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A Density Management Diagram Including Stand Stability and Crown Fire Risk for *Pseudotsuga Menziesii* (Mirb.) Franco in Spain

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A static stand density management diagram was constructed for Douglas fir (*Pseudotsuga menziesii* [Mirb.] Franco) plantations in Spain on the basis of 3 equations that were fitted simultaneously by the full information maximum

likelihood procedure to data derived from 172 plots measured across the Cantabrian and pre-Pyrenean ranges. The first equation relates quadratic mean diameter to the number of stems per hectare and dominant height. The other 2 equations relate stand volume and stand aboveground

biomass to quadratic mean diameter, number of stems per hectare, and dominant height. An estimation of the average slenderness coefficient for the 250 largest trees per hectare and the canopy bulk density were included. The stand density management diagram outlined here enables rapid, straightforward comparisons among different thinning schedules for forest plantations in mountain regions, in which timber production, risk of crown fire, and the risk of damage from wind or snow are considered.

Keywords: Stand management diagrams; slenderness coefficient; canopy bulk density; forest management; forest plantations; Spain.

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Introduction

Douglas fir in mountain areas of northern Spain

Mountain forests satisfy a range of environmental and productive needs, but under the current socioeconomic conditions, their value for forest biomass production and storage of greenhouse gases is particularly relevant (Jandl et al 2008). Many mountain forests in the Iberian Peninsula and the rest of Europe are in fact plantations, the management of which must adapt to changing societal requirements. Furthermore, mountain ecosystems are reported to be particularly vulnerable to climate change (IPCC 2007), including the plantations in Mediterranean mountains where risk of windthrow, snow damage, and forest fires are of primary concern.

Although large-scale plantations were not established until the 1960s, particularly in areas such as La Rioja, Guipúzcoa, and Catalonia, Douglas fir plantations in northern Spain date back to the first third of the 20th century. The area occupied by plantations of this species has increased in recent years to approximately 50,000 ha primarily because of their use in the European Reforestation of Agricultural Land Program.

Employing a range of site preparation techniques and based on extensive knowledge of American seed sources, Douglas fir plantations were established to maximum growth rates (Toval et al 1993). Several provenances from

the Pacific slope forests at low to middle altitudes and latitudes of 44–50°N have been used. Although plantations are more common in mountain areas, Douglas fir has been planted across all of the north of the Iberian Peninsula, from sea level to an altitude of 1400 m. These plantations are strongly influenced by the North Atlantic climate effects and are usually established at initial densities ranging from 1600 to 2500 trees per hectare.

Stand density management

Stand density management diagrams (SDMDs) are average stand-level models that graphically illustrate the relationships among yield, density, and density-dependent mortality at all stages of stand development (Newton 1997). Their utility has been largely limited to evaluating density management outcomes in terms of mean tree size and stand-level volumetric yields, but recent innovations, including the addition of structural yield prediction in the development of SDMD (Newton et al 2005), has extended their utility in forest management decision-making.

The use of SDMDs is one of the most effective methods for the design, display, and evaluation of alternative density management regimes in even-aged stands (Jack and Long 1996). More specifically, SDMDs can be used to determine the initial spacing or thinning schedules required to achieve different management objectives: providing density thresholds that (1) minimize the temporal window for the

attainment of specified operability criteria (eg Newton and Weetman 1994), (2) control shrub development during early stages of stand development (eg Smith 1989), (3) reduce stand susceptibility to pests (Long and Shaw 2005), (4) optimize wildlife habitat (eg Sturtevant et al 1996), and (5) enhance stand stability and aboveground biomass production (Castedo et al 2009).

Risk assessment for plantations

The 3 main hazards that Douglas fir plantations face in northern Spain are windthrow, snow breakage, and fire. Different types of modeling tools have been developed to help foresters estimate stand stability, ie the resistance of a stand to wind and snow damage. In empirical modeling, regression equations or indices are developed to relate windthrow incidence to site, stand, and/or tree attributes among other things. The slenderness coefficient (SC) is considered the simplest stability indicator (Wilson and Oliver 2000; Hinze and Wessels 2002). Several studies have shown that the value of the SC (considered as a tree or stand index) is highly correlated with stem bending, windsnap, and windthrow (Becquey and Riou-Nivert 1987; Wilson and Oliver 2000). For Douglas fir, de Champs (1997) considered a tree $SC < 75$ as a threshold for stability. In the case of American commercial plantations, beyond stand heights of approximately 10 m, the mean SC of the largest 250 trees per hectare (SC_{250}) increases consistently and dramatically irrespective of the establishment density (Wilson and Oliver 2000). Consequently, early thinning is recommended in this case in order to maintain moderately stable values ($SC_{250} < 80$).

