

Site index estimation in Scots pine (*Pinus sylvestris* L.) stands in the High Ebro Basin (northern Spain) using soil attributes

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Summary

Site index curves and an edaphic discriminant rule for Scots pine stands in the High Ebro Basin (northern Spain) are presented to estimate site index under different silvicultural situations. High-grading practices strongly modify the forestry structure by the means of bias in the dominant height and stand density. In order to achieve the silvicultural and site variability of Scots pine stands in the studied area, 75 plots from the National Forest Inventory of Spain (NFI) were selected. In these plots 46 dominant trees were cut down and 104 trees were bored at stump and at breast height (1.3 m). In each plot a soil sample from the first 10 cm of soil was taken and signs of dimensional cutting were recorded. Site index curves and the edaphic discriminant rule were developed. The site index curve model used is an extension of the Richards model. The site factors selected in the discriminant rule represent the most important edaphic parameters for forest productivity (texture and the assimilability of the nutrients). Site quality of the studied stands was medium-low as compared with other site index curves for Scots pine around the world. The edaphic discriminant rule presented is useful for estimating site index classes in stands exposed to dimensional cutting and in young stands of Scots pine in the High Ebro Basin (northern Spain). Site index curves were fitted to allow an estimate of the site index of undisturbed and stands which were not high-graded.

Introduction

Site index, defined as top height (average height of the 100 trees ha⁻¹ of largest diameter) at a base age, is normally applied in forestry for site quality characterization and potential productivity estimation. On the other hand, it is an important parameter in forest growth and yield modelling. Site index can be estimated through site data,

stand data, or both combined. When dimensional cutting biases the top height (by harvesting dominant trees), the site index is underestimated if stand data are used. In order to estimate site index, site variables are useful when site trees are not suitable. Systems for evaluating site quality and predicting forest yield based upon the site-growth relationship have been developed in the last half-century. The most important

approach is based on the soil–growth relationship and is called the soil–site method. Although these kinds of relationships have been studied for a wide range of species elsewhere (e.g. Harding *et al.*, 1985; Jokela *et al.*, 1988; Monserud *et al.*, 1990; Pacheco, 1991; Wang, 1995), very few soil–site studies have been reported for Scots pine (Tamminen, 1993; Holmgren, 1994) and none in the southern area of its distribution.

In soil–site studies, topographic and edaphic factors are utilized to estimate site index in these situations. The topographic factor commonly used is altitude (Jokela *et al.*, 1988; Pacheco, 1991; Holmgren, 1994) because it is closely related to regional climate. In addition, slope and aspect (Jokela *et al.*, 1988; Pacheco, 1991; Holmgren, 1994) and geographical position (Pacheco, 1991) have been used. Topographic factors are usually utilized in combination with edaphic factors. Physical properties of soils related to soil moisture and nutrient levels are commonly analysed (Baker and Broadfoot, 1979; Jokela *et al.*, 1988; Turner *et al.*, 1990; Pacheco, 1991). The wide range of nutrients used to estimate site index and the variable analytical methods obscure the comparison of results. On the other hand, the nutrients explain a low percentage of height increment (Baker and Broadfoot, 1979). Thus, it is not surprising that some authors avoid the use of nutrients in site index estimation (Steinbrenner, 1976). Soil and horizon depths also are included in the soil characterization by some authors (Jokela *et al.*, 1988; Turner *et al.*, 1990). Linear regression has been used to relate soil properties and site index (Steinbrenner, 1976; Bara and Toval, 1983; Pacheco, 1991; Tamminen, 1993; Holmgren, 1994; Wang, 1995). However, multicollinearity among soil properties in relation to site index may also cause problems in regression analysis (McQuilkin, 1976; Verbyla, 1986). To avoid this problem, classification systems such as tree classification (Verbyla and Fisher, 1989) or discriminant analysis (Harding *et al.*, 1985) have been used previously.

