.75	0.90	12.5	2.44
2	18.8	0.86	7.19	1.99	0.86	22.0	2.62
3	23.5	2.01	10.01	3.30	0.68	11.7	2.35
4	21.2	1.21	8.40	2.54	0.91	17.5	2.52
5	19.4	1.37	9.73	2.77	0.91	14.1	1.99
6	20.9	0.70	7.12	2.05	0.59	29.7	2.93
7	17.5	2.33	8.11	4.68	0.51	7.5	2.16
8	15.4	1.66	8.01	3.22	0.62	9.2	1.92
9	20.9	1.27	9.77	3.30	0.69	16.4	2.14
10	18.1	3.01	9.90	3.66	1.18	6.0	1.83
11	29.7	1.31	6.59	2.61	1.09	22.7	4.51
13	19.1	1.42	9.35	2.64	0.97	13.5	2.04
14	21.8	2.91	9.56	5.27	0.73	7.5	2.28

[a] Critical and marginal levels reported by Ballard and Carter (1986). [b] Foliar N:P ratio interpretation as Ballard and Carter (1986), foliar N:K interpretation as Ingestad (1979).

lity values for the hypothesis H_0: $LSM_j = LSM_o$, where LSM_j is the least-square mean (mean adjusted for the covariate) of treatment «*j*» and LSM_o is the least-square mean for the control (SAS, 1989).

Results

Foliar nutrient status

The foliar nutrient concentrations of the untreated plants are presented in Table 3. On the basis of critical levels, all sites presented foliar N concentrations above the critical or marginal levels reported by Ballard and Carter (1986). Nitrogen concentrations were also higher than those considered by Bonneau (1988) as optimal levels. On the contrary, foliar P concentrations were above the critical levels only in six cases. One site showed critical foliar P concentrations and the remainders showed marginal levels. Foliar K and Ca concentrations were marginal in three and two cases, respectively. Foliar Mg concentrations were always below the critical or marginal levels. Two sites showed critical foliar Mg concentrations and the remainders showed marginal levels.

The foliar N:P and N:K ratio were very high in most of the studied plots indicating a high imbalance between these nutrients (Table 3). Five and three sites showed a high and moderately N:P imbalance, respectively, whereas foliar N:K ratio was highly unbalanced in 10 sites and moderately unbalanced in the remainders. As found previously in other nutritional studies in Galicia (Zas and Serrada, 2003; Zas and Serrada, submitted; Zas, in press), these results suggest a nitrogen excess in some sites that can lead to important nutritional and growth disorders. Trials number 2, 6 and 11 are those where these disorders are expected to be higher.

Correlation analysis

The correlation coefficients between foliar nutrient concentrations, topsoil variables and growth are presented in Table 4. Residual height growth of untreated plants (residuals of the regression between height growth and initial height) were positively correlated with foliar P, K and Ca concentrations and negatively correlated with total soil N and organic matter in the surface soil. Residual diameter growth was positively correlated with soil exchangeable K. These correlations indicate the importance of P, K and Ca for the growth of the trees and confirm the N excess found previously. The higher imbalance in relation to N excess, the lower height growth rates were found. Despite the low foliar Mg levels found (Table 3), no significant correlation was found between growth and either foliar or soil Mg concentrations.

Table 4. Pearson correlation coefficients between foliar nutrient concentrations, surface soil variables and residual height (RH) and diameter (RD) growth of untreated plants*

	Growth		**Foliar nutrients**					**Soil variables**						
	RH	**RD**	**N**	**P**	**K**	**Ca**	**Mg**	**N**	**P**	**K**	**Ca**	**Mg**	**pH**	**O.M.**
Growth														
RH	1.00	0.62		0.64	0.70	0.68		–0.64						–0.63
RD		1.00								0.54				
Foliar nutrients														
N			1.00									0.63		
P				1.00		0.77		–0.60	0.62					–0.69
K					1.00									–0.69
Ca						1.00		–0.65	0.61		0.78		0.60	
Mg							1.00				–0.57		–0.52	
Soil variables														
N								1.00			–0.57	–0.58	–0.68	0.73
P									1.00	0.55			0.68	–0.56
K										1.00				–0.57
Ca											1.00		0.77	
Mg												1.00	0.55	
pH													1.00	–0.63
O.M.														1.00

* Residual height and diameter growth are the residual of the regressions between height and diameter growth and initial height and diameter at the time of fertilization of the untreated plants. Only coefficients significant at P <0.05 are presented. O.M.: organic matter.