In Douglas fir plantations the understory cover is maintained at low levels after canopy closure, and hence fuel loads are minimal. Light-demanding bushes are only able to become re-established if the stand is severely thinned. Analysis of crown fire risk therefore appears to be one of the most important issues given that it is known that canopy crown density is directly related to the minimum spread rate to sustain an active crown fire (Schaaf et al 2007). The canopy bulk density (CBD) describes the amount of fine fuel within a unit volume of the canopy. Maintenance of low CBD values is thus an important management goal in areas where large crown wildfires (>2000 ha) can account for up to 60% of the total burned area but represent only 7% of the total number of fires (Díaz-Delgado and Pons 2001). However, the inclusion of fire risk variables in the SDMD modeling framework has not yet been previously considered.

The main aim of the present study was to develop a static stand-level density management diagram to estimate wood volume and aboveground biomass of Douglas fir plantations in Spain, thereby enabling evaluation of the effects of different density management regimes on these variables. A further aim was to use the diagrams to assess the level of risk that these stands face,

with a special emphasis on stand resistance to damage by wind and snow, and risk of crown fire.

Data

The data used to develop the SDMD were obtained from 172 temporary sample plots, thus allowing for the development of static diagrams. The size of plot ranged from 314 m² to 1200 m² depending on stand density (minimum of 30 trees per plot). The plots were located throughout the area of distribution of Douglas fir plantations in Spain and were subjectively selected in order to adequately represent the existing range of ages, stand densities, and sites (Figure 1).

Two measurements of diameter at breast height (1.3 m) were made, at right angles to each other (with callipers), on all the trees in each plot from which the arithmetic mean (d , in cm) was calculated. Total height (h , in meters) was measured in a 30-tree randomized sample. The height of the remaining trees and the total volume of each tree were calculated with a stochastic generalized height-diameter relationship and taper function developed from trees felled in the same stands (López-Sánchez 2009).

The total aboveground biomass of each tree in the plots was calculated with the equation developed by Bartelink (1996) for plantations in the Netherlands:

$$\ln WT_t = -1.62 + 2.41 \ln d \quad (1)$$

where WT_t is the total oven-dried aboveground biomass (kg tree⁻¹).

The following stand variables were also calculated for each plot: stand age (A , in years), dominant height (H , in meters) defined as the mean height of the 100 thickest trees per hectare, stand basal area (B , in m² ha⁻¹), quadratic mean diameter (d_g , in cm), number of stems per hectare (N), merchantable stand volume, considering top diameter d_i from 0.5 to 58 cm (V_m , in m³ ha⁻¹, V referring to $d_i=0$), total aboveground biomass (W_t , in kg ha⁻¹) and canopy bulk density (CBD , in kg m⁻³) defined as the ratio between crown foliage biomass and canopy volume. The last variable was obtained for each plot by using of the following relationship (Cruz et al 2003):

$$\ln CBD = -7.38 + 0.479 \ln B - 0.625 \ln N \quad (2)$$

where all the variables have already been defined.