Scots pine (*Pinus sylvestris* L.) is one of the most important species in Europe. Together with other species it dominates the forest landscape from the boreal region in northern and eastern Europe to the Mediterranean mountains in southern Europe. Intelligent management of this vast forest resource requires accurate assessment of

forest productivity both at local and regional levels. In the wide area occupied by Scots pine, accurate information on growth site relationships is needed, especially where site trees are not suitable (e.g. young and high-graded stands).

The aim of this study was to evaluate site index estimators in Scots pine stands in the mountainous areas of northern Spain. To accomplish this objective, site index curves and an edaphic discriminant rule for Scots pine stands in northern Spain were developed. A minor objective was to uncover soil–productivity relationships in Scots pine stands in the Mediterranean mountain distribution area. These objectives were accomplished by analysing soil and dendrometric data from 75 pure Scots pine stands in the the High Ebro Basin in northern Spain.

Materials and methods

Site description

The High Ebro Basin is a transitional area for Scots pine in northern Spain situated between 700 and 900 m above sea level. The climate ranges from Mediterranean to the Atlantic types, with an annual rainfall of 787 mm (123 mm in summer), an annual average temperature of 11.2°C, and no pronounced drought or severe frost. The annual variation of temperature and rainfall of the Mediterranean climate is moderated by the Atlantic Ocean influence. Soils are mostly calcareous cambisols, with luvisols in humid sites. *Pinus sylvestris* L. dominates the vegetation community with a mixture of *Quercus faginea* Lamk, *Fagus sylvatica* L., *Quercus ilex* L., *Calluna vulgaris* (L.) Hull, *Erica* spp., *Ulex* spp. and *Pteridium aquilinum* (L.) Kuch in the understorey.

Data

To represent the silvicultural variability of the area studied, 75 plots of the Second National Forest Inventory of Spain (NFIS2) were randomly selected. These plots cover a wide range of silvicultural situations (Table 1) in pure natural Scots pine stands (between 72 and 100 per cent of Scots pine in basal area) in the High Ebro Basin (northern Spain). The NFIS2 plots selected were visited to complete the database. In 23 of these plots,

chosen randomly among the plots with highest basal area ($>20 \text{ m}^2 \text{ ha}^{-1}$) and top height ($>10 \text{ m}$) and with no dimensional cut signs, two dominant, straight, unbroken and non-forked trees were cut and in the other 52 plots, cores from two dominant, straight, unbroken and non-forked trees, at stump (10 cm length from the top soil) and at breast height (1.3 m), were taken. Signs of dimensional cutting (high-grading) based upon the presence of big stumps and the presence of 'released' trees were recorded. Twelve plots were removed from the data set because they had signs of high grading practices and they are not further described.

A soil pit extending down to the first 10 cm layer was used to describe forest soil conditions according to Jokela *et al.* (1988). Soil samples were analysed to determine percentage of sand, silt and clay (using ISSS method); percentage of carbonate and organic matter; concentrations of phosphorus using the Olsen method, potassium,

calcium, magnesium and sodium following extraction with 1 N ammonium acetate; cation exchange capacity (CEC), defined as the equivalent amount of cations from the first salt that are retained on the exchange sites, in meq/100 g, pH and electrical conductivity (mmhos/cm). Soil laboratory analyses followed the standard procedures in agricultural soil research. Soil characteristics are summarized in Table 2. Only soil data from old stands (over 85 years old) without dimensional cut signs were used in developing soil-site relationships (28 plots).

In each felled tree, sections for stem analyses were made every metre from the stump to 5.3 m height and every 2 m from 5.3 m height to the tip. In each section, two radii were analysed by an optical scanner and WinDendro v 6.2 software (Régent Instrument, 1997a, b). Cores were also analysed using WinDendro software. As stated before, data from high-graded plots were removed so that a total number of 554 data

Table 1: Characteristics of Scots pine plots used to study site index estimation in the High Ebro Basin (northern Spain)

	Basal area (m^2/ha)	Volume (m^3/ha)	<i>n</i> (trees/ha)	Dg* (cm)	<i>H</i> ₀ (m)
Mean	26.64	159.97	690.28	24.10	13.42
Maximum	60.16	375.55	1743.75	37.98	23.74
Minimum	15.28	86.91	142.71	12.71	6.28
Standard deviation	9.42	62.62	407.10	6.14	3.65

*Dg is the mean quadratic diameter.

