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An ecoregional model for estimating volume, biomass and carbon pools in maritime pine stands in Galicia (northwestern Spain)

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Abstract

Stand density management diagrams, including information about stand volume, stand aboveground biomass, stand stem biomass and carbon pools, were developed for maritime pine stands in Galicia, by applying biomass regression functions and carbon estimates to data from a network of 266 plots located throughout Galicia. The models were constructed on the basis of five equations that were fitted simultaneously using the full information maximum likelihood procedure. The first equation relates quadratic mean diameter to the number of stems per hectare and dominant height. The next three equations relate stand volume, stand aboveground biomass, and stand stem biomass to quadratic mean diameter, number of stems per hectare and dominant height. The last equation relates carbon pools in stand aboveground biomass to stand aboveground biomass. Evaluation of the equations used to develop the diagrams, by the non-linear extra sum of squares method and the Lakkis–Jones test, revealed differences for the two ecoregions defined for the species in Galicia. Different stand-level models and the associated diagrams for stand volume, stand aboveground biomass, stand stem biomass, and carbon pool estimation were therefore developed for each ecoregion.

Keywords: Galicia; *Pinus pinaster* Ait.; Biomass; Carbon; Stand management diagrams

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1. Introduction

1.1. Current situation of maritime pine stands

Maritime pine (*Pinus pinaster* Ait.) is the most important coniferous species in Galicia (northwestern Spain), where there are more than 650 000 ha of pure or mixed stands, originating from both commercial plantations and natural regeneration. The wide distribution and variety of sites occupied have made maritime pine an important species in Galician forestry, with a corresponding total tree volume of more than 50 million m^3 (Xunta de Galicia, 2002).

Nowadays, maritime pine populations in Galicia show high levels of genetic diversity due to the planting of seeds of different origins. The lack of genetic homogeneity, combined with important genotype–environment interactions that favour the existence of adaptations to local ecological conditions (Alía et al., 1995, 1997), lead to significant differences in growth patterns in different areas (Álvarez González et al., 2005). The development of any growth and yield model should therefore be based on the ecoregional classification system developed by Vega et al. (1993) for maritime pine in Galicia, which differentiates coastal and interior ecoregions on the basis of both environmental conditions and seed origin (Fig. 1).

1.2. Stand density management

Stand density management is the process of controlling the level of growing stock through initial spacing or subsequent thinning to realize specific management objectives (Newton, 1997). The determination of appropriate levels of growing stock at stand-level is a complex process involving biological, technological, economical and operational factors specific to a particular management situation. The process requires the selection of the upper and lower limits of growing stock; the

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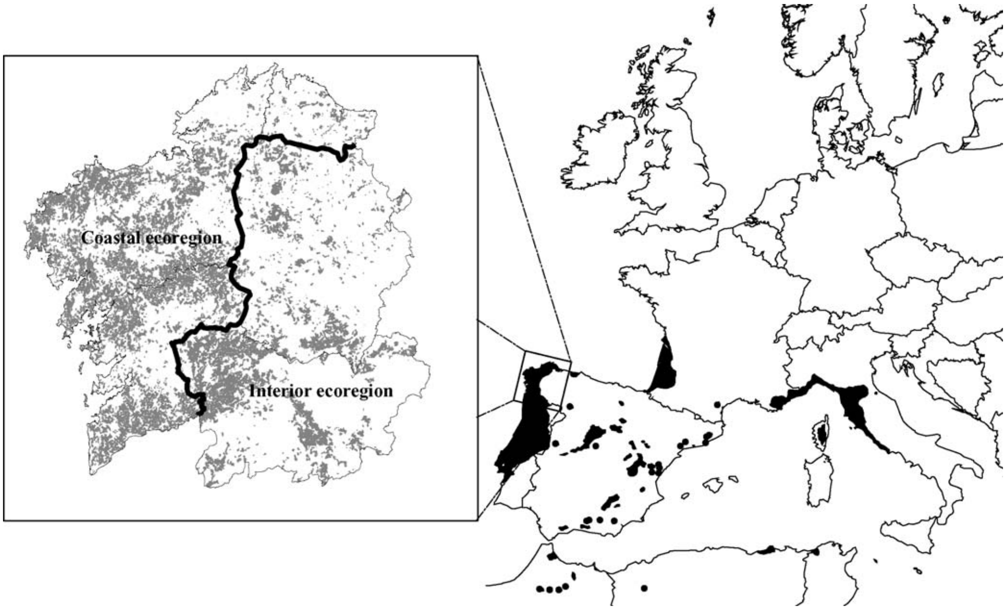

Fig. 1. Natural distribution of maritime pine in the world and limit of the ecoregions in Galicia, as defined by Vega et al. (1993).

former is chosen to obtain acceptable stand growth and individual tree vigour, while the latter is chosen to maintain acceptable site occupancy (Dean and Baldwin, 1996). From a biological point of view, levels of growing stock must therefore be constrained within stand densities corresponding to the threshold of self-thinning and canopy closure (Dean and Baldwin, 1996). However, the translation of specific management objectives into appropriate upper and lower levels of growing stock is the most difficult step in designing a density management regime (Davis, 1966).

Although field trials are the best way of determining the timing of thinnings and the theoretical limits mentioned above, they have two serious limitations (Dean and Baldwin, 1993): they take many years to complete and the results cannot be applied accurately where the site quality and management objectives differ from those encountered in the trials. An alternative approach is the use of stand density management diagrams (SDMDs), which are average stand-level models that graphically illustrate the relationships between yield and density through all stages of stand development (Newton and Weetman, 1994).