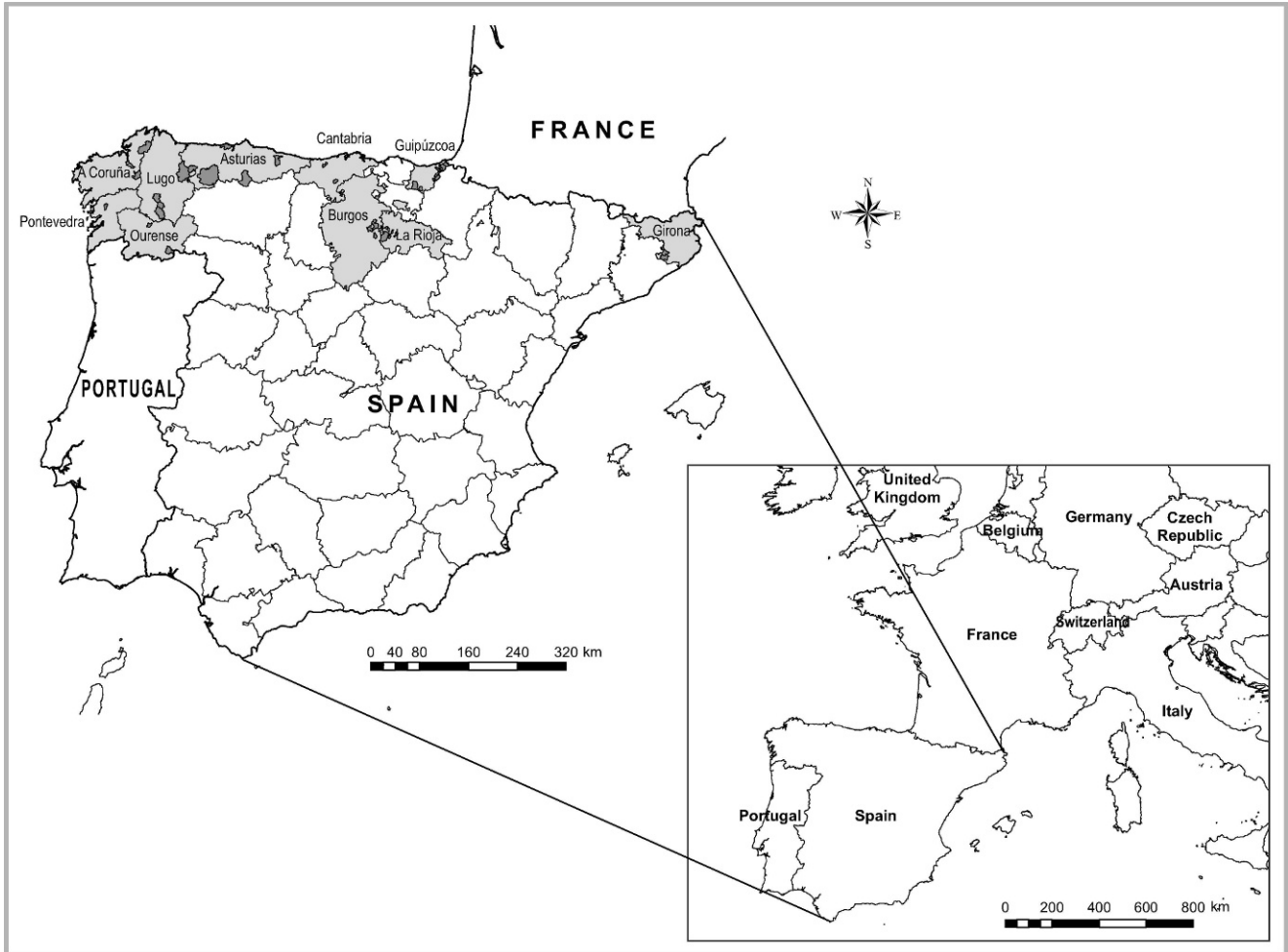
Summary statistics, including the mean, maximum, minimum, and standard deviation for each of the main stand variables calculated, are shown in Table 1.

Methods

Volume and biomass SDMDs

The stand-level model developed includes a system of 3 equations and the relative spacing index as basic components.

FIGURE 1 Location of the study areas in different autonomous communities of northern Spain (darker shading). (Map elaborated by the authors based on thematic information on municipalities, provinces, and countries provided on the website of the Spanish Institute of Statistics, www.ine.es, 2005)



The procedure for constructing the diagrams involves fitting the nonlinear system of the following 3 equations:

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

$$V_m = b_3 d_g^{b_4} H^{b_5} N^{b_6} \exp\left(b_7 d_i^{b_8} d_g^{b_9}\right) \quad (4)$$

$$W_t = b_{10} d_g^{b_{11}} H^{b_{12}} N^{b_{13}} \quad (5)$$

where V_m is the merchantable stand volume, which is equal to V for $d_i = 0$; b_i ($i = 0, 1 \dots 13$) are the regression coefficients to be estimated; and variables are as previously defined.