Table 2: Characteristics of the soil samples used to develop the discriminant rule to estimate the site index class in Scots pine stands in the High Ebro Basin (northern Spain)

Variable	Mean	Standard deviation	Maximum	Minimum
Sand (%)	62.08	14.06	85.23	37.05
Silt (%)	20.06	9.13	37.40	6.75
Clay (%)	16.80	8.67	34.85	5.35
P (p.p.m.)	3.50	4.48	23.00	1.00
K (p.p.m.)	140.32	97.59	445.00	19.00
Ca (meq/100 g)	16.91	13.69	49.40	0.20
Mg (meq/100 g)	0.19	0.21	0.60	0.00
Na (meq/100 g)	0.84	1.08	4.95	0.05
Carbonates (%)	3.37	5.49	18.00	0.00
Organic matter (%)	4.89	2.06	10.30	1.10
CEC (meq/100 g)	19.16	8.56	34.40	5.50
pH	6.26	1.57	8.30	3.60
Conductivity (mmhos/cm)	0.19	0.11	0.41	0.02

(height/age pair values) from 116 trees in 63 plots without dimensional cut signs were used. The data used from stem analysis to develop site index curves are shown in Figure 1. According to previous works (Lembcke *et al.*, 1975; Schober, 1987; Persson, 1992; Rojo and Montero, 1996), site index is defined as top height at a base age of 100 years. The site index was estimated using stem analysis when the felled trees were older than 85 years. Otherwise, the site index was predicted from soil attributes using the discriminant rule previously developed. Table 3 shows the distribution and origin of the height/age data set.

Data analysis

Site index model A great variety of height growth models has been used in forest research. Two main groups of growth models have been used: deterministic (continuous and time-discrete) and stochastic models. The most classical and widespread approach is the deterministic, using continuous models such as those of Schumacher (1939), Von Bertalanffy (1949, 1957), Richards (1959) and its variants. Zeide (1993)

carefully described and analysed these kinds of models. Wang and Payandeh (1994), using a time-discrete model, found it useful to construct a base-age invariant site index model for *Picea mariana* (Mill.) B.S.P. The stochastic models have been explored by several authors. García (1983) used a stochastic differential equation approach including the Richards model as the deterministic part of the equation. The diffusion approach has been used by Rennolls and Little (1993) to develop a stochastic growth model. Although there is this great variety in approach and models in height growth studies, Richards' (1959) model has been extensively used in forestry because its differential form includes the basic components of biological growth: anabolism and catabolism. Models with a biological basis, like Richards' model, extrapolate consistently out of the original data range. On the other hand, in its original form, Richards' model needs to be fitted independently for each site index class. To fit site index curves Payandeh (1977) used an extension of Richards' model, previously reported by Ek (1971) (model 1). This extension has the ability to generate polymorphic curves and allows a fit of all site index classes simultaneously.