SDMDs can be used to derive density control schedules for various management objectives (Newton, 1997): (i) to minimize the temporal window for attaining specified operability criteria, (ii) to control shrub development during early stages of stand development, and (iii) to optimize density for specific timber, vegetation or wildlife management objectives. The use of SDMDs is therefore one of the most effective methods available for the design, display and evaluation of alternative density management regimes in even-aged stands.

1.3. Forest biomass and carbon pools

Forests fix, store and emit carbon during photosynthesis, respiration, decomposition and disturbances that occur throughout a series of life cycle stages from plantation or natural regeneration to harvesting. Because of the increasing concentration of CO_2 in the atmosphere and its role in global climate change through the greenhouse effect, carbon (as CO_2) has taken on both ‘‘market value’’ and ‘‘strategic importance’’ to nations. During recent years, policy-makers have striven to devise ways of mitigating the effects of increasing concentrations of greenhouse gases.

The Kyoto Protocol raised a demand for biomass and growth data that could be used to calculate the potential of forests for mitigating the anthropogenic increase in atmospheric CO_2 concentration (UNFCCC, 1997). Particular interest has been directed towards carbon stocks in forests because more C is stored in forests than in any other terrestrial ecosystem. Thus, afforestation and other management measures aimed at increasing forest yield may lead to the sequestration of significant quantities of atmospheric CO_2 (Dixon et al., 1994).

Changes in total carbon stocks in forest stands can be assessed by direct measurement of net sources and sinks over periods of one or more years. However, this approach has so far met with little success in estimating the carbon budgets for large areas and in the long term because of a lack of data covering all stages of the life cycle, as well as a lack of data on the impacts of disturbances such as fire, windthrow, drought, pollution, pests, and diseases (Bolin and Sukumar, 2000). Forest inventories and ecosystem process models are therefore widely used for broad-scale quantification of forest C budgets at global, national and regional levels (e.g. Grigal and Ohmann, 1992; Birdsey et al., 1993; Brown et al., 1999; Fang et al., 2001).

Forest inventories usually quantify the yield of the stand as wood volume ($m^3\ ha^{-1}$) or biomass ($Mg\ ha^{-1}$) and this data must be converted to carbon contents in biomass ($Mg\ C\ ha^{-1}$) for estimating carbon pools. Several conversion methods and factors have been developed for this purpose, for a wide range of forest types (e.g. Isaev et al., 1995; Schroeder et al., 1997; Fang et al., 2001).

In northwestern Spain the mild climate and, in recent decades, the increased demand for raw industrial material have favoured the establishment of extensive commercial forest plantations focused on fast-growing species such as blue gum (*Eucalyptus globulus* Labill.), radiata pine (*Pinus radiata* D. Don) and maritime pine. The existence of these plantations implies the storage of large amounts of carbon in the short and mid-term as they are considered as potentially rapid carbon sinks and reservoirs. However, studies of biomass, carbon stock and net primary productivity (NPP) of these stands have only recently been carried out in the region (Merino et al., 2005).

The aim of the present study was to develop a practical stand-level model to estimate the amount of wood volume, aboveground biomass and carbon pools in pure and even-aged maritime pine stands, also making possible evaluation of the effects of different stand management regimes on these variables.

2. Data

The data used to develop the SDMDs were obtained from three different sources of temporary or permanent plots. The plot size ranged from 625 to 1200 m^2, depending on stand density, to achieve a minimum of 60 trees per plot. The plots were located throughout the area of distribution of maritime pine in Galicia, and were subjectively selected to represent the existing range of ages, stand densities and sites.

The first set of data was collected by the Instituto Forestal de Investigaciones y Experiencias between 1965 and 1972 to develop yield tables for this species in northwestern Spain. The data set consisted of 248 inventories (57 in the coastal ecoregion and 191 in the interior ecoregion) of 106 permanent plots measured between one and four times.

The second data set consisted of 211 inventories (100 in the coastal ecoregion and 111 in the interior ecoregion) of 126 plots measured between one and four times. These plots were established by the Centro de Investigaciones Forestales de Lourizán with the objective of quantifying the site quality and the effect of fertilization in stands of this species (Bará and Toval, 1983).

The third data set was obtained in 34 plots (12 in the coastal ecoregion and 22 in the interior ecoregion) established by the Escuela Politécnica Superior de Lugo (University of Santiago de Compostela) in 1995 and 2003 with the objective of gathering information on the yield of maritime pine in sites not represented by previous studies.

Two measurements of diameter at breast height (1.3 m aboveground level) were made, at right angles to each other (using callipers), on all the trees in each plot and inventory, and the arithmetic mean (d, cm) of the two measurements was calculated. Total height (h, m) was measured in a 30-tree randomized sample. The height of the remaining trees was estimated using the stochastic generalized height-diameter relationship developed by Castedo et al. (2005). The total volume of each tree was calculated using the volume equations developed by Rodríguez Soalleiro (1997). The dry weight (the weight to constant mass at 65 °C) of each aboveground tree fraction (needles, twigs, thick branches, thin branches, stem wood and stem bark) was estimated with the compatible system of equations developed by Merino et al. (2005). Carbon pools in tree biomass were estimated by fractions as a percentage of the corresponding aboveground dry biomass (Merino et al., 2005). Stand volume (V, m^3 ha^{-1}), stand aboveground biomass (W_t, Mg ha^{-1}), stand stem biomass (W_s, Mg ha^{-1}), and carbon pools in stand aboveground biomass (C_t, Mg C ha^{-1}) were aggregated from the corresponding tree values for each plot and inventory. The following stand variables were also calculated for each plot and inventory: age (t, years), dominant height (H, m) defined as the mean height of the 100 thickest trees per hectare, stand basal area (G, m^2 ha^{-1}), quadratic mean diameter (d_g, cm), number of stems per hectare (N), and site index (SI, m) defined as the dominant height at a reference age of 20 years. The latter variable was obtained for each plot using the site quality system developed by Álvarez González et al. (2005):

