

Stand Density Management Diagrams for two Mediterranean pine species in Eastern Spain

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Abstract

Stand Density Management Diagrams are useful tools for designing, displaying and evaluating alternative density management regimes in even-aged stands, with which to achieve a desired future stand condition. The stands studied, of *Pinus halepensis* and *Pinus pinaster*, have low productivity, and managers need easy, efficient tools to obtain the best yield. These diagrams help the managers of these stands determine thinning prescriptions. The relationship between stand density, dominant height, quadratic mean diameter and stand volume is represented in just one graph. Two equations were fitted simultaneously: one that relates quadratic mean diameter with stand density and dominant height, and another that relates total stand volume with quadratic mean diameter, stand density and dominant height.

Additional key words: *Pinus halepensis*, *Pinus pinaster*, silviculture.

Resumen

Diagramas de Manejo de Densidad para dos especies de pino mediterráneas en el este de España

Los Diagramas de Manejo de Densidad de Masa son útiles herramientas para el diseño, desarrollo y evaluación de regímenes de densidad alternativos en masas regulares, para alcanzar unas condiciones de masa deseadas. Las masas estudiadas, de *Pinus halepensis* y *Pinus pinaster* tienen una baja productividad, y los gestores necesitan herramientas fáciles de usar y eficientes para obtener la mayor rentabilidad. Estos diagramas ayudan a los gestores de estas masas en la toma de decisiones selvícolas. La relación entre la densidad de masa, la altura dominante, el diámetro medio cuadrático y el volumen total de la masa se representa en sólo un gráfico. Se ajustaron dos ecuaciones simultáneamente: una que relaciona el diámetro medio cuadrático con la densidad de la masa y la altura dominante, y otra que relaciona el volumen total de la masa con el diámetro medio cuadrático, densidad de la masa y altura dominante.

Palabras clave adicionales: *Pinus halepensis*, *Pinus pinaster*, densidad, selvicultura, diagrama.

Introduction

Forest managers in low productivity areas, as in Mediterranean basin and other dry regions, face society demands as timber and fuelwood production, wildlife conservation leisure areas or adequate landscape management under strong budget limitations. Usually, foresters adopt extensive silviculture approaches that include limitate thinning operations, use of natural regeneration and avoid any intervention that can not be self-financed. To help foresters to adopt adequate decisions under these circumstances, simple whole-stand models should be developed.

Fire is considered one of the basic problems for Mediterranean forests, while adequate silviculture

(regulation of stand density) is one of the main tools to prevent catastrophic fires (Scarascia-Mungoza *et al.*, 2000), and keeping the stand at a correct stand density level can reduce the impact and frequency of fires. Mediterranean forests usually have low productivity, and this factor can be one of the reasons for the low-cost management. Therefore, if we provide managers with a quick, cheap tool, reducing management costs and increasing it in these stands, we can, for example, reduce fire impact and frequency. Stand density regulation is the tool the forester use to control the level of growing stock to target different specific management objectives (Newton, 1997). Adequate stand density levels determination is a difficult task that involves biological, technological, economical and operational factors drive by species, site and management frameworks (purposes, budget, technical background, ...).

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By selecting adequate upper and lower growing stock levels, forester bounds the adequate thinning regime. So, selection of the growing stock limits is one of the most difficult step in designing a density management regime and should be done carefully.

Thinning experiment sites are the best option to determine adequate thinning alternatives and density targets. However, stand densities can occur in an almost infinite array of combinations, and as a result, it is unreasonable to expect that all possible combinations could be test in field experiment before apply it in operational forestry. So an alternative cost-effective approach as the Stand Density Management Diagrams (SDMDs) is needed. This is specially true in areas where silvicultural practice must be implemented under strong budget limitations.

Stand Density Management Diagrams (SDMD) are stand models that graphically represent the relations between stand density, height, diameter and volume for even-aged stands (Archibald and Bowling, 1995; Newton, 1997; Álvarez-González *et al.*, 2005). Stand Density Management Diagrams provide the necessary stand variables values to adopt silvicultural decisions in that level. These diagrams are based on the self-thinning rule and the relationships between diameter, dominant height, density and volume for even-aged stands (Archibald and Bowling, 1995), as well as in the forestry production theories, empirical yield-density relationships, and use high functional significant variables that describe very well forest stand evolution (Jack and Long, 1996; Newton, 1997). These yield-density relationships describe at the stand level the accumulated effect of some underlying competition processes. Temporal dependency of these processes is governed by competition and site quality, represented by Reineke index and site index, respectively. In fact, these diagrams can be used to predict size-density trajectories under different silvicultural strategies (Newton, 1997).

Using SDMD is one of the most effective methods for the design, development and evaluation of alternative density management regimes for even-aged stands (Newton, 1997). These diagrams are developed describing the growth of the stand, with index that join the size of the tree (volume, height, diameter) with the stand density (trees per hectarea) (Álvarez-González *et al.*, 2005). Other options of SDMD uses are the application of these tools to more specific management situations, like the susceptibility of stands to the attack of pest (Whitehead *et al.*, 2001), wind resistance (Mitchell, 2000) or getting a larger diversity of stands

(Powelson and Martin, 2001). In Southern Europe, different SDMD have been developed for plantations (Álvarez-González *et al.*, 2005) and atlantic forests (Álvarez-González *et al.*, 2005; Barrio-Anta and Álvarez-González, 2005). However, SDMD for Mediterranean species have been not developed yet.