Foliar nutrient concentrations were significantly correlated with their respective soil levels only in the case of P and Ca. Foliar levels of these nutrients were also negatively correlated with total soil N, indicating the negative influence of the high levels of soil N in the uptake of these nutrients. Furthermore, the higher total soil N levels, the lower pH and exchangeable Ca and Mg were found. Under acid pH, availability of P, Ca and Mg increase as pH does (Larcher, 1983). It seems that availability of these nutrients decrease as total soil N increases.

Principal component analysis (PCA)

Two principal component analysis corresponding to soil and foliar data of control samplings were carried out.

In the first PCA, the percentage of variance accounted for 47.9% for axis 1 and 20.4 for axis 2. The distribution of the variables included in the analysis along these two axis (Fig. 2a) was used to classify them in two groups. Height and diameter growth, soil pH, available P and exchangeable K appeared close together at the right-down corner of the graphic and were classified as favourable parameters. High values of these parameters are related with high rates of tree growth. Soil organic matter and total soil N appeared at the opposite side and were classified as unfavorable parameters for Douglas fir growth. The distribution of sites (Fig. 2b) shows trial 3 and 14 located in the same position as the favourable parameters and trials 2, 4 and 12 located close to the unfavourable parameters.

In the same way, results of the PCA corresponding to foliar data are present in Fig. 3. The first principal component accounted for 47.8% of the overall variance whereas the second axis explained 19.3%. At the positive end of axis 1 and around null values of axis 2 were situated the height and diameter growth and the foliar P, K and Ca levels, whereas at negative values of this axis and at the positive end of axis 2 were situated the foliar N and Mg concentrations (Fig. 3a). Foliar P, K and Ca were then considered as favourable parameters while foliar N and Mg were considered unfavourable parameters for Douglas fir growth.