$$H_2 = H_1\left(\frac{1-\exp(-zt_2)}{1-\exp(-zt_1)}\right)^{1.4202+0.0801I} \quad \text{with } z = (0.1352 + 0.0276I)\left(\frac{H_1}{t_1}\right)^{0.9831+0.0940I} t_1^{-0.2108-0.0929I} \qquad (1)$$

where H_1 and t_1 represent the predictor height (m) and age (years), respectively; H_2 the predicted height at age t_2, and I is a dummy variable whose value is equal to 1 for the coastal ecoregion and 0 for the interior ecoregion. To estimate SI given H and t, simply substitute SI for H_2, 20 for t_2, H for H_1 and t for t_1 in Eq. (1).

Mean, maximum, minimum and standard deviation for each of the main stand variables calculated from the 493 inventories available (169 in the coastal ecoregion and 324 the interior ecoregion) are shown in Table 1.

3. Methods

3.1. Volume, biomass and carbon SDMDs

The stand-level model developed includes a system of five equations and the relative spacing index as basic components. The format of all the equations is conditioned by the variables represented on the major axes of the SDMD, but it also must be biologically consistent. The first of the five equations relates quadratic mean diameter to number of stems per hectare and dominant height. This equation is based on the relationship among average tree size, density and one indicator of productivity. The expression proposed includes the same independent variables used by Goulding (1972) to estimate the quadratic mean diameter in Douglas-fir plantations.

For predicting the current yield (as volume or biomass), explicit functions using some of the following variables could be used: stand height, an indicator of stand density, basal area, and site index (Clutter et al., 1983). Therefore, it seems reasonable to relate the stand productivity to the product of the

Table 1
Summary statistics of the data set used

Stand variable	Coast (105 plots, 169 inventories)				Interior (161 plots, 324 inventories)			
	Mean	Minimum	Maximum	Standard deviation	Mean	Minimum	Maximum	Standard deviation
t	16.8	8	39	6.4	20.5	9.0	50.0	7.5
N	1679	423	4642	1010.0	1660	275	3580	667.5
H	12.2	4.5	24.0	3.7	11.2	4.5	24.6	3.6
SI	14.6	7.6	19.2	2.6	11.2	6.1	16.1	2.0
d_g	17.0	6.3	35.0	6.3	16.1	5.1	36.5	6.1
G	30.5	5.2	56.5	10.8	29.7	3.2	72.5	12.7
V	177.4	13.1	480.0	93.6	158.7	7.5	527.1	100.0
W_t	101.2	7.3	298.8	57.7	89.9	4.3	337.9	59.9
W_w	62.0	2.5	209.1	40.9	53.0	1.5	246.0	41.7
C_t	48.7	3.6	143.0	27.5	43.3	2.1	161.2	28.6

t is the age (years), N the number of stems per hectare, H the dominant height (m), SI the site index (dominant height in meters at a reference age of 20 years), d_g the quadratic mean diameter (cm), G the basal area (m^2 ha^{-1}), V the stand volume (m^3 ha^{-1}), W_t the stand aboveground biomass (Mg ha^{-1}), W_w the stand stem biomass (Mg ha^{-1}), and C_t is the carbon pools in stand aboveground biomass (Mg C ha^{-1}).

volume or biomass of one representative tree (given by the quadratic mean diameter and dominant height) and the number of trees per hectare. In the same way, the second, third and fourth equations provide an estimate of the stand productivity relating stand volume, stand aboveground biomass and stand stem biomass to quadratic mean diameter, number of trees per hectare and dominant height.

The last equation estimates C pools in stand aboveground biomass using a linear relationship for the stand aboveground biomass.

The relative spacing index is used for characterizing the growing stock level. This index was first proposed for plantations by Hart in 1928, was later (in 1954) referred to as a spacing index by Becking (1954), and as relative spacing by Clutter et al. (1983) and Gadow and Hui (1999). This index is calculated as the ratio, expressed as a percentage, between the average distance among trees and the dominant height. Assuming a triangular spacing it can be written as follows:

$$\mathrm{RS} = \frac{\sqrt{20\,000/(N\sqrt{3})}}{H} \times 100 \qquad (2)$$

where RS is the relative spacing index (%), N the number of stems per hectare, and H the dominant height. RS is useful in stand density management because, from a biological point of view, dominant height growth is one of the best criteria for establishing thinning intervals. The linkage between dominant height growth and forest production adds further utility to these diagrams for forest management purposes.

The model can be graphically displayed in a similar way as Barrio and Álvarez González (2005) did for developing thinning schedules for English oak (*Quercus robur* L.) stands in northwestern Spain. Dominant height is represented on the x-axis and number of stems per hectare on the y-axis, while isolines for relative spacing index, quadratic mean diameter, and any of the following variables: stand volume, stand aboveground biomass, stand stem biomass, or carbon pools in stand aboveground biomass are superimposed on the bivariate graph mentioned above.

The procedure for the construction of the diagrams involved the following steps:

1. Fitting of the non-linear system of the following five equations:

$$d_g = b_0 N^{b_1} H^{b_2} \qquad (3)$$

$$V = b_3 d_g^{b_4} H^{b_5} N^{b_6} \qquad (4)$$

$$W_t = b_7 d_g^{b_8} H^{b_9} N^{b_{10}} \qquad (5)$$

$$W_w = b_{11} d_g^{b_{12}} H^{b_{13}} N^{b_{14}} \qquad (6)$$

$$C_t = b_{15} + b_{16} W_t \qquad (7)$$

where all the variables are previously defined, and b_i ($i = 0, 1, \ldots, 16$) are the regression coefficients to be estimated.