Pine stands are the most extended coniferous stands in the mediterranean zone. Aleppo pine (*Pinus halepensis*) and Maritime pine (*Pinus pinaster*), are two important coniferous species in the Mediterranean basin. *Pinus halepensis* is one of the most studied Mediterranean trees, specially its post-fire regeneration (Ne'eman *et al.*, 2004; Montero *et al.*, 2001; Núñez and Calvo, 2000) and its growth and yield (Montero *et al.*, 2001). *Pinus pinaster* has been widely studied too, but the only growth models available for Maritime pine in the Spanish Mediterranean area are the yield tables for maritime pine stand in the Central Mountain Range (García-Abejon and Gómez-Loranca, 1989), and the site index curves and growth model (Bravo-Oviedo *et al.*, 2004).

Mediterranean species as Aleppo pine and Maritime pine don't have a high productivity, and this implicates than the management costs must be minimized to obtain equilibrate economic balance. Our objective is to develop SDMD for *Pinus halepensis* and *Pinus pinaster* Mediterranean even-aged stands in Eastern Spain, to help foresters decision making process in a cost effective way.

Material and Methods

Study area

Eastern Spain was selected as study area for both species (Fig. 1) because a mix of silvicultural and ecological situations can be found in this area. *Pinus halepensis* stands in the study area are found between 200 and 600 meters, with precipitations between 859 and 340 mm/year and a medium temperature between 17 and 11.9°C. *Pinus pinaster* stands have a lower range of altitude variation, between 800 and 1,200 meters, while annual precipitation ranges between 1,005 and 455 mm, and average temperature between 15.5 and 9.4°C.

Data

In order to develop SDMD for *Pinus halepensis* and *Pinus pinaster* stands in Eastern Spain data were

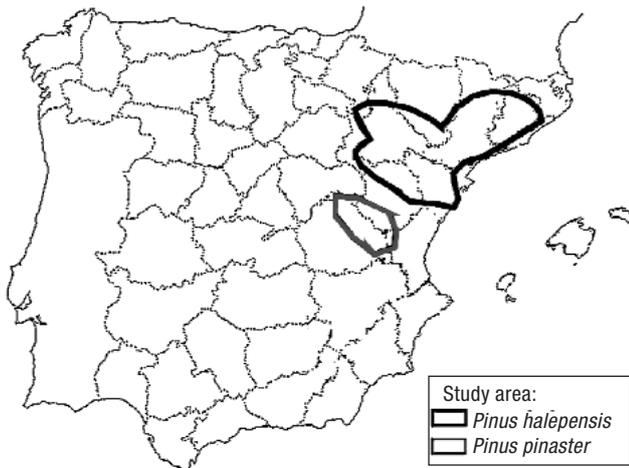


Figure 1. Map showing *Pinus halepensis* and *Pinus pinaster* study areas in Eastern Spain.

obtained from the Second Spanish National Forestry Inventory (2SFI). Data selection has been done with BASIFOR 2.0 software (Río *et al.*, 2001; Bravo *et al.*, 2005). Main plots characteristics are summarised in Table 1. Plots of the 2SFI are systematically distributed using a grid one square kilometer. Each plot consists of four concentric subplots with radius 5, 10, 15 and 25 m. For those subplots, the minimum diameter recorded is 7.5, 12.5, 22.5 and 42.5 cm respectively. In order to expand the data to hectare the following expansion factors have been used, 127.32, 31.83, 14.15

Table 1. Main characteristics of the data set used to develop SDMD for *Pinus halepensis* and *Pinus pinaster* stands in Eastern Spain

Variable	Mean	Minimum	Maximum	Standard deviation
<i>Pinus halepensis</i> (n = 1,147)				
QMD	16.97	7.55	43.90	5.48
N	439.94	5.09	2,405.01	407.34
SDI	198.61	10.67	1,289.66	172.18
H ₀	7.26	2.07	21.35	2.22
VT	29.37	0.96	281.13	30.60
<i>Pinus pinaster</i> (n = 145)				
QMD	21.78	12.60	48.88	5.70
N	696.73	120.53	2,139.75	416.33
SDI	490.35	219.74	1,127.42	208.42
H ₀	11.64	6.64	21.30	2.57
VT	114.83	33.61	361.47	64.19

QMD: quadratic mean diameter (cm). N: density expressed as trees/ha. SDI: Reineke index. H₀: dominant height (m). VT: stand volume (m³/ha).

and 5.09 for each minimum diameter respectively. At plot establishment, the following data were recorded for every tally tree: species, diameter at 1.3 m (QMD) to the nearest millimeter, total height to the nearest quarter meter, and the distance and azimuth from the plot center in meters and degrees, respectively. Diameters were measured with a caliper in two perpendicular directions. A comprehensive description of Spanish National Forest Inventory can be found in (Bravo *et al.*, 2002). Data from the 2SFI have been used previously to develop yield (Bravo and Montero, 2003) and growth (Trasobares *et al.*, 2004) models.