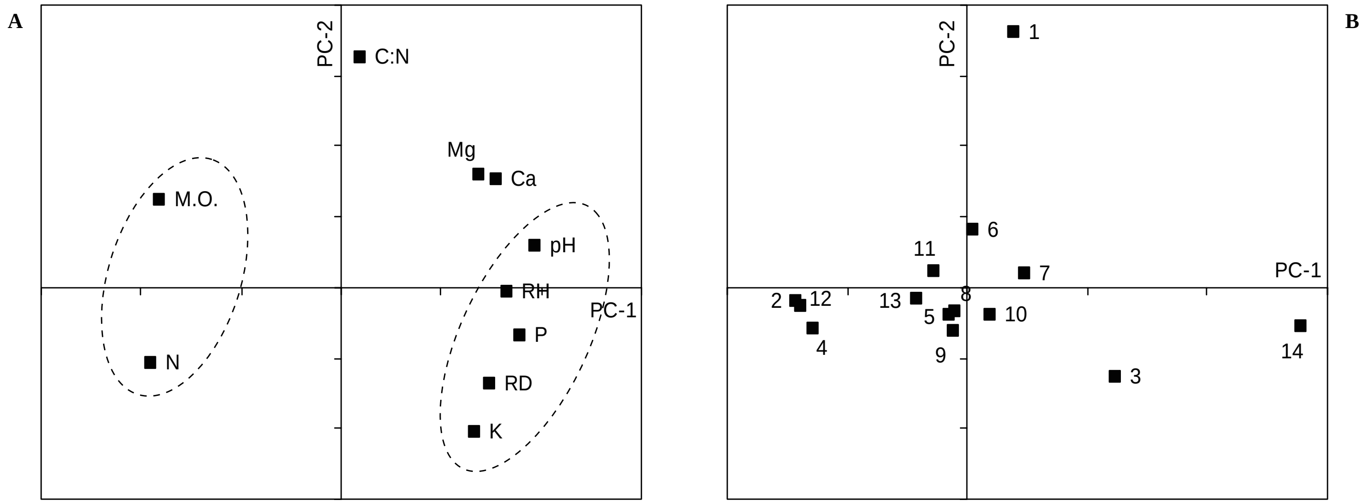

Figure 2. Principal component analysis for soil and growth data [residual heigth (RH) and diameter (RD) growth of untreated plants]. Distribution of (A) parameters and (B) sites throught the two first principal components (PC-1 and PC-2). (A) parameters are classified in two groups: favourable and unfavourable parameters for Douglas fir growth.

The distribution of sites shows (Fig. 3b) trial 14 and 11 as the nearest to favourable and unfavourable parameters, respectively.

Growth response to fertilizer

The results for the combined analysis of covariance (all trials together) for the height and diameter growths are presented in Table 5. Both, the fertilization treatments and the site x fertilization treatment interaction had a significant effect on height growth. Despite the variation among sites in height growth response to fertilization, a general trend in this response was observed in all sites (Fig. 4). The fertilization with urea and potassium sulphate significantly reduce the height growth, whereas no significant effect was observed after the application of superphosphate. The results for the diameter growth were slightly different. The fertilization treatments did not significantly influence the diameter growth whereas site x treatment interaction was highly significant. Thereby, no general trend in the diameter growth response to fertilization treatments can be observed throughout all the studied sites.

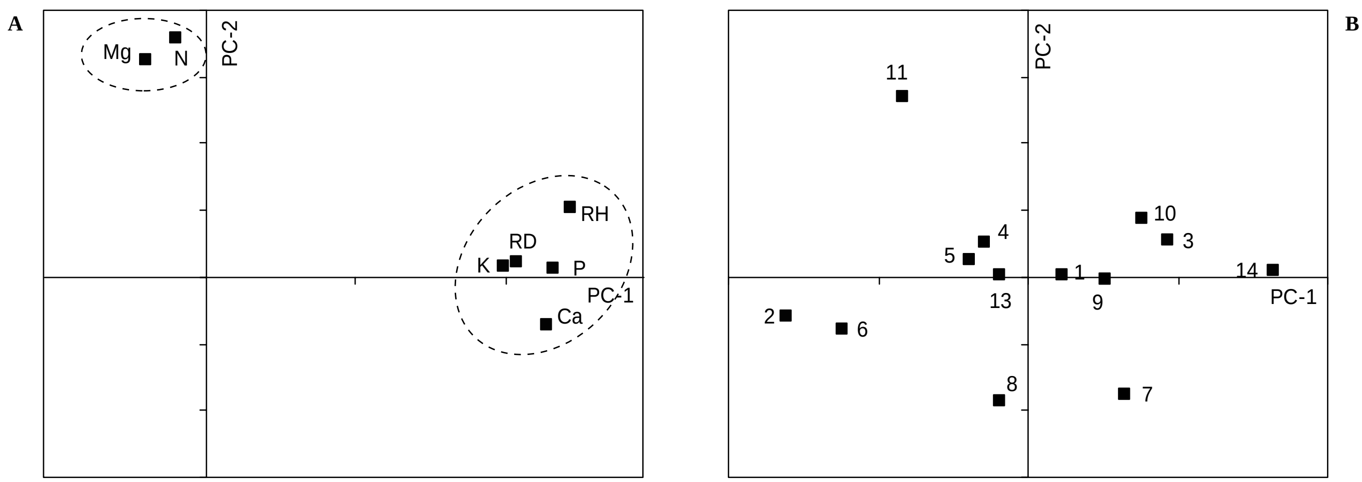

Figure 3. Principal component analysis for foliar (macronutrient concentrations) and growth data [residual heigth (RH) and diameter (RD) growth of untreated plants]. Distribution of (A) parameters and (B) sites through the two first principal components (PC-1 and PC-2). (A) parameters are classified in two groups: favourable and unfavourable parameters for Douglas fir growth.