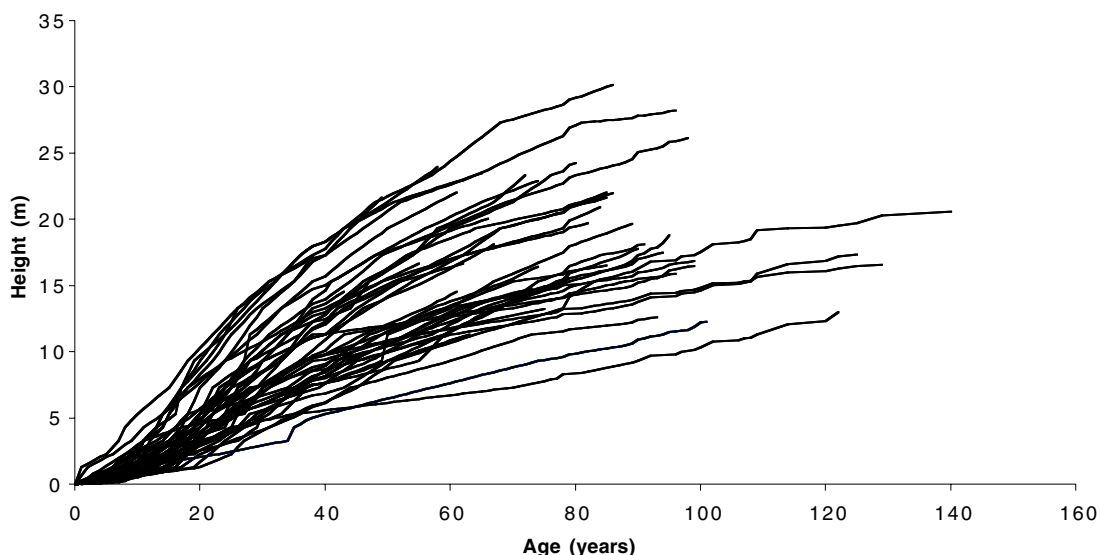


Figure 1. Stem analysis data set used to develop site index curves for Scots pine in the High Ebro Basin (northern Spain).

Table 3: Origin of height/age data set used to fit the site index curve model

Site index	Core plots (trees)	Stem analysis plots (trees)	Total plots (trees)
14	19 (34)	8 (16)	27 (50)
17	8 (15)	1 (2)	9 (17)
20	7 (12)	5 (10)	12 (22)
23	6 (9)	9 (18)	15 (27)
Total	40 (70)	23 (46)	63 (116)

$$H_0 = a * S^b * \left| 1 - e^{c * t} \right|^{d * S} \quad (1)$$

where H_0 is the dominant height, t is the total age, S is the site index and a , b , c , d and e are the parameters.

Model (1) does not fit the definition of site index (H_0 predicted at the base age is not the SI), so Newnham (1988) and Payandeh and Wang (1994) proposed a modified site index model (2):

$$H_0 = a * S^b * \left| 1 - e^{-c * t_i} \right|^{f(a, b, c, t_i, S)} \quad (2)$$

where

$$f(a, b, c, t_i, S) = \frac{\ln \left| \frac{S^{(1-b)}}{a} \right|}{\ln \left| 1 - e^{(c * t_i)} \right|}$$

and t_i is the base age.

Nonlinear regression using the Marquardt algorithm has been utilized to fit site index curves. Seed values of parameters to start the non-linear fitting process were obtained from site index curves for Scots pine in the central range of Spain (Rojo and Montero, 1996). The PROC NLIN procedure of SAS was used.

Edaphic discriminant models Discriminant functions studied include edaphic variables related to nutrients, assimilability and soil structure. Fifteen discriminant models were studied in order to determine site index class. In addition a variable number of site index classes were tested (three, four or five). The central points for each one of these site classes were 14, 17, 20, 23 and 26 m (five classes), 14, 17, 20 and 23 m (four classes) and 14, 20 and 26 m

(three classes), so 45 combinations (15 discriminant rules for each number of site index classes) were tested. The variables considered for discriminant analysis are normally distributed (Table 4) and are not strongly correlated (Table 5). No correlation between silt fraction and CEC was found by Ilvesniemi (1991) in Scots pine forest soils. Edaphic variables showing lack of normality (Table 4) were not further used in the analysis. The discriminant rules studied were as follows:

- (3) constant + sand + $\sqrt[3]{(K)}$ + organic matter + CEC
- (4) constant + silt + $\sqrt[3]{(K)}$ + organic matter + CEC
- (5) constant + silt + $\sqrt[3]{(K)}$ + organic matter + conductivity
- (6) constant + silt + organic matter + conductivity
- (7) constant + sand + $\sqrt[3]{(K)}$ + organic matter + conductivity
- (8) constant + $\sqrt[3]{(clay)}$ + $\sqrt[3]{(K)}$ + organic matter + conductivity
- (9) constant + $\sqrt[3]{(clay)}$ + organic matter + conductivity
- (10) constant + $\sqrt[3]{(clay)}$ + organic matter + CEC
- (11) constant + $\sqrt[3]{(clay)}$ + organic matter
- (12) constant + $\sqrt[3]{(clay)}$ + CEC

