SIGNIFICANCE OF BEDROCK AS A SITE FACTOR DETERMINING NUTRITIONAL STATUS AND GROWTH OF MARITIME PINE

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Abstract

Relationships between soil properties, foliar nutrients and growth were studied in 128 plots of *Pinus pinaster* established in soil over different types of bedrock in Galicia (NW Spain). Plots were classified into the following groups of bedrocks according to geological maps and samples: granitic rocks, quaternary sediments, quartzite and sandstone, slates and phyllites, biotitic schists, micaschists, gneiss and migmatites. Bedrock type significantly influenced exchangeable Ca, total N, soil depth, foliar N, P, Ca, K and Mg and site index. Bedrock was also related to elevation, temperature and slope, as a result of the distribution and geomorphology. Soils developed from biotitic schists, gneiss, migmatites and granitic rocks were the most favourable for tree growth. The poorest growth and most severe nutrient deficiencies were observed in soils developed from quaternary sediments, mica schists, phylites and slates, quartzite and sandstone. Two regression models were developed to predict site index: a complete model explained 52% of the total variation in site index, and a model for granitic rocks explained 53% of the variation. Both indicated the importance of soil depth, elevation and foliar K and Ca as predictive variables.

Key words: bedrock, nutrition, growth, maritime pine

1. Introduction

Pinus pinaster is one of the most important tree species in Spain, in terms of both area covered (1.68 Mha as pure and mixed species) and wood production (more than 3.1 Mm^3 felled in 2010, making it the second most important species in terms of volume production after *Eucalyptus globulus*). This species is not site demanding and is usually planted for wood production, restoration and landscaping. Its importance in Galicia (NW Spain), where it covers 0.53 Mha as pure and mixed stands, is due to its extraordinary adaptation to poor and sandy soils (Gandullo and Sánchez Palomares, 1994). However, use of the species in northern Spain has declined in favour of other faster growing but more nutrient-demanding species, such as *Pinus radiata D. Don* and *Eucalyptus globulus Labill* (Sánchez-Rodríguez et al., 2002; Merino et al., 2003).

Galician soils, which are characterized by very intense weathering, are highly acidic, with low concentrations of exchangeable Ca, Mg, K, a cationic exchange complex saturated by Al and a low concentration of available P (Macías and Calvo, 1992). This is due to the predominance of scarcely alterable minerals in the rocks, high rainfall and open systems that quickly eliminate the more mobile cations (Macías et al., 1982). These soils are also poor in P, possibly because the P binds with Fe and Al to form different compounds and is therefore not available to plants (Dambrine et al., 2000). The relationships between soil properties and nutritional status of the species depend greatly on factors such as climate, soil type and management practices (Ballard, 1980).

The nutrient status of a forest can be evaluated by comparing foliar concentrations of nutrients with limiting levels of nutrients. The nutrient deficiency levels for *Pinus pinaster* proposed in the area are as follows: <9.8 mg g^{-1} for N, <0.8 mg g^{-1} for P, <0.6 mg g^{-1} for Ca, <0.7 mg g^{-1}

for Mg and <4.5 mg g^{-1} for K (Bará, 1998; Bonneau, 1995; Balboa, 2005). Nutrient (particularly macronutrient) deficiencies are frequently observed in this species, in the following order, from most limiting to less limiting elements: P>K>Mg>Ca>N (Martins et al, 2009; Álvarez-Álvarez et al., 2011). Deficiencies in B and Cu are also observed in very sandy and acid soils (Bará, 1998). Foliar levels affect volume growth, and site index (defined by categorical classes) has been shown to be related to foliar K (Bara and Toval, 1983). Foliar nutrition concentrations have been studied in *Pinus pinaster* forests in France (Bonneau, 1995; Saur et al., 1992), and P has been indicated as the most limiting nutrient for forest growth in the sandy podzols of the Landes, whereas soluble elements can be provided by the fluctuating water table. P has also been shown to be the most limiting nutrient in Australia, and deficiency levels of other macro and micronutrients reported (Boardman et al., 1997).