Eqs. (3)–(7) together define a structurally simultaneous system of equations, where N and H are the exogenous variables (variables that appear only on the right-hand sides of the equations and whose values are determined totally independently of the system); V, W_w and C_t are the endogenous variables (variables that the model is intended to explain or predict and only appear on the left-hand side of one equation); d_g and W_t are the endogenous instrumental variables (endogenous variables that also appear on the right-hand side of other equations). Since there is correlation between the error components of the variables on the left-hand side and the right-hand side, the full information maximum likelihood (FIML) technique was applied to fit all the equations simultaneously using the MODEL procedure of SAS/ETS® (SAS Institute Inc., 2004).

2. Representation of dominant height on the x-axis, and number of stems per hectare on the y-axis, the latter in logarithmic scale.

3. Expression of the growing stock level using the relative spacing index. The isolines for this index were obtained solving for N in Eq. (2):

$$N = \frac{20\,000 \times 100^2}{\sqrt{3}\,\mathrm{RS}^2 H^2} \tag{8}$$

4. Representation of isolines for quadratic mean diameter using Eq. (3) by setting d_g constant and solving for N through a range of H:

$$N = \left(\frac{d_g}{b_0 H^{b_2}}\right)^{1/b_1} \tag{9}$$

5. Representation of isolines for stand volume, stand aboveground biomass, and stand stem biomass by substituting Eq. (3) into Eqs. (4)–(6), respectively, and solving for N through a range of H by setting V, W_t and W_w constant:

$$N = \left(\frac{V}{b_3 b_0^{b_4} H^{b_2 b_4 + b_5}}\right)^{1/(b_1 b_4 + b_6)} \tag{10}$$

$$N = \left(\frac{W_t}{b_7 b_0^{b_8} H^{b_2 b_8 + b_9}}\right)^{1/(b_1 b_8 + b_{10})} \tag{11}$$

$$N = \left(\frac{W_w}{b_{11} b_0^{b_{12}} H^{b_2 b_{12} + b_{13}}}\right)^{1/(b_1 b_{12} + b_{14})} \tag{12}$$

6. Representation of isolines for carbon pools in stand aboveground biomass by substituting Eqs. (3) and (5) into Eq. (7) and solving for N through a range of H by setting C_t constant:

$$N = \left(\frac{C_t - b_{15}}{b_{16} b_7 b_0^{b_8} H^{b_2 b_8 + b_9}}\right)^{1/(b_1 b_8 + b_{10})} \tag{13}$$

The values of all the variables used to develop the SDMDs ranged between the minimum and maximum values observed for maritime pine in Galicia (Table 1).

3.2. Comparisons of SDMDs for different ecoregions

Two tests that are based on the likelihood-ratio test and frequently applied to analyze differences among different geographic regions (Pillsbury et al., 1995; Huang et al., 2000; Calama et al., 2003; Álvarez González et al., 2005) were used to compare the regression coefficients of the SDMDs for the coastal and interior ecoregions: the non-linear extra sum of squares method (Bates and Watts, 1988), and the χ^2-test proposed by Lakkis and Jones (Kharee and Naik, 1999).

Both tests require the fitting of a reduced and a full model. The reduced model corresponds to the same set of parameters for both ecoregions. The full model corresponds to different sets of parameters for each ecoregion and is obtained by expanding each parameter including an associated parameter and a dummy variable to differentiate the two ecoregions:

$$b_i + c_i I, \quad i = 0, 1, \ldots, 16 \tag{14}$$

where b_i is a parameter of Eqs. (3)–(7), c_i the associated parameter of the full model, and I is a dummy variable whose value is equal to 1 for the coastal ecoregion and 0 for the interior ecoregion. The appropriate statistical tests are given by:

$$\text{non-linear extra sum of squares},\ F^* = \left(\frac{\mathrm{SSE_R} - \mathrm{SSE_F}}{\mathrm{d.f._R} - \mathrm{d.f._F}}\right)\frac{\mathrm{d.f._F}}{\mathrm{SSE_F}} \tag{15}$$

$$\text{Lakkis–Jones test},\ L = \left(\frac{\mathrm{SSE_F}}{\mathrm{SSE_R}}\right)^{n/2} \tag{16}$$

where $\mathrm{SSE_R}$ is the sum of squared errors of the reduced model, $\mathrm{SSE_F}$ the sum of squared errors of the full model, and $\mathrm{d.f._R}$ and $\mathrm{d.f._F}$ are the degrees of freedom of the reduced and full model, respectively. The $-2\ln(L)$ statistic follows a χ^2-distribution with $\upsilon = \mathrm{d.f._R} - \mathrm{d.f._F}$ degrees of freedom and the F^* statistic follows an F-distribution.

4. Results and discussion

4.1. Comparison between ecoregions and construction of the diagrams

The results of the non-linear extra sum of squares and the Lakkis–Jones tests, and the regression statistics of the reduced and full models of Eqs. (3)–(7), are shown in Table 2. The analyses revealed significant differences between all the equations fitted for both ecoregions at the 5% level. Thus, the full model, which considers different sets of parameters for

Table 2

Goodness-of-fit statistics and results of the non-linear extra sum of squares (F-value) and the Lakkis and Jones (L-value) tests for examining ecoregional differences between the reduced and full models

Eqs.	Reduced model			Full model			R^2	n	F-value	L-value
	SSE	d.f.	MSE	SSE	d.f.	MSE				
(17)	2374	490	4.844	2307	487	4.738	0.881	493	4.68*	14.01*
(18)	146619	489	301.1	121043	487	247.5	0.972	493	51.45*	94.50*
(19)	59725	489	122.6	44215	487	90.420	0.968	493	85.41*	148.23*
(20)	23308	489	47.86	19074	487	39.01	0.975	493	54.05*	98.83*
(21)	14.51	491	0.0296	13.29	490	0.0273	0.999	493	44.94*	43.26*

SSE is the sum of squared errors, d.f. the degrees of freedom, MSE the mean squared error, R^2 the coefficient of determination for non-linear regression (see Ryan, 1997, 419, 424 pp.), n the sample size.

