Modelling the Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) site index from site factors in Portugal

LUIS FONTES[1*], MARGARIDA TOMÉ[2], FRANK THOMPSON[1], ALISTAIR YEOMANS[1], JAIME SALES LUIS[3] AND PETER SAVILL[1]

[1] Oxford Forestry Institute, University of Oxford, South Parks Road, Oxford OX1 3RB, England
[2] Instituto Superior de Agronomia, Universidade Técnica de Lisboa, Tapada da Ajuda, 1399 Lisboa Codex, Portugal
[3] Secção Florestal, Universidade de Trás-os-Montes e Alto Douro, Quinta de Prados, Apartado 1013-5000-911,Vila Real Codex, Portugal
*Corresponding author. E-mail: luisfontes@isa.utl.pt

Summary

Although the speed of growth and adaptability of the north-west American conifer Douglas-fir has been recognized in Portugal, it represents only ~0.1 per cent of the total forest cover. This small area is spread across the mountainous areas of the north and centre of the country. This study models Douglas-fir productivity based on site factors and estimates the potential area for Douglas-fir in Portugal. Soil, climate and topographic data were collected on 39 plots across the range of sites where Douglas-fir grows in Portugal. The analysis of the data followed three steps: (1) selection of site factors related to the variation in the site index; (2) choice of candidate models; and (3) consideration of the best model to explain and predict the site index from site factor variables. The best multiple linear regression model explained 90 per cent of site index variation but included variables not readily available in the field. A model using digitized site data explained 54 per cent of the variation in the site index and mapped the areas with potential for Douglas-fir growth in Portugal. It is estimated that a potential Douglas-fir planting area of 250 000 ha exists where trees will exceed 17 m dominant height at age 30 years. This would correspond to 8 per cent of the existing Portuguese forest area. The best sites for Douglas-fir growth are located along north coastal to central regions at altitudes between 500 m and 1000 m with moisture deficit (precipitation minus evapotranspiration) above 1000 mm. Areas with acceptable sites for Douglas-fir growth are located in the north and centre of Portugal at 700–1000 m elevation and have a moisture deficit above 400 mm.

Introduction

Decision-making and strategic planning for conifer planting rely to a great extent on the ability to assess forest productivity (Hassall *et al*., 1994). Predicting forest productivity using site variables has been done many times in forestry (Curt, 1999). The Common Agricultural Policy of the European Union has been promoting the establishment of forest plantations on agricultural land in Portugal, as in other EU countries (Tyler *et al*., 1996; Corona *et al*., 1998; Curt *et al*., 2001), increasing the interest in predicting growth from site factors. Regional studies have been carried out to assess Douglas-fir site productivity based on environmental variables in Scotland (Tyler *et al*., 1996), the Massif Central area of France (Curt, 1999; Curt *et al*., 2001), central Italy (Corona *et al*., 1998), British Columbia (Green *et al*., 1989; Carter *et al*., 1990; Klinka and Carter, 1990), Oregon and Washington for inland Douglas-fir (Monserud *et al*., 1990) and in Ireland (Dunbar *et al*., 2002).

Douglas-fir was introduced to Portugal in the nineteenth century, when it was first planted at Sintra in about 1846 (Gomes and Raposo, 1939) and at Buçaco in 1871 (Goes, 1991). The first plantations were established at Estrela in 1904 (Freitas, 1989) and at Gerês in 1906 (Coutinho, 1936). Since then it has been planted on the mountainous areas in the centre and the north of the country. In 1976, the estimated area of Douglas-fir plantations was <300 ha (Goes, 1991). A few large plantations were established in the late 1970s and early 1980s at Bornes and Malcata, increasing the area of Douglas-fir to 4200 ha.

The high potential for Douglas-fir in the mountainous areas in the centre and north of Portugal has been recognized due to its speed of growth, for being able to grow under a wide range of conditions and to regenerate naturally (Diniz, 1969; Goes, 1976, 1991; Woods, 1976; Louro and Cabrita, 1989; Luis, 1989). In terms of height growth, Douglas-fir has performed better than the following species at Vila Pouca: *Pinus coulteri* D. Don., Lawson's cypress (*Chamaecyparis lawsoniana* (A. Murr.) Parl. (Woods, 1976)), maritime pine (*Pinus pinaster* Ait.), sweet chestnut (*Castanea sativa* Mill.), Corsican pine (*Pinus nigra* var. *maritima* (Ait.) Melv.), Atlas cedar (*Cedrus atlantica* (Endl.) Carr.) and Scots pine (*Pinus sylvestris* L. (Maia *et al*., 1990)). In 1986, the Portuguese Government, together with the World Bank, estimated the potential area available for afforestation with Douglas-fir at ~235 000 ha (Grupo Coordenador do Projecto Florestal–Banco Mundial, 1986). This estimate was based on the site classification system developed by Albuquerque (1982) which subdivides the country into ecological classes with similar climate, soil characteristics and altitude. However, this has just remained an estimate.

In Portugal, based on field experience, the site factors believed to have a major influence on Douglas-fir growth are precipitation, soil depth and altitude. Douglas-fir plantations are in regions where average precipitation is >700 mm a^{-1}. The less productive sites are situated where precipitation is between 700 and 1000 mm (Louro and Cabrita, 1989). Douglas-fir is distributed through a range of altitudes from 400 m to 1350 m. The most productive sites are found between 840 m and 1110 m in altitude (Louro and Cabrita, 1989). Regions where Douglas-fir is grown are high elevations in the mountains, where slopes are steep and soils generally shallow, often only 20 cm deep. Plantations are located within this zone where soils are deeper, in general 50–80 cm.

Site classification studies have already been carried out for biogeoclimatic regions (Costa *et al*., 1999), ecological zones (Direcção Geral do Ambiente, 1998) and afforestation regions (Direcção Geral das Florestas, 2002, unpublished). However, no studies have been carried out on the environmental variables affecting Douglas-fir site productivity so far. Thus, the aim of this study was to investigate the environmental factors affecting Douglas-fir productivity and, based on these factors, to model Douglas-fir productivity in order to provide information for future afforestation projects. The potential area for Douglas-fir establishment in Portugal was also estimated, using digitized data.