The nature of bedrock is the main factor affecting forest soil properties, particularly in homogeneous climate zones (Hartmann and Moosdorf, 2012). The lithology of Galicia is very diverse, with a complex of igneous and methamorphic materials dating from the Precambrian until the last stage of the Hercynian Orogeny, together with tertiary and quaternary sedimentary deposits (Parga Pondal, 1969), mostly with rocks of acidic nature. Schists and shales with a low to medium degree of metamorphism are among the most abundant materials (occupying 46% of the total area), followed by rocks of more or less deformed granitic composition (45%), basic and ultrabasic rocks with variable degrees of metamorphism (5%), and tertiary and quaternary deposits (4%).

Although several studies have reported nutritional deficiencies in stands of this species, studies covering a complete set of plots considering bedrock information as a basis for land classification are scarce. As an example, land classification for forest purposes in Spain has considered lithological properties, particularly acidity, as one of the main bases for the establishment of biogeoclimatic classification (Elena-Roselló et al., 1997). Also, traditional studies of the ecology of Iberian pines have considered bedrock as a major factor for classification, especially rock type, degree of consolidation and the presence or absence of minerals produced by weathering (Gandullo and Sánchez Palomares, 1994).

The aims of the present study were i) to investigate differences in the concentrations of available nutrients in soil, foliar levels of nutrients and site index in plots established on soils developed from a wide range of types of bedrock in Galicia, ii) to propose site index models based on type of bedrock, and iii) to determine nutritional deficiencies in relation to bedrock.

2. Materials and methods

2.1. Study plots

The study was carried out in 128 *Pinus pinaster* plots of varying age (8 to 50 years) located in Galicia (NW Spain). The plots were divided into two groups: one consisting of 31 plots, each of 600 m^2, installed in 2006 (López Varela et al., 2009), and a second one formed by a network of 97 plots, all larger than 625 m^2, established in 1974 and 1975 (Bara and Toval, 1983) (Figure 1).

Soil depth was measured and three soil samples were obtained at random from the upper layer (0 to 20 cm) in each plot and combined to form a composite sample. Sample analysis included measurement of the following parameters: pH in H_2O and KCl (Guitián and Carballas, 1976); total C and N, by combustion in a Leco analyzer; organic matter, determined by considering a fixed proportion of 58% C; exchangeable Ca, Mg and K, measured by displacement with 1M NH_4Cl (Peech et al., 1947); and available P (Olsen and Sommers, 1982).

Stand age was determined either using records of plantation age or in the case of naturally regenerated stands, by taking at least three wood cones for ring counting. Tree measurements included breast height diameter of all trees and total height of either all trees in the plot (first group of 31 plots) or a random sample of thirty trees per plot plus the dominant trees (second group of 97 plots). Site index was calculated to enable comparison of the potential growth of plots for a very broad range of ages and stand characteristics. Site index (SI) has been defined in the area as the dominant height of the stand, in metres, at a reference age of 20 years considering two different ecoregions (Ávarez-Gónzalez et al. 2005). Dominant height was calculated as the average total height of the 100 thickest trees per hectare. Average slope and elevation were also recorded.

A well-illuminated branch of the upper third of the crown was selected in three dominant trees of each plot, and a sample of one-year-old needles was obtained. The needles were dried at 65º C and milled to pass through a 0.5 mm sieve. Total N was determined in a LECO-2000 analyzer and the plant material was digested with HNO_3 in a microwave oven for determination of macronutrients. The concentrations of P, K, Ca and Mg were measured by ICP-OES after sample digestion, and Barley 502-227 and EDTA were used as certified reference material.

The average annual temperature (T) data were obtained from thermopluviometric stations close to the plots.

Lithological information for the 128 plots was obtained using the SIGPAC display, Spanish geological map 1:50000 (IGME, 1981), and maps of forests managed by the regional forest service. Each plot was identified by town council, parish, forest, location and elevation; the plot coordinates were also obtained and the bedrock was defined from the geological map and by analysis of samples collected at each site to verify the map classification.