* Indicates a significant difference at $P > 0.05$.

each ecoregion, was selected for developing the stand volume, stand aboveground biomass, stand stem biomass, and carbon pools in stand aboveground biomass diagrams for maritime pine in Galicia. The equations were as follows:

$$d_{\mathrm{g}} = (b_0 + c_0 I)N^{b_1+c_1 I}H^{b_2+c_2 I} \tag{17}$$

$$V = (b_3 + c_3 I)d_{\mathrm{g}}^{b_4+c_4 I}H^{b_5+c_5 I}N^{b_6+c_6 I} \tag{18}$$

$$W_{\mathrm{t}} = (b_7 + c_7 I)d_{\mathrm{g}}^{b_8+c_8 I}H^{b_9+c_9 I}N^{b_{10}+c_{10} I} \tag{19}$$

$$W_{\mathrm{w}} = (b_{11} + c_{11} I)d_{\mathrm{g}}^{b_{12}+c_{12} I}H^{b_{13}+c_{13} I}N^{b_{14}+c_{14} I} \tag{20}$$

$$C_{\mathrm{t}} = b_{15} + c_{15} I + (b_{16} + c_{16} I)W_{\mathrm{t}} \tag{21}$$

Most of the full models accounted for more than 96.8% of the total variability, except the quadratic mean diameter equation, which accounted for 88.1% of the variability, and provided a random pattern of residuals around zero with homogeneous variance and no detectable significant trends.

The regression coefficients of the full models (Eqs. (17)–(21)) are shown in Table 3. Ten out of seventeen regression coefficients were significant at $P = 5\%$, which indicates that the remaining seven coefficients are shared by the models of both ecoregions, even though the models are significantly different.

4.2. SDMDs and their application in developing thinning schedules and yield estimation

Four SDMDs for maritime pine in each ecoregion were developed by superimposing the expected size-density trajectories on a bivariate graph with dominant height on the x-axis and number of stems per hectare on the y-axis, using the values of relative spacing index, the isolines for quadratic mean diameter, and the isolines for each of the following variables: stand volume, stand aboveground biomass, stand stem biomass, and carbon pools in stand aboveground biomass (Figs. 2 and 3). The dominant height axis ranged from 6 to 34 m, while the number of stems per hectare ranged from 50 to 5000, according to the values observed in the sample plots.

Within the framework of the density management diagram, two factors determine the schedule of thinning: the target stand status at the rotation age and the upper and lower growing stock limits. The first factor can be defined by any logical combination of two of the following variables: dominant height, quadratic mean diameter, number of stems per hectare, stand volume, stand aboveground biomass, stand stem biomass or carbon pools in stand aboveground biomass at the rotation age, depending on the stand variable used to develop the diagram. Although the values are usually determined by timber objectives, they can also be set according to any non-timber objective that can be expressed in terms of tree size and number of stems per hectare (Dean and Baldwin, 1993).

Table 4
Values of stand conversion factors from stand volume (V, m^3 ha^{-1}) by age classes (years)

Variable	Age < 15	15 < age < 30	30 < age < 45
W_{t}	0.5465	0.5631	0.6051
W_{w}	0.2785	0.3216	0.4090
C_{t}	0.2648	0.2716	0.2897
C_{w}	0.1311	0.1516	0.1925

W_{t} is the stand aboveground biomass (Mg ha^{-1}), W_{w} the stand stem biomass (Mg ha^{-1}), C_{t} the carbon pools in stand aboveground biomass (Mg C ha^{-1}), and C_{w} is the carbon pools in stand stem biomass (Mg C ha^{-1}).

Selection of upper and lower growing stock limits often represents a silvicultural trade-off between maximum stand growth and maximum individual tree growth and vigour (Long, 1985). Thus, the decision regarding appropriate levels of growing stock will reflect stand management objectives. The upper growing stock limit can be set higher than a determined relative spacing index value to avoid density-related mortality and to maintain an adequate live-crown ratio for good tree vigour. The lower growing stock limit can also be set to maintain adequate site occupancy using the relative spacing index. However, an alternative approach to setting a constant value of relative spacing index for the lower growing stock limit is to define the thinning interval in terms of dominant height growth, or to limit the maximum increment in the relative spacing index to guarantee stand stability after thinning (e.g. Pita, 1991).

Because the development of stand diagrams allows estimation of volume, biomass and carbon pools, the use of conversion factors for whole stands are of limited interest. However, inclusion of the stand factors may be an alternative approach for rapid determination of carbon stocks using information from national or local forest inventories. The calculated values of stand conversion factors to estimate stand aboveground biomass, stand stem biomass and carbon pools in stand aboveground biomass from stand volume for three age classes are shown in Table 4. Important differences in the values

Table 3
Non-linear regression coefficients obtained by simultaneously fitting the system of five equations predicting quadratic mean diameter (d_{g}), stand volume (V), stand aboveground biomass (W_{t}), stand stem biomass (W_{w}) and carbon pools in stand aboveground biomass (C_{t}) for the full model