Equations 3, 4, and 5 define a simultaneous system of equations, where N and H are exogenous variables, V_m and W_t are endogenous variables (variables that the model is

intended to predict and only appear on the left-hand side of 1 equation), and d_g is an endogenous instrumental variable (endogenous variables that also appear on the right-hand side of other equations). Since the error components of the variables on the left-hand side and the right-hand side are correlated, the Full Information Maximum Likelihood technique was applied to fit all the equations simultaneously by use of the MODEL procedure of SAS/ETS® (SAS Institute 2004). The same plots were used to calculate volumes up to different (0.5–58 cm) top diameters, leading to an unequal number of observations among plots. For that reason the inverse of the number of observations in each plot was used for weighting all the equations in the fitting process.

The relative spacing (RS) index is used to characterize the growing stock level. This was proposed by Hart in 1928 for plantations and in 1954 was referred to as a spacing

TABLE 1 Summary statistics of the data set used. *A*, age (years); *N*, number of stems per hectare; *H*, dominant height (m); *S*, site index (dominant height in meters at a reference age of 20 years); d_g , quadratic mean diameter (cm); *B*, basal area ($m^2 ha^{-1}$); *V*, stand volume ($m^3 ha^{-1}$); W_t , aboveground total biomass ($kg ha^{-1}$); SC_{250} , the stand stability index; *CBD*, estimated crown bulk density.

Stand variable	Mean	Minimum	Maximum	SD
<i>A</i>	28.600	8.000	63.000	9.200
<i>N</i>	837.900	280.000	2128.000	370.100
<i>H</i>	19.900	6.500	34.400	5.400
<i>S</i>	14.900	9.300	27.500	3.100
d_g	24.900	8.400	49.200	7.400
<i>B</i>	36.700	4.400	68.700	12.700
<i>V</i>	313.900	16.200	782.300	142.800
W_t	358,914.000	28,520.000	762,322.000	146,442.000
SC_{250}	0.645	0.452	0.890	0.079
<i>CBD</i>	0.226	0.070	0.439	0.079

index by Becking (in Clutter et al 1983). Assuming a square spacing for plantations the index can be written as follows:

$$RS = \frac{10,000}{H\sqrt{N}} \quad (6)$$

RS is useful in stand density management because dominant height growth is one of the best criteria for establishing thinning intervals, and relative spacing itself has been used to propose thinning schedules in Douglas fir plantations in Europe (de Champs 1997).

The model can be displayed graphically by plotting dominant height on the *x*-axis and number of stems per hectare on the *y*-axis, and superimposing isolines for relative spacing index, quadratic mean diameter, and any of the following variables: stand volume, stand stability, canopy bulk density, and stand aboveground biomass on the bivariate graph. The isolines for RS, d_g and *V* were obtained by solving for *N* (in relation to *H*) in the Equations 6, 3, and 4 and substituting for Equation 3 when necessary.

$$N = \left(\frac{10,000}{RS H}\right)^2 \quad (7)$$

$$N = \left(\frac{d_g}{b_0 H^{b_2}}\right)^{1/b_1} \quad (8)$$

$$N = \left(\frac{V}{b_3 b_0^{b_4} H^{(b_2 b_4 + b_5)}}\right)^{\frac{1}{b_1 b_4 + b_6}} \quad (9)$$

No isolines were represented for W_t , although it is easy to implement the equation to calculate the aboveground

biomass of a stand once its density and dominant height are known. The values of all the variables used to develop the SDMDs ranged between the minimum and maximum values observed (Table 1).

Assessment of stand stability and fire risk

Most authors have stated that the SC calculated from only the largest trees (eg largest 100–250 trees per hectare [Reukema 1979; Cremer et al 1982; Slodicak 1995]) in a stand ensures that the SC value is unaffected by suppressed and intermediate-size trees. Given that these larger-size trees tend to have the highest timber, aesthetic, and habitat values, maintaining their stability is a critical factor. SC_{250} was calculated as the ratio between the mean heights of the largest 250 trees per ha H_{250} to their mean diameter D_{250} . Accurate estimates of H_{250} and D_{250} can be obtained from dominant height and quadratic mean diameter, respectively, by the following linear relationships:

$$H_{250} = 0.6425 + 0.9286H \quad (10)$$

$$D_{250} = 6.7828 + 0.930D_g \quad (11)$$

Equations 10 and 11 accounted for 98% and 89.6% of the total variability in the data, respectively, and provided a random pattern of residuals around zero.