The following lithological types were defined: granitic rocks (GRAN, comprising granites and granodiorites, which were quite diverse according to the grain size and composition, 55 plots), gneiss (GNEI, including orthogneiss and paragneiss, 13 plots), migmatites (MIGM, 14 plots), biotitic schists (BSCH, rich in biotite and calcium plagioclase, 5 plots), acid schists or mica schists (MSCH, richer in quartz than BSCH, 12 plots), phyllites and slates (SLAT, grouped together because the composition is the same and only the grain size differs: 14 plots), quartzite and sandstone (QUAR, both with the same composition, 9 plots) and quaternary sediments (SEDC, 6 plots).

Two main groups of granites are considered in NW Spain, according to the rock composition. The calc-alkaline series is a group of high colour index, biotite-rich granites, poor in muscovite, with the plagioclase as oligoclase or andesine, sometimes containing pyroxenes or amphiboles (hornblende). These have been formed at very high temperatures and their composition fits within the framework established by Frost et al. (2001), after application of their modified alkali-lime index to the composition obtained from IGME (1981). Granodiorites and adamelitic granites are also considered to belong to this group. A second group is the alkali granites, formed by leucogranites, leucogranodiorites and two mica-granites, with muscovite and biotite in similar proportions, no hornblende or pyroxenes, plagioclase present as albite and rich in potassium feldspar. These two groups were considered separately in the first stage of analysis and were then combined as no differences were found as regards site productivity or pine nutrition status. This was probably because for the two cases, the composition enables their classification as ferroan and peraluminous granitic rocks, according to Frost et al. (2001). No between-group differences were either found for paragneiss or orthogneiss.

A description of the ages, formations and mineralogy for each bedrock type is shown in Table 1.

2.2. Treatment and processing of data

The data were analysed to determine mean values and ranges of variation. To examine the relationships between nutrients (soil and foliar), temperature, seasonal parameters and type of bedrock, variance analysis was performed for the bedrock factor. Mean classification using the Duncan’s test was also performed to examine all possible differences in relation to type of bedrock. Pearson correlation analysis was applied to SI and all the variables, and other correlations among soil nutrients and foliar nutrients were also determined. Pearson's correlation coefficients were obtained and differences between SI and all other variables were considered. A stepwise regression procedure was applied, using the variables most closely correlated with SI and their simple transformations (quadratic, inverse, logarithmic). The MEANS, CORR, REG and GLM procedures in the SAS statistical package (SAS Institute, 2004) were used for data analysis.

3. Results

3.1. Effect of bedrock on soil parameters, foliar levels and site index

Type of bedrock did not have a significant effect on some chemical soil parameters: pH (range of average values for each bedrock 4.39 to 4.81); organic matter (SOM, 11.8 to 16.9 %); available P (4 to 9 mg kg^{-1}); exchangeable K (37.3 to 70.8 mg kg^{-1}) and exchangeable Mg (8.5 to 31 mg kg^{-1}). Regarding soil parameters, the bedrock significantly ($p<0.05$) affected exchangeable Ca, total N, C/N ratio and soil depth (Table 2 and Figure 2). The exchangeable Ca concentrations were significantly higher in soils developed over BSCH than in the other soil. The SOM was high in all the plots, whereas the C/N ratio was significantly higher for QUAR, SLAT, SEDM and MSCH. Total N was thus low in these substrates, and the maximum values were obtained for BSCH and GNEI (Table 2).

The soil depth was significantly greater ($p=0.0001$) for GNEI, SEDM, MIGM and GRAN than for the other types of bedrock (Figure 2). Differences in slope are representative of the local topography of the different types of bedrock, with the slate and quartzite areas being much more rugged (which is also associated with higher elevations and lower temperatures) than the sedimentary areas (located in the inner plateau) or BSCH (located in mild climates at low elevation).

The C/N ratio was positively and negatively correlated with elevation and temperature ($r=0.338$, $p<0.0001$ and $r=-0.289$, $p=0.0009$, respectively). Analysis of covariance revealed that the differences as regards SOM quality, expressed as the C/N ratio, were derived from elevation ($p=0.0454$) as well as from the bedrock ($p<0.0001$), which apparently affects the litter composition indirectly through the understory vegetation.