Eqs.	Parameter estimate				Associated parameter estimate			
(17)	$b_0 = 37.88$	$b_1 = -0.3304$	$b_2 = 0.6357$		$c_0 = 48.64$	$c_1 = -0.0725$	$c_2 = -0.1354$	
(18)	$b_3 = 0.000548$	$b_4 = 1.4298$	$b_5 = 1.220$	$b_6 = 0.7681$	$c_3{}^*$	$c_4 = -0.07553$	$c_5{}^*$	$c_6 = 0.02974$
(19)	$b_7 = 0.000339$	$b_8 = 1.284$	$b_9 = 1.465$	$b_{10} = 0.7277$	$c_7{}^*$	$c_8 = -0.0584$	$c_9{}^*$	$c_{10} = 0.02202$
(20)	$b_{11} = 0.000067$	$b_{12} = 1.216$	$b_{13} = 1.916$	$b_{14} = 0.7472$	$c_{11}{}^*$	$c_{12} = -0.06213$	$c_{13}{}^*$	$c_{14} = 0.02529$
(21)	$b_{15} = 0.3899$	$b_{16} = 0.4774$			$c_{15}{}^*$	$c_{16} = -0.00052$		

[*] Parameters not significant at $P > 0.05$.

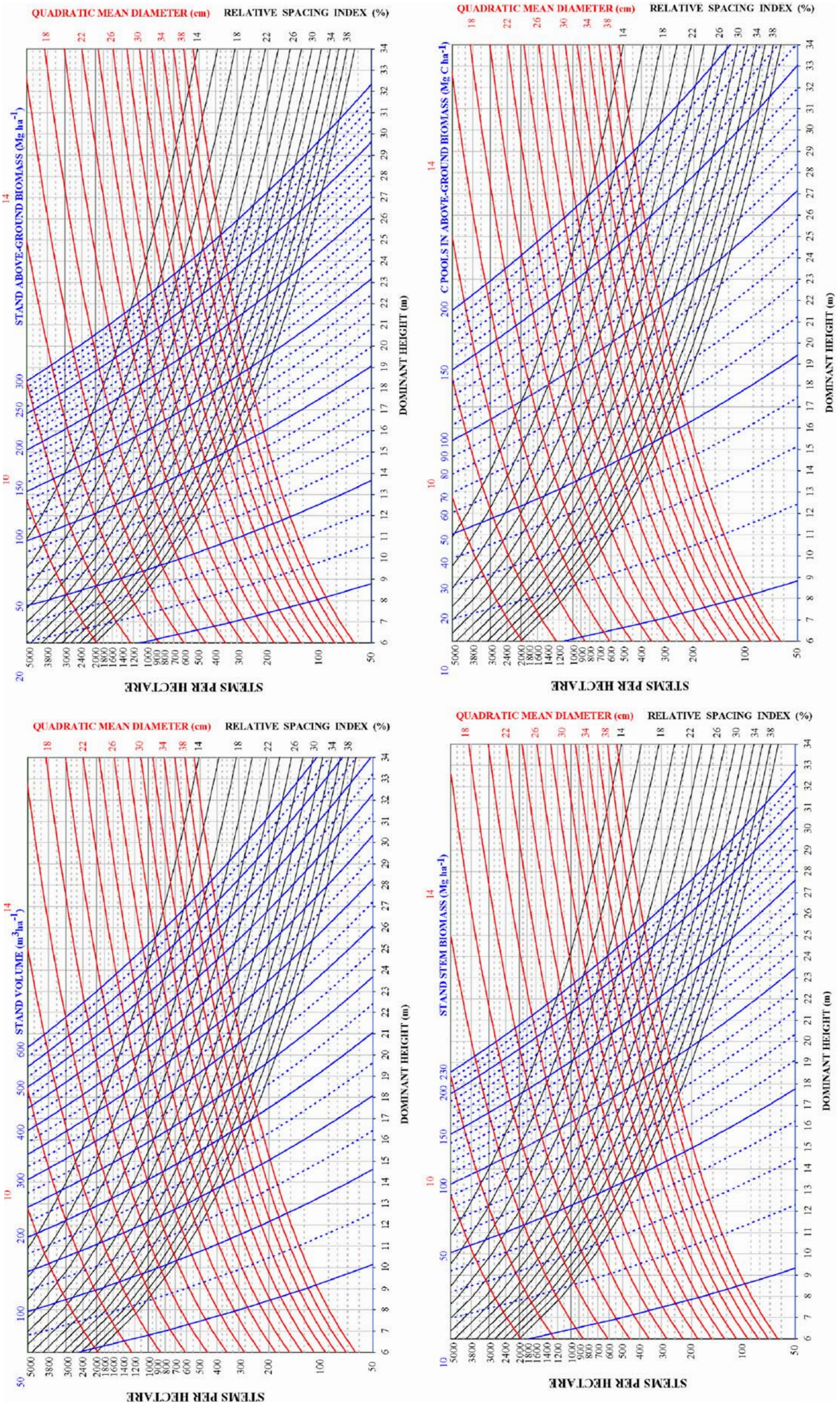

Fig. 2. Stand density management diagrams for maritime pine even-aged stands in the coastal ecoregion.