The stand slenderness coefficient can thus be expressed as

$$SC_{250} = \frac{0.6425 + 0.9286H}{6.7828 + 0.930b_0 N^{b_1} H^{b_2}} \quad (12)$$

Representation of the isolines for the slenderness coefficient involves solving Equation 12 for *N* through a

TABLE 2 Nonlinear regression coefficients obtained by simultaneous fitting of the 4-equation system, predicting quadratic mean diameter (d_g), merchantable stand volume (V_m), and stand aboveground biomass (W) (standard error in parentheses).

Eq	Parameter estimates							RMSE	R^2
2	$b_0 = 24.598$ (0.665)	$b_1 = -0.295$ (0.0029)	$b_2 = 0.655$ (0.0038)					3.026	0.821
3	$b_3 = 56E-6$ (2.27E-6)	$b_4 = 2.014$ (0.0077)	$b_5 = 0.803$ (0.0051)	$b_6 = 0.999$ (0.00332)	$b_7 = -0.058$ (0.0016)	$b_8 = 3.890$ (0.0096)	$b_9 = -3.002$ (0.011)	14.500	0.992
5	$b_{10} = 0.150$ (0.0022)	$b_{11} = 2.430$ (0.0036)	$b_{12} = 0.0038$ (0.0022)	$b_{13} = 1.034$ (0.0012)				5827.100	0.998

RMSE, root mean squared error.

range of H by setting SC_{250} constant:

$$N = \left(\frac{0.6425 + 0.9286H - 6.7828SC_{250}}{0.930b_0H^{b_2}SC_{250}} \right)^{1/b_1} \quad (13)$$

Finally, the isolines for CBD are obtained by solving for N in Equation 2 and replacing B for its expression that depends on d_g (Eqn. 3):

$$N = \left(CDB e^{7.38} \left(\frac{\pi b_0^2}{40,000} \right)^{-0.479} H^{-2b_2 \cdot 0.479} \right)^{1/(2b_1 + 1) \cdot 0.479 - 0.625} \quad (14)$$

Results and discussion

Construction of the diagrams

The regression coefficients of the basic models (Eqns. 3–5) are shown in Table 2. All the parameter estimates were significant at $P < 0.0001$, except b_{12} ($P = 0.084$). The equations provide a good level of precision, with the lowest value for the estimation of d_g (82.1% of the variation explained), which is a common situation for static stand-level models. Examination of the residuals revealed that all the regression models were unbiased with respect to the independent variables, age, and site index.

An SDMD was developed by superimposing the plots used; the expected size–density trajectories, ie the values of relative spacing index; the isolines for quadratic mean diameter; and the isolines for total stand volume (Figure 2). Merchantable stand volume to any specific top diameter can be obtained at any point on the SDMD by simply multiplying the total stand volume read from the diagram by the exponential term in Equation 4 (d_g is obtained directly from the diagram).

The dominant height axis ranges from 8 to 36 m, whereas the densities range from 100 to 3000 stems per hectare, since no naturally regenerated stands exist and the

plantation density was never higher. The uppermost isoline for the relative spacing index in the diagram corresponds to a value of 10%, with several plots corresponding to the 10–12% range. Additional relative spacing index lines range up to 46. The values of the quadratic mean diameter range from 12 to 42 cm, and the isolines slope upward from left to right and are highly sensitive to stand density. Total stand volume values range from 50 to 800 $m^3 ha^{-1}$, and the isolines slope upward from left to right, in accordance with the principle that productivity at any point in time is greatly affected by dominant height.