Table 4: Normal probabilities of Shapiro–Wilk test of edaphic variables

Variable	X	$\sqrt{X}$	$\sqrt{X+0.5}$	$\ln(X+1)$	$\log(X)$
Sand (%)	0.3115	0.2853	0.2857	0.1976	0.1945
Silt (%)	0.1909	0.3064	0.3098	0.1664	0.1468
Clay (%)	0.0436	0.3055	0.2903	0.4644	0.4637
P (p.p.m.)	0.0001	0.0001	0.0001	0.0003	0.0011
K (p.p.m.)	0.0058	0.7296	0.7232	0.5243	0.4860
Ca (meq/100 g)	0.0038	0.0488	0.0385	0.0043	0.0012
Mg (meq/100 g)	0.0001	0.0001	0.0002	0.0002	n.v.
Na (meq/100 g)	0.0001	0.0040	0.0003	0.0011	0.0455
Carbonates (%)	0.0001	0.0001	0.0001	0.0001	n.v.
Organic matter (%)	0.5217	0.5211	0.6148	0.1610	0.0291
CEC	0.1117	0.0354	0.0366	0.0068	0.0055
pH	0.0048	0.0028	0.0029	0.0018	0.0055
Conductivity (mmhos/cm)	0.2831	0.4260	0.3377	0.3382	0.0297

Values in bold indicate the normal variables selected.
n.v., values not valid for the transformation.

Table 5: Correlation between edaphic variables using the Pearson coefficient

Variables	Sand	Silt	$\sqrt{(\text{Clay})}$	$\sqrt{(\text{K})}$	MO	CEC	Conductivity
Sand	1.00000	-0.77622	-0.75655	-0.63352	-0.07854	-0.28235	-0.65050
Silt		1.00000	0.41586	0.67842	0.32249	0.48531	0.72451
$\sqrt{(\text{Clay})}$			1.00000	0.53364	0.00948	0.11875	0.48101
$\sqrt{(\text{K})}$				1.00000	0.33484	0.39082	0.53741
MO					1.00000	0.49158	0.54512
CEC						1.00000	0.37980
Conductivity							1.00000

(13) constant + silt + $\sqrt{(\text{clay})}$ + organic matter + conductivity

(14) constant + silt + $\sqrt{(\text{clay})}$ + organic matter + CEC

(15) constant + silt + $\sqrt{(\text{clay})}$ + organic matter

(16) constant + silt + $\sqrt{(\text{clay})}$ + CEC

(17) constant + silt + $\sqrt{(\text{clay})}$ + conductivity

Classificatory discriminant analysis has been applied to obtain site index groups from soil variables. The original dataset has been used both to define and to evaluate the classification criteria. The resulting error-count estimate has an

optimistic bias and is called an apparent error rate. In order to reduce this bias, cross-validation has been used (for further details, see Johnson, 1998, pp. 217–285). For all independent variables, normality, using the Shapiro–Wilk test, and correlation, using the Pearson coefficient, were studied. Different transformations of original variables were tested to eliminate non-normality. The procedures CORR, DISCRIM and UNIVARIATE of SAS were used.

Results

All the parameters of site curve model were significant at a probability level of 95 per cent (Table

Table 6: Site index curve parameter estimates by non-linear regression in Scots pine stands in the High Ebro Basin (northern Spain)

Parameter	Estimate	Standard deviation	Confidence interval (95%)	
<i>a</i>	1.0852	0.0102	1.0652	1.1051
<i>b</i>	1.0006	0.0108	0.9794	1.0219
<i>c</i>	-0.3137	0.0127	-0.3386	-0.2888

6). The mean-squared of the error and the mean-squared of the model are equal to 0.0753 and to 219.9708, respectively. The use of site index as independent variable allows the generation of polymorphic site index curves. The model fitted is:

$$H = 1.852 \times 5^{1.0006 \times t} \left(1 - e^{-0.3137 \times t} \right) \left(\frac{\ln \left(\frac{8.50006}{1.0852} \right)}{\ln \left(1 - e^{-0.3137 \times 100} \right)} \right)$$

The cross-validation of the discriminant model is shown in Table 7. The correct classification of site index is over 68 per cent in classes 14, 17 and 23. In class 20 the classification using this model is poor (8.33 per cent). The misclassifications are usually concentrated in a contiguous site index class. The performance of the model fitted is adequate with a 61.11 per cent overall correct classification.