Materials and methods

Study area and sampling strategy

Douglas-fir plantations were sampled across the whole of their range in north and central Portugal, representing a variety of landforms, parent materials and climatic environments. Stands selected were pure, even-aged and had been treated uniformly in terms of thinning, in which dominant trees had not been selected. They were located between 460 and 1300 m altitude. The study area was ~200 × 140 km

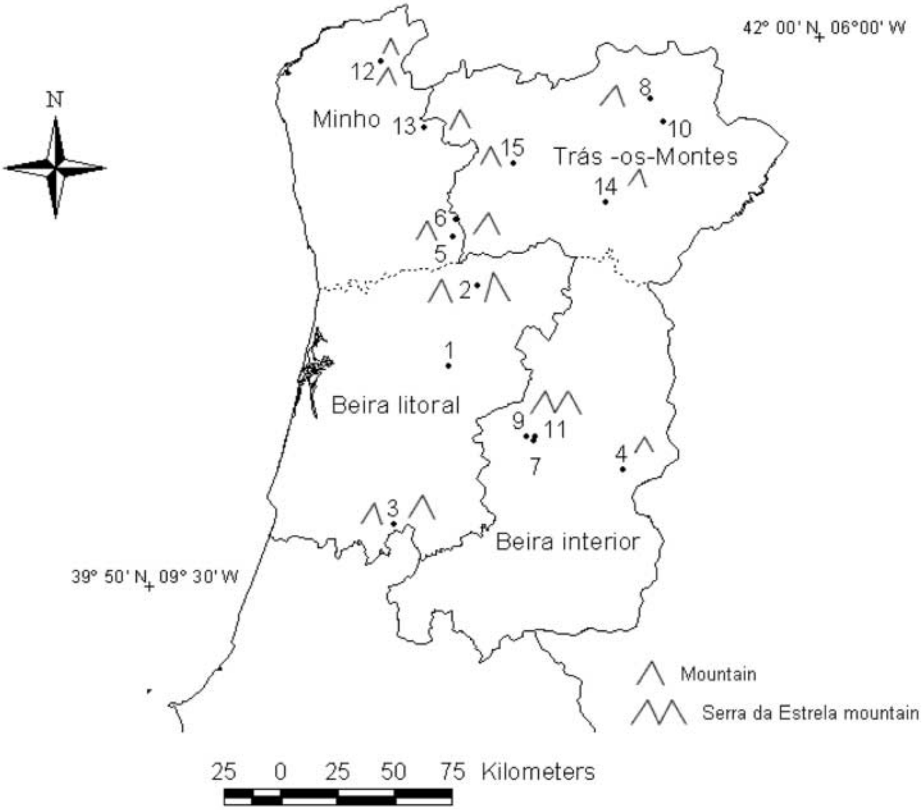

Figure 1. Location of the 15 sites where growth and environmental variables were surveyed: 1, Crasto; 2, Leomil; 3, Lousa; 4, Malcata; 5, Marão; 6, Marão Àguas; 7, Moitas; 8, Nogueira; 9, Penhas Douradas; 10, Rossas; 11, São Lourenço; 12, Soajo; 13, Vieira do Minho; 14, Vila Flor; 15, Vila Pouca.

between 40° and 42° N and 6° and 9° W (Figure 1). It included two broad geoclimatic zones: the central-north-west coastal zone and the central-north interior.

The former region is characterized by the influence of maritime weather systems from the Atlantic. Mean annual precipitation exceeds 2000 mm a year in Minho, the northern part, and ~1200 mm in Beira Litoral, in the south. The mean annual temperature is between 7.8°C and 12.3°C and maximum and minimum temperatures are 37.7°C and –11.6°C, respectively (Mendes *et al*., 1990). The region is characterized by a narrow flat strip backed by the mountains of Soajo, Peneda, Gerês, Alvão and Marão to the east.

The northern part of the central-north interior region, Trás-os-Montes, is situated behind these mountains. The southern part, Beira Interior, includes Serra da Estrela which is the biggest mountain complex in Portugal. This region is characterized by a more continental climate with mean annual precipitation in some areas as low as 520 mm. Mean annual temperatures are higher, between 6°C and 13°C, and the extremes are more pronounced, maximum and minimum temperatures being 38.2°C and –15.8°C, respectively (Mendes *et al*., 1991).

The main soil types of the study areas are cambisols that developed from the weathering of acid rocks on moderately to strongly sloping valley sides; brown Mediterranean soils, which extend

Table 1: Site variables collected measured in field and assessment method used

Site variable	Units	Assessment method
Plot coordinates	Latitude, longitude	Waypoints on GPS
Altitude	m	Altimeter
Aspect	%	Compass
Slope	%	Clinometer
Position on slope	Code	(1) Base of slope, (2) mid, (3) upper, (4) ridge
Soil depth	cm	Tape measure
Dominant height	m	Hypsometer
Site index	m	McDill-Amateis model developed by Fontes (2002)

Table 2: Soil variables obtained by laboratory work

Site variable	Units	Assessment method
Stoniness, coarse sand, fine sand, silt and clay	%	White (1979)
Organic matter	%	Nelson and Sommers (1996)
Soil pH	pH	Van Reeuwijk (1993)
Water holding capacity	PF	Richards (1965)
Total N	%	Houba (1995)
Extractable P_2O_5	mg kg^{-1}	Egner (1960)
Extractable K_2O	mg kg^{-1}	Egner (1960)
Exchangeable Ca	cmol (+) kg^{-1}	Suarez (1996)
Exchangeable Mg	cmol (+) kg^{-1}	Suarez (1996)
Exchangeable K	cmol (+) kg^{-1}	Helmke and Sparks(1996)
Exchangeable Na	cmol (+) kg^{-1}	Helmke and Sparks (1996)

into Portugal from central Spain; rankers, with dark coloured surface horizons, rich in organic matter with a low base status, directly overlying unconsolidated siliceous material; and lithosols consisting of freshly or incompletely weathered masses of hard rock fragments (Dudal *et al*., 1966).

The number of sample plots established varied between sites according to the variability of site factors such as gradient, position on the slope and aspect. For example, on sites such as Crasto, where local site conditions and Douglas-fir productivity are markedly homogeneous, two plots were established. Where site quality varied, such as in Vieira do Minho, the site was stratified after a biometric survey and two plots laid out within each stratum. Plots were all at least 20 m inside the plantation to avoid edge effects. From a 0.1-ha plot with 10 dominant trees, the tree with the height closest to the average dominant height was selected. The selected dominant tree was the centre of a circular plot of 5.65 m radius, 0.01 ha of which was used for the collection of soil samples. A total of 39 plots was sampled from the 15 sites.