Type of bedrock significantly affected the foliar concentrations of N, P, Ca, K and Mg (Table 2 and Figure 2, $p=0.0078$ for K). The highest concentrations of these nutrients were obtained in BSCH, a group represented by only five plots. In fact, in the case of Ca, no differences were found when these plots were excluded from the analysis, showing that Ca foliar concentrations are low in relation to most of the parent materials represented. For foliar N, Mg and K, the formation of lithological groups is clearer, with MSCH, SLAT, SEDM and QUAR included in a final group with low levels, and GNEI, GRAN, MIGM and, particularly, BSCH, forming a group based on higher foliar concentrations. This general trend was not observed for foliar P, as QUAR was included in a first group and GNEI and GRAN were included in the final group (Table 2).

Foliar concentrations of N and Ca ($p<0.0001$) and, to a lesser extent, K ($p<0.01$) were significantly correlated with the availability of these elements in the soil; however, there was no relationship between the concentrations of P and Mg and their availability in soil (Table 3). Foliar N was also significantly correlated with exchangeable Ca, Mg and, particularly, K. The foliar concentration of Ca also was significantly associated with total soil N and to a greater extent with soil Mg and K. Foliar K was similarly related to exchangeable Ca and Mg (Table 3).

3.2. Nutrient deficiencies in relation to bedrock

Some attempts have been made to propose deficiency levels for foliar macro and micronutrients in this species (see Eimil-Fraga et al., 2012, for a complete review). If we consider the foliar deficiency levels proposed, the percentage of plots with nutrient deficiencies can be calculated in relation to each bedrock type. The percentage of plots with no nutrient deficiencies and the percentage of plots with deficiencies in one or more nutrients are shown in Table 4. We can conclude that the most plots in SEDM, MSCH, QUAR, SLAT and MIGM show deficiencies in more than one nutrient. As well as a generalized shortage of P, which is low in most plots for all types of bedrock, the results indicate different needs of nutrition management in the sites characterised by each bedrock. For MIGM, most plots will show more than one deficient level, particularly for P, N and K. Nutritional status is better for GNEI and particularly for GRAN. K and P deficiencies are expected in these sites. A second group can be established by considering SLAT and MSCH, in which 75% of the plots display deficiencies in more than one nutrient, particularly K and N, as well as P. For these bedrock types, nutrition management would have to consider the shortage of N. The sites that are most limiting for maritime pine growth are those established over QUAR and SEDM bedrock. For QUAR, most plots show deficiencies in N, K and P with additional problems for Ca and Mg. For SEDM, the most limiting nutrients are P, K and N.

Two groups of bedrocks were established for site index ($p=0.0001$): one group comprises highly productive plantations on BSCH, GRAN, MIGM and GNEI (in migmatites, location at lower elevation and deeper soil appear to compensate for the frequent nutritional deficiencies) and the second group is formed by SLAT, QUAR, MSCH and SEDM, with lower site index (Figure 2).

Site index was positively and significantly correlated with soil depth, temperature, foliar K and, to a lesser extent, foliar Ca and Mg. In addition, site index was negatively and significantly correlated with elevation, as expected. Therefore, good site quality is associated with deep soils, high temperatures, low elevation and good nutritional status (Table 5).

3.3. Predictive models of site index

Two regression models were developed to predict site index from temperature, elevation, soil and foliar parameters. A complete model considering all the plots and undifferentiated geological material may explain a maximum of 52% of the total variability of site index, including Ca and K foliar concentration, soil depth and average annual temperature (Table 6). The foliar nutrient levels were important in the regression, and foliar Ca is included quadratically in the regression. The data indicate that growth is more dependent on foliar variables than on soil variables. Another equation was fitted for plots on granitic rock (Table 6), which explained 53% of the site index variability, including foliar K, soil depth and temperature. The specific model should be used when geological material is granite, as the bias is lower (mean residue, MRES<0.0001 versus MRES=0.019) and the accuracy is better (root of mean square error, RMSE=2.09 versus RMSE=2.21) than with the general model.