Table 5. Results of the combined analysis of covariance for all the studied sites

Source of variation	D.F.	Height growth			Diameter growth		
		MS	F value	p<F	MS	F value	p<F
Site	13	8.435.4	46.4	0.0001	298.9	22.0	0.0001
Treatment	3	234.0	14.5	0.0001	29.0	2.1	0.0946
Block(Site)	53	2.631.0	1.3	0.0879	23.0	1.7	0.0020
Site × treatment	39	305.5	1.7	0.0066	33.2	2.4	0.0001
Treatment × block(site)	157	225.1	1.2	0.0381	14.0	1.0	0.3898
Initial height / diameter	1	1.085.885.3	5.968.7	0.0001	58.047.6	4.270.7	0.0001

D.F.: Degrees of freedom. MS: type III mean square.

The results for the individual analysis of covariance for each site are summarized in Fig. 5. The fertilization treatments had a significant effect on height growth in trials 4, 7, 8, 9, 10, and 11. In all these trials, height growth was significantly lower when urea was applied. In addition, phosphorus and potassium fertilization had also a negative effect in trial 4. In the remainder sites, no significant effect of fertilization treatments on height growth was observed.

In the case of diameter growth, the fertilization treatments had a significant effect in trials 4, 6, 9, 11, 12, 13 and 14. The N treatment led to a significant reduction of the diameter growth in trials 4 and 9 whereas, in trials 13 and 14, the diameter growth was higher after the application of N. The P fertilization had a positive effect on diameter growth in trials 6, 11 an 12. Finally, in trials 4 and 6, the diameter growth was respectively lower and higher after the application of K.

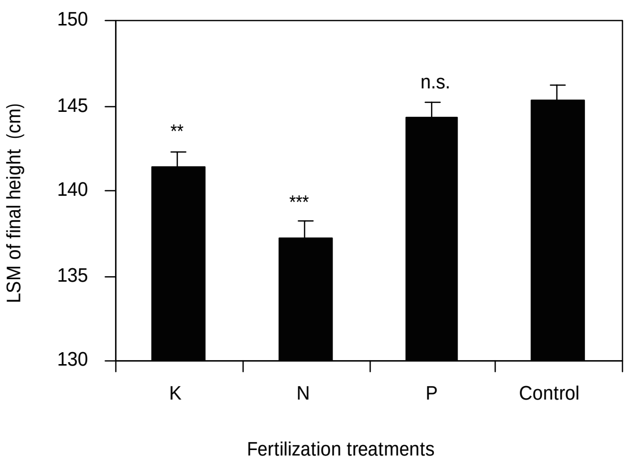

Figure 4. Effect of the fertilization treatments on the height growth for all the trials analyzed together. Least square means (LSM) adjusted for covariate + standard error are presented. Asterisks indicate significant differences between the LSM for each treatment and the control. Significance levels: n.s. $p > 0.05$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Discussion

Nutritional status

As found in a previous nutritional study of young *Pseudotsuga menziesii* plantations in Galicia (Zas and Serrada, submitted), the foliar analysis indicated an excess of nitrogen in most of the studied sites. Nitrogen excess is a common problem of European conifer plantations (Binggeli *et al.*, 2000; Mohren *et al.*, 1986). High foliar N levels were also found in other *Pinus radiata* studies in Galicia (Zas and Serrada, 2003) and in the Basque Country (Mesanza *et al.*, 1993; Palacios *et al.*, 1995). The organic amendment, a typical agricultural practice in Galicia (Bará, 1990; Sánchez, 1995; Sánchez *et al.*, 1986) that has been probably applied on the studied soils, can lead to soil nitrification, acidification, cation leaching and potentially to P, Ca and Mg deficiencies (Harrison *et al.*, 1994). Galician soils are coarse-textured and conform a subtractive system where the high precipitation levels lead to high rates of nutrient leaching (Macías *et al.*, 1982). Thus, Galician soils appear very sensitive to high rates of nitrogen input. The high foliar N:P and N:K ratios found in the studied plots (Table 3) confirm this negative influence of the excess of nitrogen. These adverse effects of nitrogen excess have been also found in areas of Europe receiving high nitrogen inputs through atmospheric deposition (Ulrich *et al.*, 1980).