Field, laboratory, climatic and digitized site data

Field data were collected using the equipment listed in Table 1. Three soil sampling points were randomly selected within each plot. Soil samples were collected using an auger, then bulked and mixed to make separate composite samples, from the A and B horizons. Soil analysis was carried out under the supervision of Professor João Coutinho from Universidade de Trás-os-Montes e Alto Douro and the methods used are summarized in Table 2.

Conditions that might inhibit root development in the profile were deduced from assessment of soil structure down the profile. Soil colour was assessed using Munsell soil colour charts (Oyama

Table 3: Digitized site data available for Portugal

Map information	Year	Source of data
Annual number of days with precipitation	1974	Average of annual means from 1931 to 1960 (Direcção Geral do Ambiente, 1998)
Annual number of days with frost	1974	Average of annual means from 1941 to 1960 (Direcção Geral do Ambiente, 1998)
Soil pH	1979	More than 20 000 pH (H_2O) samples (Direcção Geral do Ambiente, 1998)
Altitude	1982	Elevation points (m) (Direcção Geral do Ambiente, 1998)
Ecological zones	1982	Albuquerque (1954), Direcção Geral do Ambiente (1998)
Evapotranspiration	1974	Average of annual means (mm) (Direcção Geral do Ambiente, 1998)
Rock types	1982	Direcção Geral do Ambiente (1998), Silva (1982)
Soil types	1971	Carvalho-Cardoso *et al.* (1971), Direcção Geral do Ambiente (1998)
Annual mean solar radiation	1974	Average of annual means (kcal cm^{-2}) from 1938 to 1970 (Direcção Geral do Ambiente, 1998)
Annual mean temperature	1974	Average of annual means (°C) from 1931 to 1960 (Direcção Geral do Ambiente, 1998)
Annual total precipitation	1974	Average of annual means (mm) from 1931 to 1960 (Direcção Geral do Ambiente, 1998)
Annual number of hours with sun	1974	Average of annual means (hours) from 1931 to 1960 (Direcção Geral do Ambiente, 1998)
Biogeographic regions	1999	Costa *et al.* (1999)
Afforestation regions	2002	Direcção Geral das Florestas (2002, unpublished)
Moisture deficit (= annual precipitation – evapotranspiration	2002	Obtained using Arc View GIS 3.2 (ESRI, 1999)
Distance to the sea	2002	Obtained using Arc View GIS 3.2 (ESRI 1999)

and Takehara, 1970). Aeration was inferred by the soil colour; e.g. the appearance of a bluish-grey colour is associated with reduced Fe compounds (White, 1979).

The measurement of bulk density was carried out on site using the excavation method (Blake, 1965). The cation exchange capacity (CEC), expressed in cmol (+) kg^{-1}, was calculated as the sum of the exchangeable bases plus total acidity (Sumner and Miller 1996). The base saturation (BS), expressed as a percentage, was calculated, based on the ratio of the quantity of exchangeable bases to the CEC, as follows (White, 1979):

$$BS = \frac{\sum \mathrm{Ca, Mg, K, Na}}{\mathrm{CEC}} \times 100$$

Digitized site data were obtained from Direcção Geral do Ambiente (1998) and from the Direcção Geral das Florestas. The scale of these data is 1 : 1000 000 and the size of the pixel is 2531 m^2. The digitized information (Table 3) was analysed and processed using ArcView GIS 3.2 (ESRI (Environmental Systems Research Institute), 1999).

Average monthly temperatures, evapotranspiration and precipitation for the period 1951–1980, were obtained from meteorological stations (Mendes *et al.*, 1990, 1991). Variations in temperature due to altitude differences between the meteorological stations and Douglas-fir stands were corrected using an adiabatic lapse rate gradient of –0.01°C m^{-1} increase in elevation (Monteith, 1973). The variations in evapotranspiration, due to differences in aspect and gradient of the meteorological stations and Douglas-fir plots, were corrected using methods applied by Frank and Lee (1966). Mean values of temperature, evapotranspiration, precipitation

Table 4: Types of categorical variables

Type	Categorical variables
Soil related	Soil classes Soil sub-classes Parent material
Site classification	Biogeographic regions Ecological regions Afforestation regions
Related to field position	Aspect Position on slope

and moisture deficit were calculated for the periods from July to September and from April to September. Most of the data available are quantitative variables, although there is a group of categorical (or qualitative) variables (Table 4).

Data analysis

Multiple linear regression was used to study the variation in the site index of Douglas-fir in relation to site factors that had been measured (Carter *et al*., 1990; Klinka and Carter, 1990; Monserud *et al*., 1990; Corona *et al*., 1998; Curt *et al*., 2001). Categorical variables were substituted by a set of (k – 1) dummy variables (k is the number of categories) (Myers, 1990). Modelling the site index from environmental factors was carried out using SAS (2001) to perform multiple linear regressions. The following relationship was assumed:

$$\mathrm{SI} = \beta_0 + \beta_1 + \chi_1 + \ldots + \beta_n \times \chi_\mathrm{n} + \varepsilon$$

where SI is the site index, $\chi_1 \ldots \chi_n$ are variable vectors corresponding to site variables, $\beta_1 \ldots \beta_n$ represent model coefficients and ε is the additive error term.

The analysis of the data followed three steps:

1. Selection of site factors related to the variation in the site index
2. Selection of the candidate models
3. Selection of the best model to explain and predict the site index from site factor variables.

1 *Selection of site factors related to the variation in the site index* Within the site factor variables it is necessary to select the ones that can be used to model the site index variation. The analysis started by looking at the variables available in terms of their relationship with the site index and their distribution throughout the country. Simple plots of the site index versus potential predictor variables were analysed (Corona *et al*., 1998), in an attempt to understand the relationship between the variables and the site index (e.g. suggesting linear or non-linear relationships). The range of digitized site data corresponding to Douglas-fir plots was mapped for the whole of Portugal in order to gain a picture of its potential distribution.