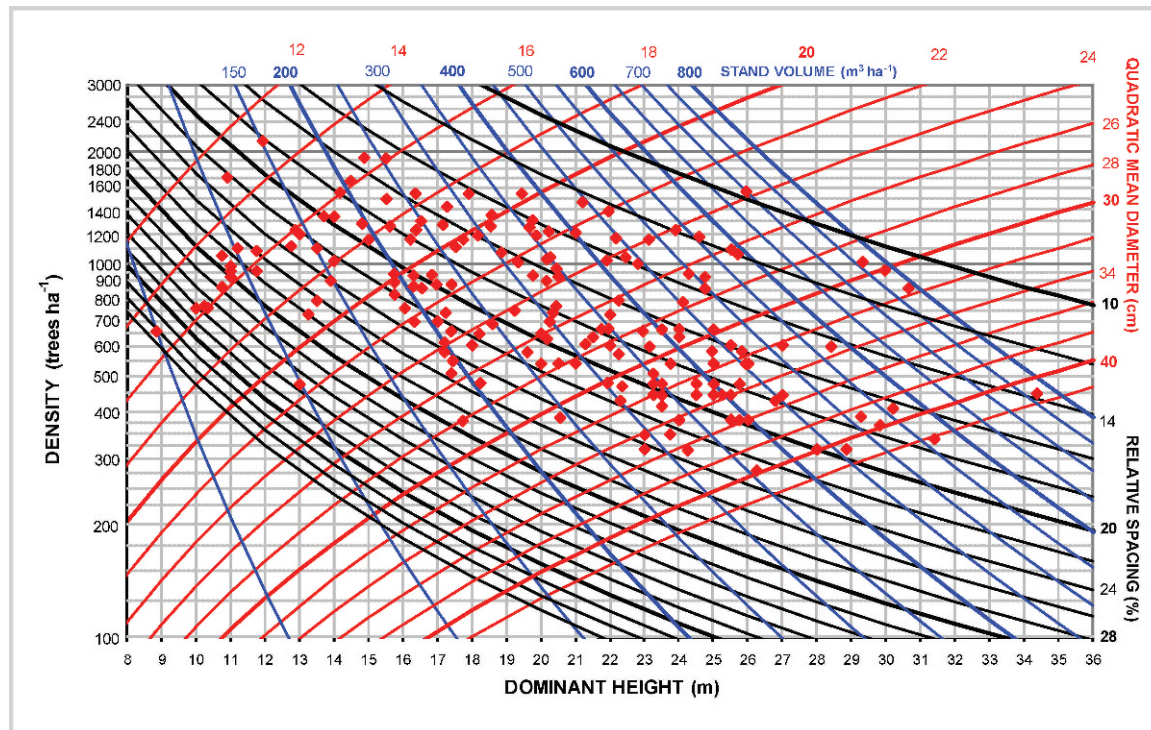
The isolines corresponding to the 40–110 range of SC_{250} values were superimposed on the SDMD (Figure 3). These isolines slope downward from left to right and are highly sensitive to stand density and dominant height. Three zones of stability can be considered according to Becquey and Riou-Nivert (1987) and Wilson and Oliver (2000) for SC_{250} thresholds of 60 and 80. No stability risk is evident for H lower than 10 m, even for the highest plantation density, but stability becomes a critical factor as the stand dominant height increases. The isolines for the CBD represented a range from 0.1 to 0.5 $kg m^{-3}$ and also slope downward, although less rapidly than the isolines of RS or SC_{250} .

Practical use of the diagrams

From the first development of SDMDs for Douglas fir it was considered that these management tools enable rationalization of the trade-off between maximizing individual tree size and stand yield (Drew and Flewelling 1979). It is also clear from the diagrams in Figures 2 and 3 that there should also be a trade-off between the accumulation of biomass (and the corresponding storage of carbon) and the maintenance of appropriate levels of stand stability and crown fire risk levels. If we consider the maximum size–density relationship for plantations of this species (Drew and Flewelling 1979), it becomes clear that the SC_{250} ratio will tend to increase if no early thinnings are applied.

Note that any proposed management regimes can be included in the diagram as series of horizontal lines (assuming no mortality) and vertical lines representing thinning segments while assuming that low thinning has

FIGURE 2 Stand density management diagrams for Douglas fir plantations including representation of the sample plots.



no effect on dominant height. The rapidity with which the stand moves along horizontal lines depends on the site index, or dominant height growth over time. This means that users need to simulate stand development through time using the height isolines in combination with the site index functions. Total yield and aboveground biomass can be obtained directly for any point on the diagram from the volume and biomass. The volumes removed from thinnings can be estimated as the difference between volume before and after thinning. The sum of these volumes throughout the rotation is an estimate of stand yield by a specific density management regime.