4. Discussion

4.1. Influence of the bedrock on soil properties and site index

The results of this study showed that the bedrock plus elevation can be considered basic information for determining the growth potential of maritime pine. The role of bedrock as an explanatory factor for vegetation cover and tree growth has long been recognised and recently highlighted (Hahm et al., 2014).

Several chemical properties of the soil were not affected by bedrock in this study. This may be because the effect of the bedrock on soil properties becomes weaker for highly weathered soils (Macías et al., 1982). Nonetheless, differences were found for exchangeable Ca, which may be related to the higher content of calcic plagioclase in biotitic schists, and also for *Pinus radiata* in the region (Sánchez-Rodríguez et al., 2002). Total soil N was lower for QUAR, MSCH or SEDM, along with high C/N ratios, which may be attributed to slow decomposition of plant remains in sites predominantly located on steep slopes at high elevations, where processes of podsolization and extreme acid conditions have been reported, particularly for quartzite (Macías et al., 1982). Site fertility for maritime pine growing in the Landes is known to be determined by SOM content (Bakker et al, 2006). In the present study, the contents were always high and the effect on N nutrition was derived from the quality of the SOM.

Soil depth is known to result from rock weathering and the extent of rock fracturing, topography and intensity of erosion (Macías et al., 1982). Soils may be shallow because the underlying rock is very resistant to alteration as QUART, SLAT or non-tectonized granite in this study. The presence of steep slopes may also be important, being higher for QUART and SLAT in the present study. The greater soil depth of many soils developed over rocks that are resistant to weathering, such as the granites in this study, may be related to a higher degree of tectonization in areas with abundant faults or fractures. The plantations over BSCH are growing on former agricultural land that has been transformed by reforestation, with parent bedrock rich in biotite and calcic plagioclases; all of these factors lead to a good nutritional status of trees, even though the observed soil depth may be only moderate.

4.2. Estimation of site index based on site variables and nutrition

The result of this study showed that foliar K concentration can be considered a key element for ascertaining the growth potential of the species, as well as the effects of Ca and Mg.

It is therefore not surprising that nutrient concentrations are important variables for inclusion in site index models. Bara and Toval (1983) reported general relationships between growth and soil and climate properties, with elevation, soil depth, soil K and soil Ca explaining 48% of the total variation. López Varela et al. (2009) found that site index was significantly and positively correlated with soil depth, K foliar concentration and average annual temperature. In a study in northern Portugal, Pacheco-Marques (1991) found that site quality was also related to topographic, climatic and edaphic factors and that foliar K also influenced the productivity of this species. Although P is the main nutrient limiting growth in the area, the narrow range of foliar concentrations, which are always below or very close to deficiency levels, probably decreases the utility of this variable as predictive of SI.

The results are consistent with those reported by Gandullo and Sánchez Palomares (1994) with regard to the low influence of soil parameters on tree growth, as only soil depth was included in the regression model in our study. This was also the case in a recent study in Asturias (Álvarez-Álvarez et al., 2011) and again indicates the low site-demanding character of maritime pine in comparison with other pine species. In *Pinus radiata* plantations in the same area of study, site index strongly depended on some soil properties, particularly soil pH, and it was negatively related to soil N accumulation (Sánchez-Rodríguez et al., 2002).

The findings of this study highlight the need to apply site-specific management for pine species, as proposed for other species (Turner et al., 2001; Louw and Scholes, 2002). Stands in cold sites (average annual temperature below 10ºC, 11th percentile of the plots) on shallow soils will display very poor growth if located on sites over bedrock, leading to shortages in K and Ca availability. In such cases, nutrient shortages can be prevented through careful selection of plantation sites to bypass certain types of bedrock. The design of fertilization patterns should also be site specific, and the results show that in most sites the key nutrients that should be added are K and Ca. Target foliar concentrations of nutrients to be reduced by fertility, based on the modelling applied in this study are as follows: 5.4 mg g^{-1} K and 1.3 mg g^{-1} Ca, which correspond to the 70th percentile of the plots. These values would be more easily reached in soils over granite rock.