The error rates of the discriminant rules ranged from 0.6967 to 0.3278. The error rate decreased when the number of site index classes decreased, so a compromise between a low error rate and an

adequate number of site index classes was needed. In addition, a low error rate is more important in the highest site index classes. Error in the site index estimation in a high productivity stand involves a higher bias in the growth and yield prediction than in a low productivity stand. Error distributions with the best discriminant rule for each number of site index classes are presented in Table 8. Model (16), with four site index classes, had no error in classes 23 and 17; in addition the misclassifications in class 20 (error rate equal to 80 per cent) were distributed between adjacent classes 23 and 17. Therefore model (16) and four site index classes were selected and the parameters of this model are shown in Table 9. When dimensional cutting is not used in a given stand, the site index curves may be utilized to determine site index. Otherwise, and in young stands, the edaphic discriminant rule may be applied.

Discussion and conclusions

The site quality of Scots pine stands in the studied area is medium-low compared with other site

Table 7: Cross-validation of the site index model using stem analysis data from trees older than 85 years in Scots pine stands in the High Ebro Basin (northern Spain)

Actual site index class	Predicted site index class*			
	14	17	20	23
14	71.74%	21.74%	6.52%	0.00%
17	25.00%	68.75%	6.25%	0.00%
20	50.00%	41.67%	8.33%	0.00%
23	2.78%	4.17%	20.83%	72.22%

* The height-age values over 20 years and the site index curves fitted have been used to predict the site index classes.

Table 8: Error rates by site index class and overall for the selected edaphic discriminant rules using the index class for five, four and three sites in Scots pine stands in the High Ebro Basin (northern Spain)

Model	SI					Total
	14	17	20	23	26	
16	0.6667	0.0000	0.7500	1.0000	0.2500	0.5333
16	0.6667	0.0000	0.8000	0.0000		0.3667
7	0.4000		0.3333		0.2500	0.3278

Table 9: Edaphic discriminant rule to estimate site index class for Scots pine in northern Spain

Variables	Site index			
	14	17	20	23
Constant	-14.87014	-11.45326	-13.60515	-5.82951
Silt	0.03833	0.05722	-0.07621	-0.02714
$\sqrt{(\text{clay})}$	5.37847	3.59074	5.72787	3.62204
CEC	0.26128	0.38393	0.22954	0.16047

index curves for natural stands and plantations around Europe and the eastern United States (Decourt, 1965; Hamilton and Christie, 1971; Hannah, 1971 in Carmean *et al.*, 1989; Lembcke *et al.*, 1975; García Abejon, 1981; García Abejon and Gomez Loranca, 1984; García Abejon and Tella Ferreiro, 1986; Schober, 1987; Persson, 1992; Jansen *et al.*, 1996; Rojo and Montero, 1996). Usually the highest class of our system corresponds with the medium class of the other systems. The maximum SI in the other classes is over 29 m. If one compares the site index curves presented in this paper with the Rojo and Montero (1996) site index curves for central Spain, those estimate a superior site class in the young stands, but at 70 years of age the estimation tends to stabilize in the actual site class. This effect is analogous to the density-dependent behaviour of site index curves developed in natural stands when they are used in plantations. Elfving and Kiviste (1997) tested 13 different functions to develop site index equations for Scots pine but the modified Ek-Payandeh model was not used. They advise the use of the Hossfeld

equation in 10–80-year-old stands but not in older stands. This is correct because as the Hossfeld equation has no clear asymptote it overestimates the site index in older trees. In the previous Spanish site index curves for Scots pine (García Abejon, 1981; García Abejon and Gómez Loranca, 1984; García Abejon and Tella Ferreiro, 1986) the Hossfeld equation was used, so these curves may not be used for site index estimation. The use of the Richards model or its modification avoids this problem. The sets of new site index curves for Spain, those of Rojo and Montero (1996) for Central Spain and the curves we show here for northern Spain, avoid this problem by using the Richards model or its extensions.