Comparing with our previous study on nutritional status of 1-2 years-old Douglas fir plantations (Zas and Serrada, submitted), some important differences can be observed in the nutritional status, especially in the K and Mg status. Whereas foliar K levels were below the critical levels in almost all cases in the previous work, foliar K concentrations found here were relatively high (Table 3). On the contrary, foliar Mg concentrations are relatively lower than those found pre-

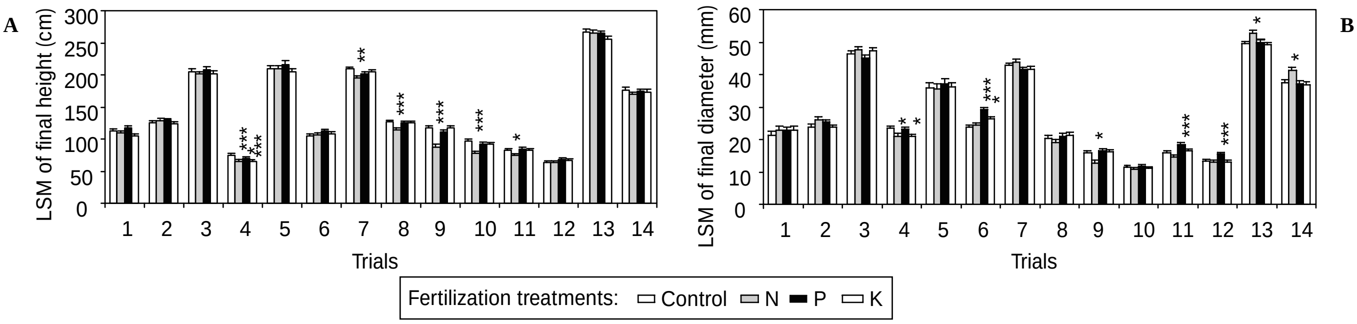

Figure 5. Effect of the fertilization treatments on the (A) height and (B) diameter growth for each trial analyzed independently. Least square means (LSM) adjusted for covariate + standard error are presented. Within each trial, the asterisks indicate significant differences between the LSM for the treatment and the control. Significance levels: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

viously. These differences can be due to differences in the plantations age between both studies. It seems that the K uptake increases and the Mg uptake decreases as the stands get older. The fertilization with Mg, not considered in this work because no important Mg disorders were found previously, could be reconsidered for further research.

Correlation and principal component analysis

Both correlation analysis and principal component analysis identified N as an excessive nutrient that may limit Douglas fir growth. High foliar or soil N levels were related to low growth rates (Table 4, Fig. 2 and 3). Height growth of Douglas fir (Zas and Serrada, submitted) and *Pinus radiata* (Gandullo *et al.*, 1974; Mesanza *et al.*, 1993; Romanya and Vallejo, 2000; Sánchez *et al.*, 1998; Sánchez *et al.*, 2000; Zas and Serrada, 2003) has been observed to be negatively correlated with either soil or foliar N in northern Spain. Despite the negative effect on P and cation uptake that can be induced by the N excess, it is well known that high N levels in the foliage of field-grown trees increase both number and size of lateral shoots, and the trees with lower N 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 to ensure a good stem form (Knight, 1973; Will, 1971).

On the other hand, P, K, and Ca were positively related to Douglas fir growth (Table 4, Fig. 2 and 3). Availability of these nutrients must be promoted to ensure high growth rates. These results, together with the variability of the foliar P, K and Ca diagnosis (Table 3) suggest that these nutrients are not always well supplied, and, in some cases, the low nutrient levels may restrict the trees growth. Some authors have observed that growth of *Pinus radiata* in Galicia is positively correlated with foliar P concentration (Sánchez *et al.*, 1998; Zas, in press) and foliar K concentrations (Zas and Serrada, 2003).