5. Conclusions

Differences in *Pinus pinaster* growth were found in relation to the type of bedrock, indicating the interest in basic geological information for land classification and matching of forest species to site. For maritime pine, the highest site index was associated with low elevation, high temperatures and deeper soils. The poorest growth and highest nutrient deficiencies were observed in the soils over SLAT, QUAR, MSCH and SEDM, which explains the corresponding low site indexes. Foliar concentrations of K, Ca and Mg were the most closely related to site index, and the foliar K varied greatly depending on the bedrock. This indicates that *Pinus pinaster* is best adapted to soils over GNEI, MIGM and GRAN, characterised by being moderately deep on average and having higher levels of foliar K. These will also be the most suitable materials for promoting sustainable development of this species.

Acknowledgements

Founding for this research was received from the competitive reference all of the Regional Government of Galicia, cofounded by ERDF. We thank Christine Francis for revising the English version.

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Table 1. Description of ages, formations and mineralogy of each bedrock type

BEDROCK TYPE	AGE	FORMATIONS	MINERALOGY
Granitic Rocks	Precambrian, Hercynian (sincematic) or Late-Hercynian (postcinematic granites)	Two-mica granites, biotitic granites, granodiorites, calcoalkaline granites	Quartz, K- feldspar, Na-plagioclase, mica, biotite (Fine), medium to coarse grain Variable presence of fractures
Gneiss	Preordovician	Ortogneiss, paragneiss, biotitic gneis	Similar to granite but with foliated, easily ruptured planes
Migmatites	Precambian to Devonian	Migmatites, migmatitic granitoids, migmatitic gneiss	Similar to granite. Alternating fine micaceous layers with coarse quartz-feldespatic minerals
Biotitic Schists	Hercynian	Biotitic Schists	Biotite (abundant), chlorite, feldspar, quartz, amphiboles
Mica Schists	Precambian, Ordovician, Siluriam, Devonian	Mica schists, quarzitic schists, graphitic schists, green schists	Moscovite, quartz, biotite, chlorite, albite
Slates	From Cambrian to Devonian-Carboniferous	Phyllites, slates with bands of sandstone, slates alternating with quartzites	Quartz, muscovite, sericite, chlorite, biotitic
Sediments	Oligocene, Miocene, Pleistocene	Alluvial sediments, conglomerates	Predominantly quartz and muscovite.
Quartzites and sandstones	Cambrian to Ordovician	Quartzites, quartzites alternating with slates, quartzites and mica schists, sandstones and slates	Quartz > 90%

Table 2. Average values (and standard deviations) of several parameters in relation to type of bedrock (for explanation of abbreviations, see Material and Methods), with the respective p values for the ANOVA. Letters correspond to mean classification by Duncan's test.

Variable	BSCH	GNEI	MIGM	GRAN	SLAT	QUAR	MSCH	SEDM
Elevation (m) $p<0.0001$	306 (138) c	360 (192) c	283 (220) c	403 (206) bc	587 (137) ab	627 (219) a	544 (186) ab	563 (25) ab
Total N (%) $p=0.0009$	0.52 (0.19) ab	0.65 (0.21) a	0.41 (0.14) bc	0.43 (0.20) bc	0.40 (0.15) bc	0.31 (0.12) c	0.34 (0.13) bc	0.35 (0.15) bc
C/N $p<0.0001$	14.40 (1.99) d	15.48 (1.76) cd	18.97 (3.94) bc	18.88 (4.31) bc	21.20 (3.54) ab	24.12 (3.78) a	20.58 (3.17) ab	20.90 (3.72) ab
Exchangeable Ca (mg kg^{-1}) $p=0.0159$	86.8 (84.8) a	17.3 (36.8) b	11.5 (11.7) b	23.3 (39.2) b	28.4 (21.6) b	20.0 (13.6) b	14.3 (10.2) b	5.2 (5.7) b
Foliar N (mg g^{-1}) $p=0.002$	11.2 (1.0) a	11.1 (1.2) a	9.7 (2.2) ab	11.1 (1.8) a	9.8 (1.7) ab	9.5 (1.2) ab	9.7 (1.3) ab	9.3 (0.9) b
Foliar P (mg g^{-1}) $p=0.0054$	1.03 (0.22) a	0.78 (0.14) bcd	0.75 (0.14) cd	0.87 (0.18) abc	0.80 (0.15) bcd	0.93 (0.28) ab	0.81 (0.24) bcd	0.69 (0.12) d
Foliar Ca (mg g^{-1}) $p<0.0001$	2.65 (1.07) a	1.28 (0.64) b	1.17 (0.52) b	1.22 (0.44) b	1.04 (0.36) b	0.93 (0.31) b	1.15 (0.2) b	0.92 (0.18) b
Foliar Mg (mg g^{-1}) $p=0.0083$	1.65 (0.49) a	1.44 (0.58) ab	1.32 (0.43) ab	1.63 (0.60) a	1.25 (0.42) ab	0.95 (0.33) b	1.13 (0.30) ab	1.26 (0.42) ab
Temperature (° C) $p<0.0001$	12.3 (0.6) ab	12.3 (1.1) ab	13.2 (1.7) a	11.8 (1.4) bc	11.5 (1.1) bcd	10.5 (1.3) d	11.3 (0.9) bcd	10.8 (0.2) cd