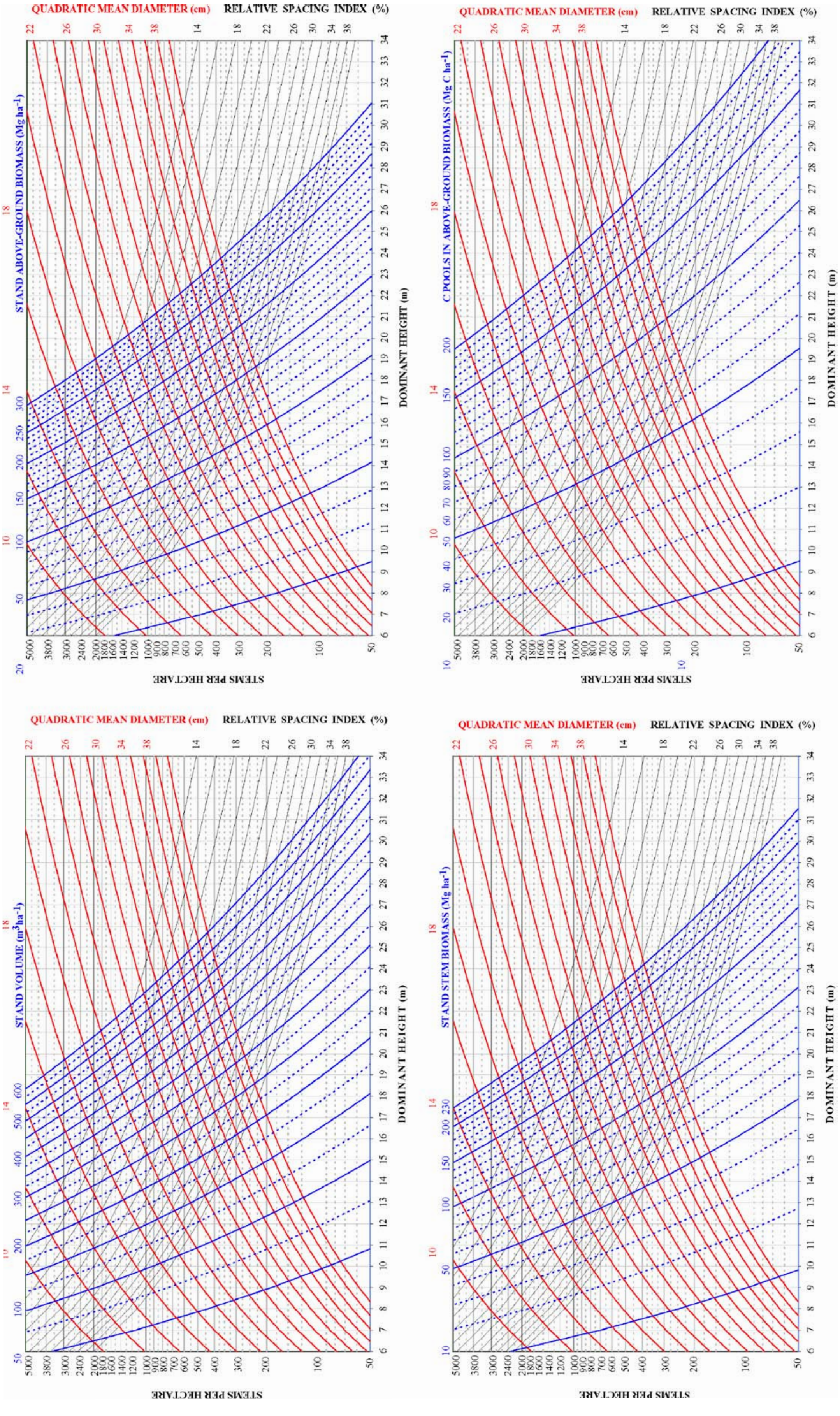

Fig. 3. Stand density management diagrams for maritime pine even-aged stands in the interior ecoregion.

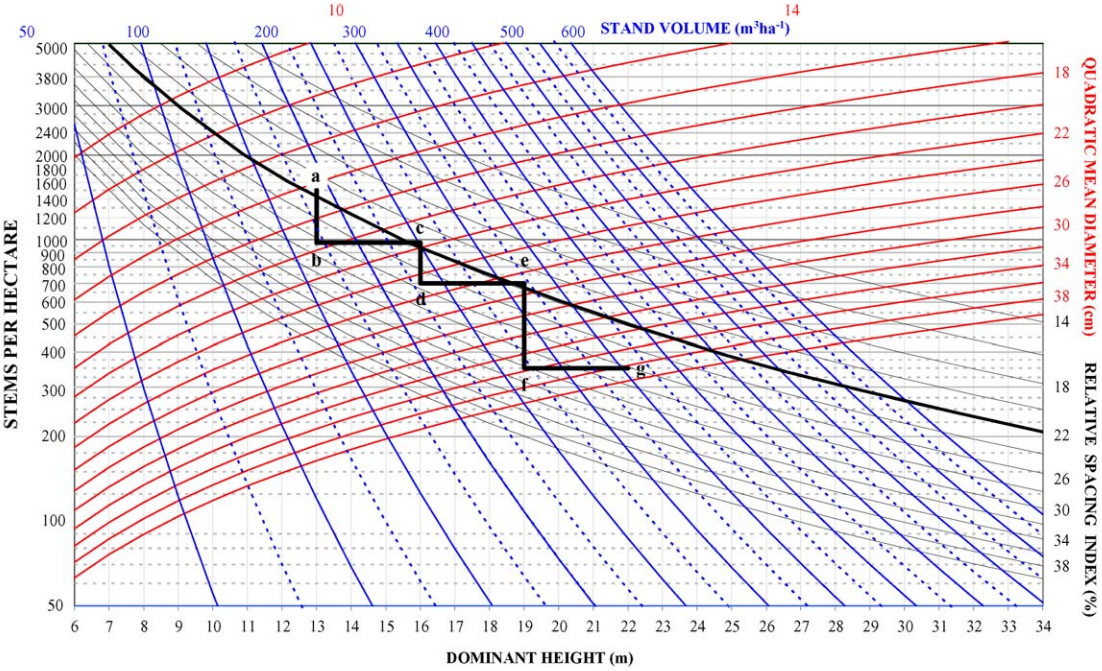

Fig. 4. Stand density management diagram for maritime pine even-aged stands in the coastal ecoregion and thinning sequence for a hypothetical management regime.

of the stand conversion factors across age were observed, especially in estimating stand aboveground biomass and stand stem biomass. Similar results were obtained by Isaev et al. (1995), Turner et al. (1995), Alexeyev et al. (1995), and Krankina et al. (1996).