The Mg nutrition of the studied plots is much more difficult to interpret. Although foliar Mg concentrations were below the marginal level in all cases (Table 3), the results of the PCA showed foliar Mg concentration as an unfavourable parameter for Douglas fir growth (Fig. 3a). Some other factors may influence the uptake of Mg. Normally, Mg availability and uptake increases as pH does (Larcher, 1983). However, in our studied plots, foliar Mg concentrations correlated negatively with soil pH (Table 3). The negative correlation between foliar Mg and soil Ca suggests a negative interaction between both nutrients. Mg deficiencies are common in *Pinus radiata* stands in northern Spain (Romanya and Vallejo, 1996; Zas and Serrada, 2003) and may be induced by high nitrogen inputs through sludge amendments (Harrison *et al.*, 1994).

Growth response to fertilization

The critical level for a particular element is the foliar concentration below which growth is normally limited by that element. Above the critical level little growth response should be expected with increasing supply of the element. Below the critical level, application of the element should increase tree growth (Ballard and Carter, 1986). However, the growth response to fertilization treatments found in the present work did not correspond with the foliar diagnosis of untreated plants through the critical levels method. Only in the case of N, the lack of a positive growth response or even the negative influence of urea application, agree with the relative excess of nitrogen found in the control foliage samples. However, P and K fertilization did not generate the expected response. As derived from foliar diagnosis, a positive response to P and K addition should be expected in seven and three sites (Table 3), respectively. However, this positive response was only observed in three and one sites (Fig 5b), respectively. Furthermore, in trial 4, although the foliar control samples were marginal in P, plants fertilized with this nutrient grew significantly less than untreated plants. Several hypothesis can be offered to explain this lack of consistence. Firstly, the critical levels for Douglas fir have been developed in British Columbia (Ballard and Carter, 1986) and their portability to other regions may require a previous recalibration. Foliar nutrients levels may vary between regions (Turner and Lambert, 1986) but similar values of critical or recommended foliar nutrient concentrations for Douglas fir can be observed among different countries (Ballard and Carter, 1986; Binns *et al.*, 1980; Bonneau, 1988). We think that the lack of a positive response to the fertilization treatments is due to the low fertilization rates employed and/or the short time passed between fertilization and response evaluation. In addition, some other factors not considered in this work could have influenced the response to the fertilization treatments. For example, the foliar Mg concentrations indicated a marginal or critical Mg deficiency in all sites (Table 3). Despite the low foliar P and K levels found in some cases, these Mg deficiencies may encrypt the positive effect of the addition of these nutrients. Foliar Mg concentrations correlated negatively with exchangeable soil Ca. The application of superphosphate, that also supplies calcium, can generate disorders in the Mg nutrition and, hence, no positive influence of the P amendment takes place. The nutritional status of other micronutrients and other interactions between nutrients should also be considered. The application of other fertilizers, rates and combined fertilization treatments must be studied to ensure the viability of foliar critical levels for the Galician plantations and to propose a fertilization prescription for young Douglas fir plantations in Galicia.

As a practical and general conclusion of this paper, no nitrogen should be added to young Douglas fir plantations on abandoned agricultural land in Galicia. Nitrogen application may be only considered in specific locations when a previous diagnostic indicates a clear and severe nitrogen deficiency. Further research is needed to generate a practical fertilization recommendation for the remainder nutrients.

Acknowledgements

This study was carried out in the Forest Production Department of the Lourizán Forestry Research Center. The author thanks Dr. Josefa Fernández for her logistic help, Dr. Luis Sampedro and Dr. María Jesús Briones for their useful help, Roberto Jorge for field assistance and Dr. María Abuín, Dr. Esther Merlo, Dr. Raquel Díaz and Elena Arregui for their helpful language review.

References

BALLARD T.M., CARTER R.E., 1986. Evaluating forest stand nutrient status. Ministry of Forests, British Columbia. Land Management Report, No. 20, Ministry of Forests, Victoria, British Columbia, 60 pp.

BARÁ T.S., 1990. Fertilización Forestal. Consellería de Agricultura, Gandería e Montes. Xunta de Galicia, Santiago, 175 pp.