Since stepwise regression is considered the best method of automated variable selection (Draper and Smith, 1998) it was chosen for this study. However, a model that is a result of an automated variable selection may not be biologically sensible and needs to be evaluated on biological grounds.

Quadratics of site variables were used to investigate non-linear relationships, and the product of site variables to explore the interactions between them. These are often not straightforward. They can be synergistic or antagonistic (Battaglia *et al*., 1999), e.g. the effect of solar radiation on photosynthetic rates is lost if temperatures are low and photoinhibition occurs (Holly *et al*., 1994).

2 *Selection of the candidate models* Having identified a group of variables that are significantly related to the site index, the next step was to select the potential candidate models. This used the selection based coefficient of determination R^2, and adjusted coefficient of determination R^2_a (SAS, 2001). It starts by running regressions of all one-variable models and then ordering them by the calculated R^2 and R^2_a in descending order. Then regressions of all two-variable models are run, ordering them by the calculated R^2 and R^2_a in descending order, and so on until in the last stage the regression for the model using all the variables is run. Model rankings are based, respectively, on R^2 and R^2_a. R^2, in particular, tends to suggest the use of models with too many variables since these explain more variation. However, complex models often show unstable estimates of the parameter as a consequence of multicollinearity among the regressors. The best models were selected for further analysis.

3 *Selection of the best model to explain and predict the site index from site factor variables*

The criteria used to evaluate which model would be best for explaining and predicting the site index from site factors were:

- Coefficient of determination R^2 and adjusted coefficient of determination R^2_a.
- Significance of each parameter. The estimate of each parameter should be significantly different from zero. The hypothesis $H_0 = \beta_0 = \beta_1 = \ldots = \beta_n = 0$ is tested and parameters that are not significantly different from zero are rejected.
- Normality of the studentized residuals. A graph of studentized residuals plotted against their expected values under normality – the so called QQ-plots – will display a straight line with a slope of 1 in an ideal situation, when the errors are normal. The residuals are ranked in increasing order $e_{[1]} < e_{[2]} < \ldots e_{[n]}$ and are plotted against the cumulative probability of a normal distribution $P_i = (i - 1/2)/n$, $i = 1, 2, \ldots, n$ (Myers, 1990).
- Homogeneity of variance of studentized residuals. Plotting the studentized residuals against the fitted values $\hat{y}_i$ highlighting deviations from the homogeneous variance assumption.
- Statistics based on prediction sum of squares (PRESS) residuals. This considers a set of data in which the *i*th observation is set aside from the sample and the remaining $n - 1$ observations are used to estimate the coefficients for the candidate model. The procedure continues until all the observations have been removed, one at a time, and thus the candidate model is fitted *n* times. Each candidate model will have *n* PRESS residuals $y_i - \hat{y}_{i,-1} = e_{i,-1}$ $(i = 1, 2, \ldots, n)$ (Myers, 1990). Since $\hat{y}_{i,-1}$ is independent from y_i PRESS residuals are considered prediction errors.

  PRESS residuals are used for examining the predictive abilities of the candidate models when sample sizes are small (Green, 1983). The mean of the PRESS residuals (MPRESS) is a measure of bias of a model, the ideal value for the MPRESS is zero while the mean of the absolute PRESS residuals (MAPRESS) is used to evaluate the precision of a model (Soares and Tomé, 2001).
- Modelling efficiency (ME), which can be expressed as follows (Soares *et al.*, 1995):

$$\mathrm{ME} = 1 - \frac{\sum_{i=1}^{n}(y_i - \hat{y})^2}{\sum_{i=1}^{n}(y_i - \bar{y})^2}$$

  ME provides an index of model performance on a relative scale, where 1 indicates a 'perfect' fit, 0 reveals that the model is no better than a simple average, and negative values indicate a poor model (Vanclay and Skovsgaard, 1997).
- Analysis of multicollinearity through variance inflation factors (VIF). If *x* variables are highly correlated, they convey essentially the same information. When this happens, the *x* variables are collinear and the results show multicollinearity. Multicollinearity leads to the estimation of the regression coefficients, i.e. the coefficients are very dependent on the particular data set that generated them. For example, if multicollinearity is a serious problem, to remove one of a large set of regressor variables may change by large amounts and perhaps change the signs of the new estimates of the coefficients. On the other hand, the prediction at points that represent extrapolation outside the range of data can be adversely affected by multicollinearity (Myers, 1990). VIFs were calculated using SAS (2001) and when they are larger than 10 this indicates that there is strong multicollinearity (Myers, 1990).
- Analysis of the biological background. Regression techniques are designed to investigate statistical associations and not true causal relationships. An assessment was made as to whether selected predictors made sense (including agreement of coefficient values and signs) within reasonable expectations (e.g. since Portuguese summers are dry, it is expected that the moisture deficit in the summer will have a positive effect on the Douglas-fir site index).

Analysis of subgroups of regressor variables

Due to the different sources of data (field measurements, existing records, digitized and laboratory analyses) and the different natures (soil, climate and field measurements), a first approach to the modelling was to use the different types of data separately. A subgroup termed 'directed selection' was created where the variables were selected based on their significant impact on Douglas-fir productivity known from previous work (Carter *et al.*, 1990; Corona *et al.*, 1998; Curt *et al.*, 2001), and when it was thought that they were important for Douglas-fir growth in Portugal. It was considered that growing season water deficit, mineralizable nitrogen (Carter *et al.*, 1990), soil water storage capacity, elevation (Curt *et al.*, 2001), annual precipitation, clay content and aspect (Corona *et al.*, 1998) were important. Soil depth was also considered since it appears to be important for Portuguese site conditions due to the frequent occurrence of shallow soils (Goes, 1976). The degree-days corresponding to each plot were calculated since they relate temperature with water availability for growth. They were calculated in the following way: (1) all months with average temperatures of <5°C were considered as zero, assuming that in those conditions the trees do not grow; (2) if the temperature was >5°C then 5 was subtracted from its value which was then multiplied by the number of days on which it occurred in the month; and (3) if there was no moisture in the soil (calculated from moisture deficit and soil water holding capacity) the degree-days were considered zero for that month. The interactions of these variables were also considered (e.g. radiation × summer moisture deficit).