4.3. A practical example

The development of a maritime pine stand in the coastal ecoregion of Galicia under a particular management regime for obtaining saw timber is illustrated in Fig. 4. This management

Table 5
Mensural data for the thinning sequence shown in Fig. 4

Variable		Thinning (a and b), 13	Thinning (c and d), 16	Thinning (e and f), 19	Harvest (g), 22
N	Before thinning	1500	975	700	350
	After thinning	975	700	350	–
d_g	Before thinning	16.4	21.6	27	38.4
	After thinning	19.5	24.7	35.6	–
V	Before thinning	189.1	251.5	320.5	355.4
	After thinning	169.6	231.3	269.1	–
W_t	Before thinning	107.8	148.7	195.2	221.7
	After thinning	96.6	136.6	163.5	–
W_w	Before thinning	65.4	96.2	133.3	155.2
	After thinning	57.3	86.8	107.7	–
C_t	Before thinning	51.8	71.3	93.5	106.1
	After thinning	46.4	65.5	78.4	–
RS	Before thinning	21.3	21.5	21.4	26.1
	After thinning	26.5	25.4	30.2	–
MAI		12.6	14.3	15.7	15.4
MAI-C[a]		3.5	4	4.5	4.6
t[b]		15	19	23	29

The numbers 13, 16, 19 and 22 represent the H at thinning. H is the dominant height, N the number of stems per hectare, d_g the quadratic mean diameter (cm), V the stand volume (m^3 ha^{-1}), W_t the stand aboveground biomass (Mg ha^{-1}), W_w the stand stem biomass (Mg ha^{-1}), C_t the carbon pools in stand aboveground biomass (Mg C ha^{-1}), RS the relative spacing index (%), MAI the mean annual volume increment (m^3 ha^{-1} $year^{-1}$), t the age (years), MAI-C the mean annual increment in carbon pools (Mg C ha^{-1} $year^{-1}$).

[a] A tonne of carbon is equivalent to a 3.6667 tonne reduction in CO_2.

[b] Estimated using dominant height curves developed by Álvarez González et al. (2005).

schedule consists of three thinning operations, and the target harvest age (point g in Fig. 4) was defined by a dominant height of 22 m and a quadratic mean diameter of 38.4 cm.

The lower growing stock limit was defined by a relative spacing index value of 22% and the thinning interval was based on a dominant height increment of 3 m, in accordance with the thinning schedules proposed for maritime pine stands in France (ONF, 1996). Using these values, the sequence of three thinnings to reach this point was found by backwards stair-stepping (Fig. 4). To determine the age at which thinning and harvesting should be carried out, Eq. (1) must be used. For this example, the ages associated with thinnings and harvesting were obtained considering a hypothetical stand with a site index of 17 m at a reference age of 20 years. Thus, we substituted 17 for H_1, 20 for t_1, and the dominant height of the stand H at thinning time for H_2 in Eq. (1), to calculate iteratively the corresponding age t_2 at thinning.

Thinning segments were drawn parallel to the y-axis on the assumption that low thinning has no effect on dominant height (Fig. 4). The post-thinning linear segments were also drawn parallel, in this case to the x-axis, on the assumption that mortality did not occur between thinning intervals. This assumption is based on the insignificant competition-related mortality observed in the sample plots for both ecoregions (Rodríguez Soalleiro, 1997). A similar assumption was also adopted for the construction of stand density management diagrams for maritime pine in Portugal (Luis and Fonseca, 2004) and for other species using different size-density indices (e.g. McCarter and Long, 1986; Dean and Baldwin, 1993; Kumar et al., 1995).

Total yield, aboveground biomass, stem biomass and carbon pools can be obtained directly for any point on the diagram using the volume, biomass and carbon isolines. For example, the volumes removed during the first, second and third thinnings (the difference between volume before and after thinning) were 19.5, 20.2 and 51.4 $\mathrm{m}^3\,\mathrm{ha}^{-1}$; volume at the end of the rotation reached 355.4 $\mathrm{m}^3\,\mathrm{ha}^{-1}$. The sum of these volumes represents an estimate of stand volume by this specific density management regime. Stand aboveground biomass, stand stem biomass and carbon pools in stand aboveground biomass were obtained in a similar way using the corresponding SDMDs. Mensural data for this example of a thinning sequence are shown in Table 5.

5. Conclusions

A stand-level model was developed for determining stand volume, stand aboveground biomass, stand stem biomass and carbon for even-aged maritime pine stands in Galicia under a wide range of conditions. The model has wide potential use as the data required for the equations and diagrams are easy to obtain and are usually available from common timber inventories.

As expected, there were differences among the parameters of the fitted equations corresponding to each ecoregion (coastal and interior) delimited for maritime pine in the area of study and, therefore, a different diagram was developed for each.

The plots used for developing these diagrams had been thinned with a wide range of weights, therefore the stand-level model will be of additional use because silvicultural treatments can induce changes in stand structure over time and this is taken into account in the model.

Although this stand-level model was primarily developed for deriving thinning schedules and for making rapid estimates of volume, biomass and carbon, it is also useful for other purposes. Thus, if additional information becomes available, the diagram can be used to describe the dynamics of maritime pine stands from various resource management perspectives (e.g. non-timber resource production or habitat requirements of wildlife species) by overlaying this information on a density management diagram, thereby facilitating management decisions.

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