It becomes clear from Figure 2 that most of the plantations sampled are in fact well above the density levels proposed as optimal for the same species (maintenance of relative spacing below 23%; de Champs 1997). This state is characterized by a simplified vertical structure and cover and could not be considered as acceptably stable in terms of carrying up a protective function in mountain areas, as has been shown for pure and homogeneous stands of Norway spruce (Motta and Haudemand 2000). The alternative of rising *RS* to 23% would maintain the SC_{250} well below 60, and the *CBD* would tend to decrease in the range 0.2–0.1 kg m⁻³. Once the *CBD* value is estimated for a stand, the use of crown

fire models can provide further information on the threshold conditions for passive versus active crown fire spread in terms of fuel moisture and wind (see Cruz et al 2005).

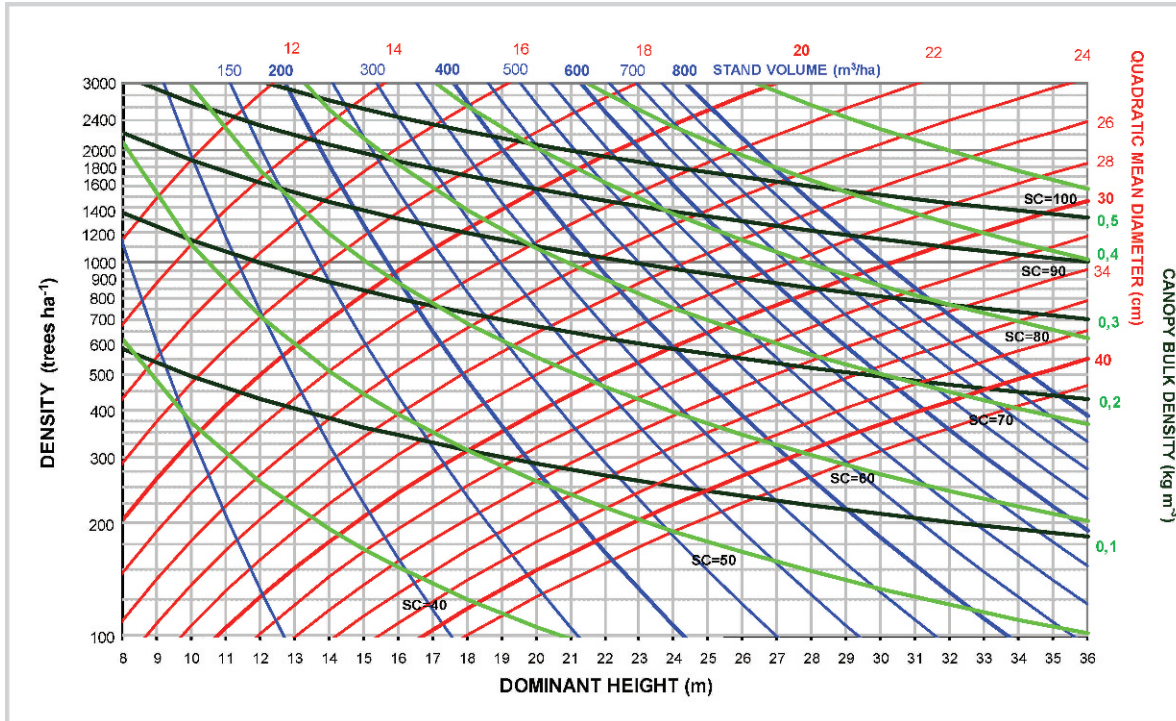
The static diagram developed in this study lacks a net density change submodel, which accounts for mortality. This limits its utility in density management decision-making given that future size–density trajectories are not explicitly modeled. Future research effort should be directed in this area.

Conclusions

A stand-level static model was developed for determining stand volume and stand aboveground biomass for Douglas fir stands under a wide range of conditions. The SDMDs also allow rapid estimation of resistance to windthrow and snow breakage or the risk of crown fire at any stage of stand development. This information can help silviculturists to check several indicators of sustainable forest management related to the growing stock or woody biomass.

The stand slenderness coefficient and the canopy bulk density were successfully incorporated into the stand density management diagram. The model is of great potential use because the data required for the equations

FIGURE 3 Stand density management diagram for Douglas fir plantations with stand stability (SC) and risk of crown fire (CBD) isolines.



and diagrams are usually available from common forest inventories. In addition, it is relatively easy to develop alternative thinning schedules by calculating

merchantable volumes and to compare these alternatives with economic criteria, thereby facilitating management decisions.

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