The digitized site data were analysed separately. The model found to be best suited for explaining the site index was used to estimate the potential area where Douglas-fir could be grown in Portugal, using Arcview GIS (ESRI, 1999).

Global and practical models

Some models may have good statistical properties but include less readily available variables (Klinka and Carter, 1990). Others have a more management oriented approach using only variables that are easily available (Corona *et al.*, 1998). Both types of models are developed here. The first is termed 'global' as all variables are considered. The second is termed 'practical' since only readily available variables are considered. The modelling approach used is empirical, as in other previously published models (Carter *et al.*, 1990; Klinka and Carter, 1990; Monserud *et al.*, 1990; Corona *et al.*, 1998; Curt, 1999; Curt *et al.*, 2001).

Results

The area of potential distribution of Douglas-fir in Portugal for each digitized site factor is presented in Figure 2. It shows that some site factors, such as altitude and ecological zone, give very restricted potential areas. Others such as the number of days with precipitation show a wide range, indicating that Douglas-fir could be grown over almost the entire country.

As explained in Materials and methods, the subgroups of variables based on soils, climate, field measurements, digitized site data and directed selection were analysed separately. The best model for each group is presented in Table 5. Within the different sub-groups, the field data allowed the construction of the best model (F.1, highest R^2 = 59 per cent and R^2_a = 0.52). The ability for prediction of F.1 is one of the best among the models of the subgroups considered (precision, APRESS = 2.488 m, bias MPRESS = 0.049 m and ME = 0.462) with similar values to the soil model (S.1; Table 5).

Using ARCVIEW GIS 3.2 (ESRI, 1999) and model D.1, the potential area for Douglas-fir in Portugal was estimated (Figure 3). The components of the model were selected using stepwise regression as explained for model S.1. The model predicts that the areas best suited to Douglas-fir are distributed through the north and centre of Portugal at altitudes above 500 m. Three classes, indicating high, medium and low productivity were chosen rather than individual site index model estimates, since their precision (MPRESS) is 2.6 m at the top height. The 'high potential' areas were defined as having a dominant height at 30 years >23 m (corresponding to a yield class higher than 20 m^3 ha^{-1} a^{-1}; Hamilton and Christie, 1971), 'low potential' areas as having dominant height at 30 years of <17 m (corresponding to a yield class lower than 13 m^3 ha^{-1} a^{-1}) and medium potential areas in between. The high potential areas are concentrated in the west and central part of the country, whereas the low ones are in the interior. The area of lowest potential growth corresponds to

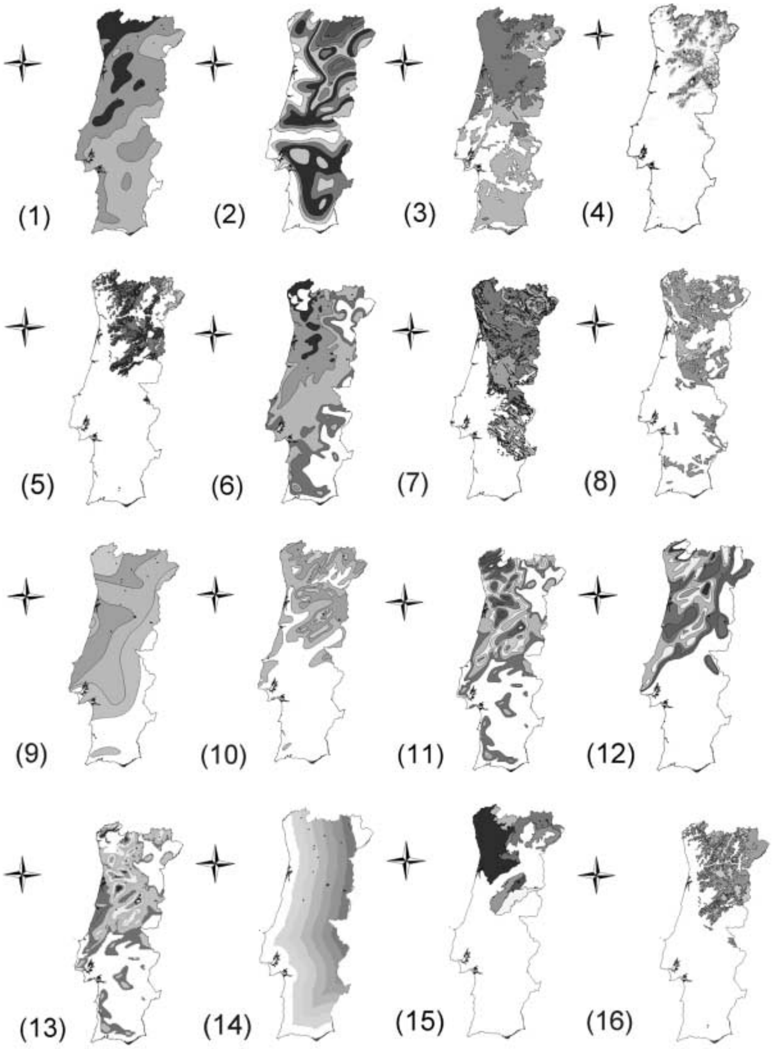

Figure 2. Maps showing the potential area where Douglas-fir will grow in Portugal depending on each site variable. The lighter shading corresponds to the lower classes. 1, Number of days with precipitation per year (lower class from 50 to 75 days and higher class >100 days). 2, Number of days with frost per year (lower class from 10 to 20 days and higher class >80 days). 3, Soil pH (lower class <4.5 and higher class between 5.6 and 6.5). 4, Altitude (lower class between 500 and 600 m and higher class between 1300 and 1400 m). 5, Ecological zones (Albuquerque, 1954; Direcção Geral do Ambiente, 1998). 6, Evapotranspiration (lower class between 450 and 500 mm and higher class between 700 and 800 mm). 7, Rock types (Silva, 1982; Direcção Geral do Ambiente, 1998). 8, Soil groups (Carvalho-Cardoso *et al*., 1971; Direcção Geral do Ambiente, 1998). 9, Solar radiation per day (lower class <140 kcal cm^{-2} and higher class between 150 and 155 kcal cm^{-2}). 10, Temperature (lower class 7.5°C and higher class 15°C); 11, Total precipitation (lower class 800 mm and higher class 2400 mm). 12, Total radiation (lower class 2200 h and higher class 2700 h). 13, Moisture deficit (lower class between 0 and 190 mm and higher class between 1710 and 1900 mm). 14, Distance from the sea (lower class between 23 and 46 km and higher class between 140 and 164 km). 15, Biogeographic regions (Costa *et al*., 1999). 16, Afforestation regions (Direcção Geral das Florestas, 2002, unpublished).