BEAUFILS E.R., 1973. Diagnosis and Recommendation Integrated System (DRIS). Department of Soil Science and Agrometorol. University of Natal. Soil Sci. Bull. No. 1., Pietermaritzburg, SA, 132 pp.

BINGGELI P., BLACKSTOCK P., MCGILL C., 2000. Potassium deficiency in conifers on former agricultural land. Q. J. For. 94 (3), 229-233.

BINNS W.O., MAYHEAD G.J., MACKENZIE J.M., 1980. Nutrient deficiencies of conifers in British forests. An illustrated guide. Leaflet, Forestry Commission, UK, 23 pp.

BONNEAU M., 1988. Le Diagnostic foliaire. Rev. For. Fr. 40 (Special), 19-28.

BUHRKE V.E., JENKINS R., SMITH D.K., 1998. Preparation of specimens for X-ray fluorescence and X-ray diffraction analysis. John Wiley & Sons, Inc., New York.

GANDULLO J.M., GONZALES A.S., SÁNCHEZ P.O., UBEDA, J.M., 1974. Ecología de los pinares españoles. IV. *Pinus radiata* D. Don. Monografia INIA No.13, Madrid, 187 pp.

HARRISON R.B., HENRY C.L., XUE D.S., 1994. Magnesium deficiency in Douglas-fir and grand fir growing on a sandy outwash soil amended with sewage sludge. Water, Air, and Soil Pollution 75 (1-2), 37-50.

INGESTAD T., 1979. Nitrogen stress in birch seedlings. II. N, K, P, Ca, and Mg nutrition. Physiol. Plant. 45 (1), 149-157.

KNIGHT P.J., 1973. Influence of nitrogen supply on the growth and branching habit of *Pinus radiata* seedlings. N. Z. J. For. 18 (2), 273-278.

LAMBERT M.J., GREY D.C., SCHONAU A.P.G., SCHUTZ C.J., 1984. The use of foliar analysis in fertilizer research.

IUFRO Symposium on Site and Productivity of Fast Growing Plantations. Vol. 1, Pretoria, South African Forest Research Institute, pp. 269-291.

LARCHER W., 1983. Physiological plant ecology. Springer-Verlag, Berlin.

MACÍAS F., CALVO R.M., GARCÍA C., GARCÍA-RODEJA E., SILVA B., 1982. El material original: su formación e influencia en las propiedades de los suelos de Galicia. An. Edafol. Agrobiol. 42, 1746-1768.

MESANZA J.M., CASADO H., CASTILLO F.J., 1993. Nutrient concentrations in *Pinus radiata* D. Don needles in the Basque Country (Spain): a preliminary classification of parameters and sites. Ann. Sci. For. 50 (1), 23-36.

MOHREN G.M.J., BURG J., BURGER F.W., 1986. Phosphorus deficiency induced by nitrogen input in Douglas fir in the Netherlands. Plant Soil 95 (2), 191-200.

NEEDHAM T.D., BURGER J.A., ODERWALD R.G., 1990. Relationship between diagnosis and recommendation integrated system (DRIS) optima and foliar nutrient critical levels. Soil. Sci. Soc. Am. J. 54 (3), 883-886.

PALACIOS P.L., CASADO H., MESANZA J.M., CASTILLO F.J., 1995. *Pinus radiata* site quality study in the Basque Country (Spain) using nutritional and physiographical criteria. Water, Air, and Soil Pollution 85 (3), 1275-1280.

ROMANYA J., VALLEJO V.R., 1996. Nutritional status and deficiency diagnosis of *Pinus radiata* plantations in Spain. For. Sci. 42 (2), 192-197.

ROMANYA J., VALLEJO V.R., 2000. Productivity factors of *Pinus radiata* D. Don plantations in Spain. International Symposium on Managing Forest Soils for Sustainable Productivity, Vila Real, 18-22 September 2000, Portugal, pp. 155-156.