Table 3. Correlation between the concentrations of nutrients in needles and soil

	Total N	Exchangeable Ca	Exchangeable Mg	Exchangeable K
Foliar N	0.474***	0.197*	0.209*	0.555**
Foliar Ca	0.182*	0.378***	0.275**	0.269**
Foliar Mg				- 0.194*
Foliar K		0.262**	0.290**	0.329**

* $p < 0.05$; ** $p < 0.01$; *** $p < 0.0001$

Table 4. Percentage of plots with deficiencies in no, one or more nutrients for each type of bedrock

Geological material	BSCH	GNEI	MIGM	GRAN	SLAT	QUAR	MSCH	SEDM
No deficiencies	80%	30.8%	7.1%	36.4%	7.1%	11%	0%	16.7%
Deficiencies in one nutrient	20%	15.4%	21.4%	29.1%	21.4%	22%	25%	0%
Deficiencies in more than one nutrient	0%	53.8%	71.5%	34.5%	71.5%	67%	75%	83.3%

Table 5. Correlation between SI, nutrient foliar concentration, soil depth, average annual temperature and elevation

	Foliar Ca	Foliar Mg	Foliar K	Soil depth	Temperature	Elevation
SI	0.193*	0.216*	0.346***	0.404***	0.550***	- 0.599***

* $p < 0.05$; ** $p < 0.01$; *** $p < 0.0001$

Table 6. Regressions between SI, soil depth, average annual temperature and nutrient foliar concentration

Model	n	Regression	R^2	SSE
Complete	128	SI= 20.64457 + 0.55389* K + 2.6763* soil depth - 141.74174* 1/ average annual temperature + 0.18717* Ca^2	0.5179	567.93
Granitic rocks	55	SI= 21.99113 + 0.56813* K + 2.82062* soil depth – 155.71762* 1/ average annual temperature	0.5330	218.78

HIGHLIGHTS

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- Bedrock significantly influences nutrient status and site index of maritime pine.

- Soils on biotitic schists, gneiss, migmatites and granites are favourable for tree growth.

- Shortages of nutrients are widespread and can be avoided based upon bedrock.

- 52% of site index can be explained soil depth, elevation and foliar K and Ca.