In areas with high silvicultural, environmental or both of these variabilities, models that predict site class rather than exact site index may be more appropriate. Therefore developing a classification or discriminant rule is more useful in these situations than using a linear model. Verbyla and Fisher (1989) showed the advantages of using a classification instead of a linear regression. In addition, under these circumstances it is easier to

determine site class than an exact site index. These stands in northern Spain show a high silvicultural variability, including high-graded areas, so the discriminant analysis is the correct way to estimate SI. The discriminant rule should be used when the estimation by means of dominant height and age are not secure; for instance, in young stands or in dimensionally cut stands. The discriminant rule estimates the distance between the observation and the different groups so the observation must be classified in the closest group. Site factors representing the most important edaphic parameters for forest productivity, e.g. texture (represented by the percentage of silt and the root-squared of percentage of clay) and the assimilability of the nutrients (represented by the cation exchange capacity) made the greatest contribution in discriminating between site index classes. Wang (1995) found that in white spruce (*Picea glauca* (Moench) Voss), soil physical properties explained more variance (54 per cent) than soil chemical properties (29 per cent). However, the same author found that the combination of soil chemical and physical properties explained up to 60 per cent of the total site index variance. In Scots pine stands in Sweden, soil texture and element ratios have a strong importance for the estimation of site index (Holmgren, 1994). Jokela *et al.* (1988) found that soil drainage conditions (percentage of silt) and fertility (CEC) were important in estimating forest productivity. The failure of soil nutrients alone to explain a large proportion of the total variance of site index in different species such as white spruce (Payandeh, 1986; Wang, 1995), Douglas fir (Monserud *et al.*, 1990), Ponderosa pine (Verbyla and Fisher, 1989) or Scots pine in this case, does not suggest that soil nutrients are not tree-growth limiting. As Wang (1995) stated: (1) there are many nutrients affecting tree growth and the limiting nutrient(s) may vary with site; (2) there are complex interactions between nutrients not described by linear relationships; (3) soil nutrients from chemical analysis may not be perfect measures of nutrient availability to tree growth; and (4) normally the internal nutrient cycling is not considered. The discriminant rule fitted shows that as the CEC becomes lower the texture is more important (Figure 2) to determine the site index (SI) class. Sandy soils usually have a lower SI while clay soils tend to have a higher SI. Study-

ing the regeneration process in the Scots pine stands in the High Ebro Basin (northern Spain), González-Martínez and Bravo (2001) found that in sandy sites the Scots pine showed a higher density of viable seedlings (related to a faster height growth) than in non-sandy sites; however, the authors had no statistical conclusive results in sandy sites due to interaction with other variables (competition and site preparation) and the lack of a strong sample. The site index in silty soils depends strongly on clay percentage and the CEC. Tamminen (1993) found that texture was weakly correlated with site index in southern Finland. However, our study shows that texture is a key variable in determining site index in Mediterranean sites where the soil capacity to retain water is very important to forest growth. The different decomposition rates in boreal and mountain Mediterranean forest soils complicate the interpretation of this finding, but in general the nutrient supply has a lower impact than water supply in tree growth in the studied forest stands. Berg *et al.* (1995) supported this idea because they found that the annual actual evapotranspiration was positively related with mineral (N, P, S and K) decomposition so that when the cycling rate was high (warm sites), an adequate supply and retention of water has the highest importance for tree growth.