SÁNCHEZ F.R., ÁLVAREZ J.G.G., RODRÍGUEZ R.S., 1998. Resultados preliminares del estudio de curvas de calidad de estación y de los factores ecológicos implicados en la productividad de *Pinus radiata* D. Don en Galicia (España). Primer Congreso latinoamericano de IUFRO, Valdivia, Chile, 22-28 November 1998.

SÁNCHEZ R.B., 1995. La fertilidad de los suelos de la provincia de Orense. Consejo Superior de Investigaciones Científicas. Misión Biológica de Galicia, Pontevedra, 464 pp.

SÁNCHEZ R.B., GARCÍA S.A., DIOS V.G., 1986. La fertilidad de los suelos de la provincia de Pontevedra. Consejo Superior de Investigaciones Científicas. Mision Biológica de Galicia, Pontevedra, 143 pp.

SÁNCHEZ R.F., RODRÍGUEZ R.S., MERINO A.G., 2000. Site factors determining forest productivity in *Pinus radiata* D. Don stands in Galicia (NW Spain). International Symposium on Managing Forest Soils for Sustainable Productivity, Vila Real, 18-22 September 2000, Portugal, pp. 161-162.

SAS, 1989. SAS STAT user guide, Version 6. Fourth Edition. SAS Institute Inc., Cary, NC, 943 pp.

SHUMWAY J.S., CHAPPELL H.N., 1995. Preliminary DRIS norms for coastal Douglas-fir soils in Washington and Oregon. Can. J. For. Res. 25 (2), 208-214.

SVENSON G.A., KIMBERLEY M.O., 1988. Can DRIS improve diagnosis of nutrient deficiency in *Pinus radiata?* N. Z. J. For. Sci. 18 (1), 33-42.

TURNER J., LAMBERT M.J., 1986. Nutrition and nutritional relationships of *Pinus radiata*. Ann. Rev. Ecol. Syst. 17, 325-350.

TRUMAN R., LAMBERT M.J., 1980. The use of DRIS indices to determine the balance between nitrogen, phosphorus and sulphur in *Pinus radiata* foliage. Symposium on Managing Nitrogen Economies of Natural and Man Made Ecosystems, CSIRO Division of Land Resources Management, Mandurah, W.A., pp. 369-377.

ULRICH B., MAYER R., KHANNA P.K., 1980. Chemical changes due to acid precipitation in a loess-derived soil in central Europe. Soil Sci. 130 (4), 193-199.

VEGA A.G., RODRÍGUEZ S.R., ARENAS R.S.G., GARCÍA S.S., MANSILLA V.P., VEGA A.P., RUIZ G.A.D., 1998. Manual de Selvicultura del pino oregon. Proxecto Columella. Area Forestal. Serie Manuales Técnicos. Universidad de Santiago de Compostela, Santiago, 84 pp.

WADT P.G.S., NOVAIS R.F., ÁLVAREZ V.V., FONSECA S., BARROS N.F., 1998. Valores de referencia para macronutrientes em eucalipto obtidos pelos metodos DRIS e Chance Matematica. Rev. Bras. Cien. Solo 22, 685-692.

WALWORTH J.L., SUMNER M.E., 1987. The diagnosis and recommendation integrated system (DRIS). Adv. Soil Sci. 6, 149-188.

WILL G.M., 1971. Nitrogen supply, apical dominance and branch growth in *Pinus radiata*. Plant Soil 4 (2), 515-517.

XUNTA DE GALICIA, 1992. Plan Forestal de Galicia. Síntesis. Consellería de Agricultura, Gandería e Montes, Xunta de Galicia, Santiago de Compostela, 141 pp.

ZAS R., in press. Interpretación de las concentraciones foliares en nutrientes en plantaciones jóvenes de *Pinus radiata* D. Don en tierras agrarias en Galicia. Invest. Agrar.: Sist. Recur. For.

ZAS R., SERRADA R., 2003. Foliar nutrient status and nutritional relationships of young *Pinus radiata* D. Don plantations in northwest Spain. For. Eco. Manage. 174 (1-3), 167-176.

ZAS R., SERRADA R., submitted. Nutritional status and deficiency diagnosis of young *Pseudotsuga menziesii* plantations in northwest Spain. Forestry.