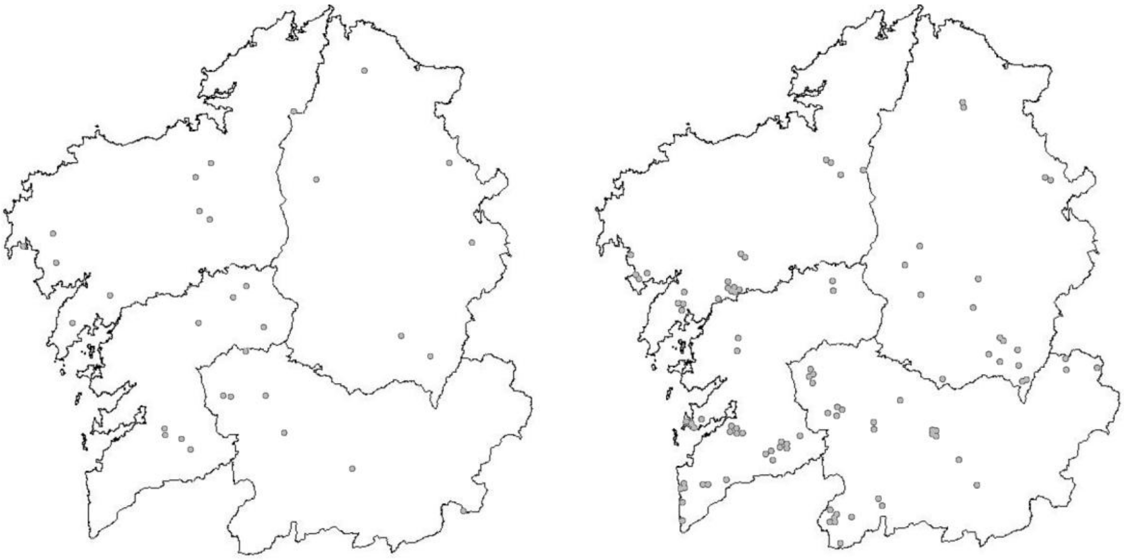

Figure 1. Location of the 128 plots of *Pinus pinaster* in Galicia (NW Spain) considered in this study: the first group is shown in the map on the left (31 plots) and the second group on the right (97 plots).

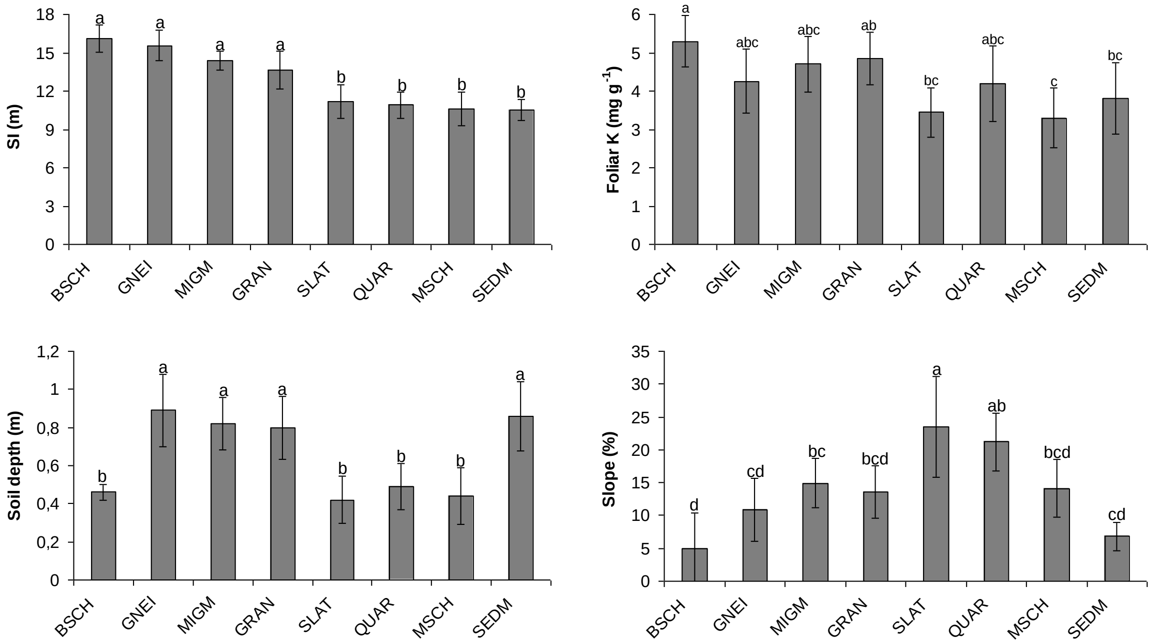

Figure 2. Average values (and standard deviations: error bars above and below average) for soil depth, slope, foliar K and SI in relation to the type of bedrock. Letters correspond to the groups according to Duncan's test.