In conclusion, the site index curves fitted allow estimation of site index classes in pure Scots pine stands in northern Spain. An overall 61.11 per cent correct classification has been found using the site index curves developed. Additionally, an edaphic discriminant rule was developed which is useful for high-graded and young stands of Scots pine in the High Ebro Basin (northern Spain). The edaphic model selected tends to classify plots into the correct site index group with an error rate of 64 per cent, which is a normal value for this kind of study. Soil analysis is expensive in money and time, so foresters must balance the model's reliability, prediction and alternative systems for estimating site index with the expense of collecting the necessary data. The edaphic rule must be used in high-graded and in young stands while the site index curves must be the general tool in predicting site index in Scots pine stands in the High Ebro Basin (northern Spain). On the other hand, in developing new stands by plantation in the studied area, priority

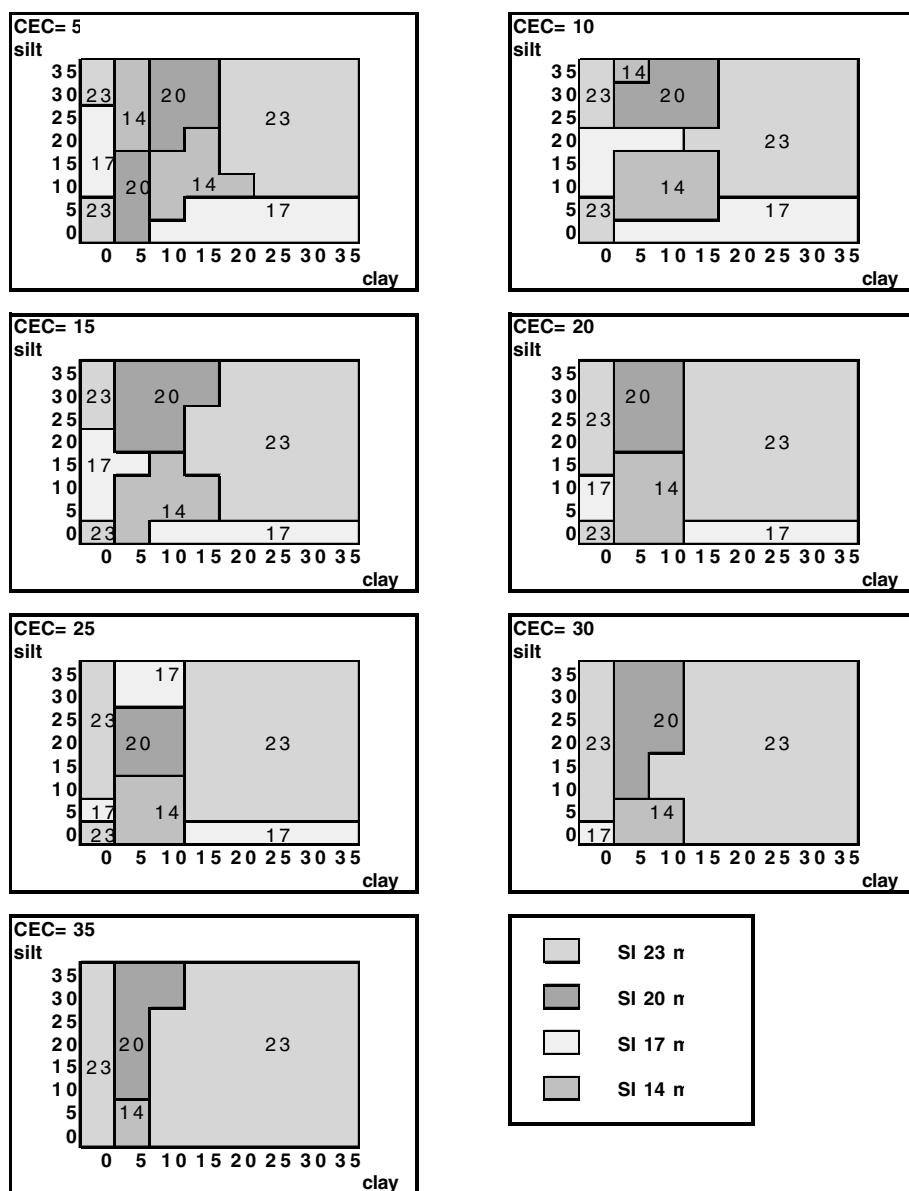


Figure 2. Site index classification using CEC, clay and silt as classificatory variables for Scots pine stands in the High Ebro Basin (northern Spain).

must be given to non-sandy sites. Further analysis is needed to study the influence of texture upon tree growth and its importance on successful forest regeneration.

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