Table 5: Models of the Douglas-fir site index based on site factors

Function		R^2	R^2_a	Mean of prediction sum of squares residuals (MPRESS)	Mean of absolute prediction sum of squares residuals (APRESS)	Modelling efficiency (ME)
Soils						
S.1	SI = 28.644 – 6.720 × BD + 0.346 × ACEC – 28.837 × AVGNA + 0.104 × BBS – 0.113 × AST	0.55	0.48	–0.04	2.41	0.48
Climate						
C.1	SI = 25.576 + 0.012 × NTSMMR	0.33	0.31	–0.02	2.92	0.27
Field measurements						
F.1	SI = –106.505 + 3.023 × ASP1 – 5.015 × ASP5 + 0.00003 × LONW + 0.00003 × LATN	0.59	0.52	0.05	2.49	0.46
Digitized site data						
D.1	SI = 31.034 + 0.00003?NTRAD – 0.602 × SQACID – 0.000006 × SQALT + 0.031 × SQTEMP	0.54	0.49	–0.03	2.61	0.43
Directed selection						
DS.1	SI = 25.536 + 0.00008 × RADNMSR	0.34	0.33	–0.02	2.91	0.29
Global model						
G.1	SI = 17.119 + 0.00006 × RADNMSR + 0.215 × BBS – 26.362 × BNA – 4.286 × ASP7 – 6.307 × ASP2 + 11.545 × ANT + 3.455 × PSLO1 – 0.215 × AARG – 4.888 × ECOL3 + 2.559 × ECOL8	0.90	0.87	–0.09	1.42	0.82
Practical model						
P.1	SI = 16.805 + 0.000008 × NTRAD + 4.375 × ASP1 – 0.000006 × SQALT – 3.103 × ECOL9 + 2.319 × BIOG2	0.76	0.72	–0.02	1.92	0.68

BD = bulk density; ACEC = cation exchange capacity in the A horizon; AARG = clay content in the A horizon; BNA = the value of Na in the A horizon; ANT = total content of N in the A horizon; AVGNA = the average value of Na; BBS = base saturation in the B horizon; AST = the percentage of stones in the A horizon; NTSMMR = moisture deficit in the summer (monthly average between July and September); NTRAD = moisture deficit × radiation; RADNMSR = radiation × moisture deficit summer; ASP1 = north/north-west aspect; ASP2 = north-east aspect; ASP5 = south/south-east aspect; ASP7 = east aspect; LONW = longitude; LATN = latitude; SQACID = soil pH squared; SQALT = altitude squared; SQTEMP = temperature squared;. PSLO1 = bottom slope position; ECOL3 = SA.OA ecological zone (between 100 and 1300 m); ECOL8 = SA.MA ecological zone (between 400 and 700 m); ECOL9 = SA.MA.AM ecological zone (between 400 and 700 m); BIOG2 = Miniense litoral biogeographic region.

384 000 ha, medium potential 1018 000 ha and high potential 358 000 ha. If the actual land use of these areas is considered (Direcção Geral das Florestas, 2001) and only the areas with forest cover and uncultivated land are taken into account then these values are smaller totalling, for high and medium potential sites together, ~1000 000 ha.

The model with the best statistical properties was obtained when all regressor variables were considered. This model (G.1) explains 90 per cent of Douglas-fir site index variation. The practical

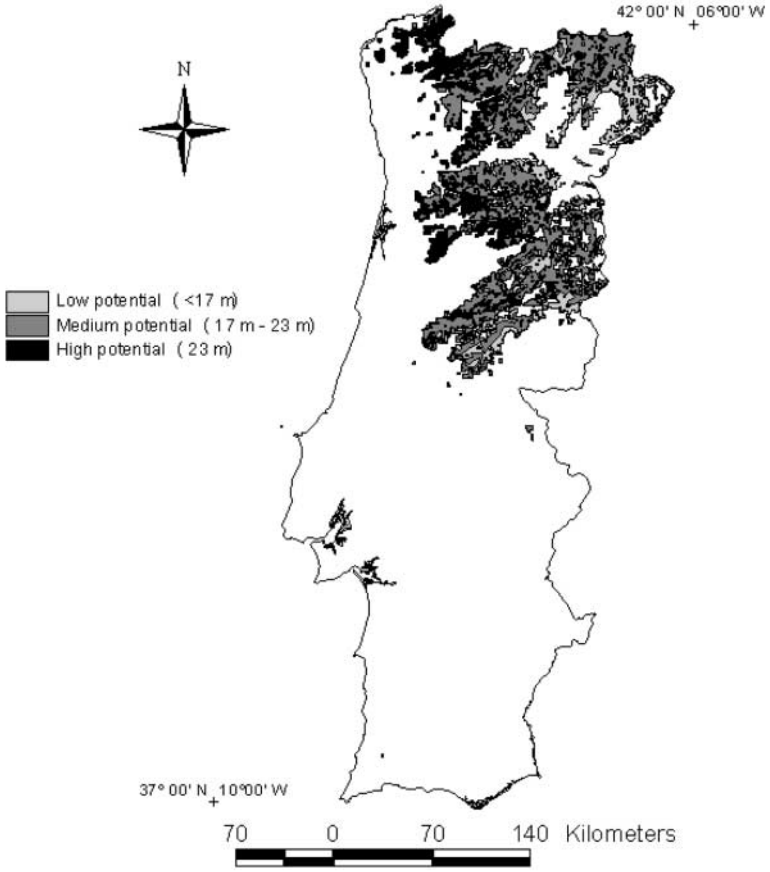

Figure 3. Map showing the potential area of distribution for Douglas-fir production based on model D.1.

model which considered only readily available variables, field measurements and digitized site data, explains 76 per cent of the variance in the site index (Table 5).

Plots of the studentized residuals against fitted values for the models presented (not shown here) did not highlight any model under-specification or major deviation from the homogeneous variance assumption. The normal probability plots for the models (not shown here) did not show any severe departures from normality.

Discussion

The model developed based on soil variables alone explained 55 per cent of site index variance. This is quite satisfactory compared with only 16 per cent of site index variance explained by soil factors for inland Douglas-fir in the USA (Monserud *et al*., 1990). A possible explanation for the good results could be due to the use of three soil sampling points per plot, since one pit per plot was thought to be a reason for a failure in sampling soils in the previous study (Monserud *et al*., 1990). Soil water-holding capacity was not significantly related to the Douglas-fir site index in Portugal in accordance with the work of Monserud *et al.* (1990) but in disagreement with Curt (2001) and Carter *et al.* (1990). The average sodium (Na) content in A and B horizons (AVGNA model S.1; Table 5) and the Na content in B horizon (BNA model G.1; Table 5) were found to have significance with the Douglas-fir site index. The importance of Na is almost certainly due to proximity to the sea, and the fact that prevailing wind and rain come from the west. It is known that a lot of Na can come in rainfall and as aerosols (Miller, 1979).

The best model developed from climatic variables alone (C.1) explained only 33 per cent of Douglas-fir site index variation. The growing season water deficit was significantly related to the site index, in agreement with the work by Klinka and Carter (1990). The poor performance of the climatic model is probably due to the quality of the climatic data used. Since there was no meteorological station at any Douglas-fir plot it was necessary to use data from the national meteorological stations. Although corrections were made for variations in temperature due to altitude (Monteith, 1973) and evapotranspiration due to aspect and slope (Frank and Lee, 1966) they were probably not good enough to represent the climatic conditions in the Douglas-fir plots.

The field measurements model (F.1) explained 59 per cent of Douglas-fir site index variation. Longitude proved to be significantly related to site productivity, as in Monserud *et al.* (1990), and latitude was also significant contrary to the findings of Monserud *et al.* (1990). In Portugal, latitude and longitude increases tend towards the north-west coastal region, corresponding to high productivity sites. Douglas-fir tends to thrive on northerly exposures in the southern part of its native range (Silen, 1978). In Portugal, northerly exposures are also the more productive sites. In addition, the model developed shows a positive effect of west-facing slopes on Douglas-fir growth, in agreement with Corona *et al.* (1998).

Digitized site factors explained 54 per cent of the variance in the site index. The interaction between moisture deficit (precipitation – evapotranspiration) and solar radiation was significant as well as the quadratics of soil acidity, elevation and temperature. Solar radiation and water availability are known to influence plant growth, so the significance of their interaction might be expected. Elevation is also known to affect Douglas-fir productivity significantly (Monserud *et al.*, 1990; Curt *et al.*, 2001). The tree is also known to grow well in acidic soils and as such soils predominate in Portugal the relationship between soil pH and the site index is, as might be expected, inverse. Within the distribution of Douglas-fir in Portugal there are altitudes above 1000 m with low mean annual temperatures, thus Douglas-fir shows an expected increase in growth with increasing mean annual temperature.

The best 'directed selection' model (DS.1) explained only 34 per cent of site index variance. One reason for this relatively low performance is that different published studies have been concerned with different site conditions (e.g. France (Curt *et al.*, 2001), USA (Carter *et al.*, 1990; Klinka and Carter, 1990) and Italy (Corona *et al.*, 1998)), where the variables, which constrain Douglas-fir growth are different. In addition, the number of studies of Douglas-fir productivity is relatively small considering that it is so widely distributed, so many variables might be missing. This is in agreement with the study of Hackett (1996), which showed that using only personal knowledge of tree species is not adequate for modelling growth of forests.

The global model (G.1) was developed in an attempt to find the one with the best statistical properties using all variables; it explains 90 per cent of Douglas-fir site index variance. This is remarkably high compared with previously published models, the highest previous value being 84 per cent (Klinka and Carter, 1990). However, both models have a common problem. They are based on factors not easily accessible such as the amount of exchangeable sodium in the B horizon (model G.1), or evapotranspiration during May and June (Klinka and Carter, 1990).

To construct a model that can easily be used by management (P.1), the site variables considered were the digitized site factors, plus the variables from field measurements. The model developed is based on the interaction between radiation and moisture deficit, north/north-west aspect, altitude squared, sub-montano SA.MA.AM ecological region (Albuquerque, 1954) and Orensano Sanabriense Biogeographic region (Costa *et al.*, 1999). It explained 76 per cent of the site index, which is higher than the 42 per cent explained by elevation, habitat type, precipitation and longitude (Monserud *et al.*, 1990), higher than the 46 per cent explained by spring temperature, topographical exposure, crop age, winter precipitation and site drainage (Tyler *et al.*, 1996), and higher than the 58 per cent based on aspect, annual water balance surplus, clay content in the 25–50 cm horizon and annual precipitation

(Corona *et al*., 1998). The adjusted R^2 of P.1 is 72 per cent, which is higher than the 40 per cent found for a model based on soil nutrient status, elevation, water seepage index, soil water storage capacity and Topex (Curt *et al*., 2001). Model P.1 has a bias (MPRESS) of –0.017 m and a precision (APRESS) of 1.9 m.

Unexplained variance

The unexplained variance in the Douglas-fir site index in different studies has been more than 50 per cent (Curt *et al*., 2001), 42 per cent (Corona *et al*. 1998) or 24 per cent (model P.1). It might be caused by the following:

- Field measurements and sampling errors (Curt *et al*., 2001). Any study of this nature will experience this problem since there are constraints which make it impossible to use the most exact methods for measurement (e.g. felling a tree to measure the dominant height).
- Missing variables or consistent descriptors to explain variance in site productivity, failure to measure the true causes of site productivity (Monserud *et al*., 1990; Corona *et al*., 1998). An example is fog drip which represents an important input of water in forests on slopes in humid coastal or foggy areas or at high elevations (Kimmins, 1997). In afforested coastal areas of Portugal, in some years, the only water input during July and August is due to fog drip (Gomes, 1956). In a Douglas-fir stand in the Netherlands the losses of precipitation due to interception accounted for 38 per cent of annual precipitation (Tiktak and Bouten, 1994). Thus, growing season water deficit has been shown to be very important for Douglas-fir productivity (Klinka and Carter, 1990) but it is not easily determined when data for fog drip and interception loss are not available.
- Inadequate sampling for the ecological complexity of the study area (Monserud *et al*., 1990; Corona *et al*., 1998). Portuguese Douglas-fir is spread across the centre and north of Portugal with a broad range of site factors (e.g. annual precipitation of 2800 mm at Soajo and 520 mm at Vila Flor). Factors likely to be important at some sites (such as annual precipitation at Vila Flor) are probably insignificant in others (annual precipitation at Soajo).
- Genetic variation (Tyler *et al*., 1996; Corona *et al*., 1998). Provenance trials in Spain have shown that trees of the best seed sources averaged up to three times taller than those of the worst at age 6 years (Toval Hernandez *et al*., 1993). In Portugal most plantations have a common genetic background with the exception of stands at Vila Flor and Soajo (Fontes, 2002).
- Age of the stands (Curt *et al*., 2001). Any study of correlation between the site index and site factors should be done with stands with an age close to the base age (30 years or older). Since, in Portugal, the area of Douglas-fir is relatively small, younger stands (e.g. Malcata 20 years old) were included in the study.
- Silviculture (Macmillan, 1991). The effect of the period, often measured in decades, in which a plantation is established usually has an effect on the site index that is explained by changes (improvements) in silvicultural practices, the genetic material used, and sometimes climatic variations.

Mapping the areas with potential for Douglas-fir

The map of areas with potential for Douglas-fir is very useful for showing where it might be possible to create forests, using this species, based on site factors. The areas with high and medium potential for Douglas-fir total ~1000 000 ha. This is probably an overestimate of the potential for Douglas-fir since there was a degree of intuitive site selection by the foresters who established the plantations that were sampled. This can lead to biased sampling of the site factors existing in those areas of Portugal. For example, Douglas-fir plantations tend to be on sites where the soil is deepest, not waterlogged, and with a predominantly north to north-west aspect. For this reason, within the areas mapped for its potential use, the actual area likely to be suitable for growing Douglas-fir is estimated to be 250 000 ha. This value is one-quarter of that first estimated, meaning that the potential planting should be restricted, taking into account other parameters which were not available as digital information for modelling such as north and north-west aspects. However, it is probable that in some areas aspect will not be as important as in others, e.g. in north-west Portugal where other aspects might be acceptable. However, other parameters such as bottom slope positions or avoidance of shallow soils need to be taken into account. These concerns for potential area restriction are in accordance with the analysis of unsuccessful establishment of Douglas-fir stands in Portugal in the past (Louro and Cabrita, 1985). In any case, Douglas-fir appears to be a species with great potential for future expansion in accordance with the results obtained by the Portuguese Government and World Bank (Grupo Coordenador do Projecto Florestal – Banco Mundial, 1986).

The map of the potential area for Douglas-fir in Portugal (Figure 3) is based on extrapolation of model D.1. Douglas-fir, however, does grow well in some other areas, e.g. in Sintra (Parque da Pena). This is a relatively small area and was not studied. It was excluded from the range of Douglas-fir sites due to its low altitude. Since this area would always be very small in forestry terms, its non-inclusion is unimportant. In the Minho region, at lower altitudes, it is possible to predict from the high annual precipitation and acid soils that Douglas-fir will grow reasonably well. Its non-inclusion is due to an absence of plots in that area. This too does not seem important since the region is characterized by small estates that practice intensive agriculture where tree planting will be very limited.

Conclusions

The different modelling approaches used identified significantly different site factors. For example the interaction between radiation and moisture deficit was important for models P.1 and D.1 (see Table 5), whereas bulk density was found to be significant in model S.1. The 'directed selection', which considered only information from site factors found to be relevant in other studies of Douglas-fir productivity did not produce very satisfactory results. The model based on all site variables (G.1) fitted the data best, although it would be very difficult to apply since it would require, for example, a knowledge of the proportion of Na in the B horizon.

Model P.1 based on field and digitized site data proved to be a good practical model in comparison with previous work (76 per cent of variation explained, with –0.017 m bias and 1.9 m precision). Model D.1 has the advantage of predicting areas of potential for Douglas-fir in Portugal. The area of 250 000 ha for model predictions of >17 m dominant height at age 30 years is important and corresponds to 8 per cent of the actual Portuguese forest area. In comparison with the areas occupied by of the two major Portuguese forestry species, maritime pine and cork oak, the potential for Douglas-fir is relatively small. However, at its full potential of an estimated 250 000 ha, it would be the fifth forestry tree species, after maritime pine (976 000 ha), cork oak (*Quercus suber* L.; 712 000 ha), eucalyptus (*Eucalyptus globulus* Labill., 672 000 ha) and holm oak (*Quercus rotundifolia* Lam.; 462 000 ha).

The best models developed are, on average, better than previously published ones. There were, however, limitations such as the use of climatic stations not located on the sites of the plantations studied. In addition, data concerning fog drip and interception loss would have been very useful as they represent important water inputs or losses, respectively, in the summer period. On the other hand, given the heterogeneity of the existing geoclimatic zones, an increase in sampling intensity within each region would allow the development of regional models likely to have better predictive ability than the models produced.

Modelling the site index using environmental site factors allows the establishment of site parameters for the best and acceptable levels of Douglas-fir growth in Portugal. There is a high potential for Douglas-fir in coastal areas in the north (Arcos de Valdevez, Montalegre and Terras do Bouro regions) and centre of Portugal (Castro d'Aire region) from 500 m to 1000 m altitude, with an annual moisture deficit of over 1000 mm. The regions with medium potential for Douglas-fir are located on the northern (Vinhais and Bragança regions) and central area (Covilhã, Manteigas and Guarda regions) of the country, from 700 m to 1000 m altitude and with an annual moisture deficit in excess of 400 mm. The current recommendations for choosing sites for Douglas-fir in Portugal are: aim for north or north-west aspects, bottoms of slopes; avoid soils with high clay percentages, at risk of water logging, high Na content and high stone percentages.

Since this work is so recent, there have been no reactions yet to the possibility of increasing the area of Douglas-fir in Portugal. However, in common with most countries that plant non-native species, the suggestion is likely to generate some discussion among environmentalists, ecologists and foresters. However, it is unlikely that there will be significant opposition since the species is already reasonably well known in the country.

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