For both species, the upper growing stock limit was determined by the criteria of avoiding density-related mortality, which appears when the stand density index (SDI) is over the 60% of maximum SDI found for each species (Dean and Baldwin, 1993). The lower limit establish the moment when an adequate site occupancy is maintained, and can be set at 35% of maximum SDI for the species (Long, 1985). Keeping the stand between these two limits guarantees adequate density for the stand, avoiding density-related mortality that can provide biomass in case of a forest fire, which can increase its intensity. So, maintaining a stand at the correct density can reduce forest fire impact and intensity.

Model structure and statistical methods

Both data available and user objectives determine the type and structure of model that can be developed. In Mediterranean low productivity forests managers need simple and accurate tools to plan and implement right silvicultural prescriptions. The 2SFI data have the following characteristics: (1) just one measurement is available for the whole country at this moment, (2) plot design is based in four nested subplots based upon QMD and, therefore, stand variables must be computed from expansion factor for each subplot and (3) increment cores were not extracted from each tree. As a result of these limitations, a whole stand yield model that can be expressed as a SDMD is the only alternative.

Two linear models (equations [1] and [2]) relating diameter at breast height and stand volume with density, dominant height, and diameter at breast height are the basic component of SDMD.

$$\text{Ln QMD} = \beta_0 + \beta_1 \cdot \text{Ln N} + \beta_2 \cdot \text{Ln H}_0 \quad [1]$$

$$\text{Ln VT} = \beta_3 + \beta_4 \cdot \text{Ln QMD} + \beta_5 \cdot \text{Ln H}_0 + \beta_6 \cdot \text{Ln N} \quad [2]$$

where:

- N = stand density (stems/ha)
 QMD = quadratic stem diameter (cm)
 H_o = dominant height (m)
 VT = stand volume (m³/ha)
 β_i (i=0-6) = regression coefficients

The two equations together define a system where Ln N and Ln H_o are exogenous variables (defined independently of the system) while VT and QMD are instrumental endogenous variables (Borders, 1989). This equation system was fitted simultaneously for each species and zone. It has been used FIML in both equations with the order MODEL of the program SAS/ETS to make the adjust (SAS Institute Inc., 2001).

The fitted model was graphically through as a graph where quadratic mean diameter is represented on the abscise axis (logarithmic scale) while the number of stems per hectare (logarithmic scale) is represented on the ordenada axis. Isolines representing dominant height, total volume and stand density index (Reineke index) are superimposed on the bivariate graph previously described (Barrio-Anta and Álvarez-González, 2005).

Results

Results of the simultaneous fit of equations [1] and [2], the coefficients estimated and the regression estatistic values can be found in Tables 2 and 3. All coefficients were significant at a 0.05 significance level. The R² adjusted for the validation data set are over 0.69 for the quadratic mean diameter model and

Table 2. Results of the variance analysis, adjust and non linear regression obtained from making the simultaneous adjust of the system of equations to calculate the quadratic mean diameter (QMD) and the stand volume (VT) for the Aleppo pine and Maritime pine

Equation	Adjust and analysis			
	<i>Pinus halepensis</i>		<i>Pinus pinaster</i>	
	QMD	VT	QMD	VT
DF model	3	4	3	4
DF error	1,141	1,140	142	141
SSE	1,0543.4	31,429.6	1,206.0	6,476.6
MSE	9.24	27.57	8.49	45.93
R ²	0.6907	0.9706	0.7422	0.9891
R ² adjusted	0.6901	0.9706	0.7386	0.9889

Table 3. Coefficients of the linear regression obtained from the simultaneous fit of the system of equations to estimate quadratic mean diameter and stand volume for Aleppo pine and Maritime pine

Parameters	Coefficients of regression	
	<i>Pinus halepensis</i>	<i>Pinus pinaster</i>
<i>Quadratic stem diameter equation</i>		
β ₀	11.58212 (0.4015)	26.35118 (6.8972)
β ₁	-0.15971 (0.00325)	-0.24827 (0.0231)
β ₂	0.63958 (0.0157)	0.56295 (0.0609)
<i>Volume equation</i>		
β ₃	0.000124 (7.3 E-6)	0.000021 (3.823E-6)
β ₄	1.763149 (0.0206)	2.363876 (0.0599)
β ₅	0.820647 (0.0179)	0.700337 (0.0488)
β ₆	0.958842 (0.00573)	1.010311 (0.0134)

Between tags the typical error of the estimated parameter.

over 0.98 for the volume model. These results show a correct choice of the model form and the independent variables. Problems of multi-collinearity between explanatory variables were not detected. Thus, the linear two-equation model, which considers the same set of independent variable, was selected to develop the Stand Density Management Diagrams. Stand Density Management Diagrams for *Pinus halepensis* and *Pinus pinaster* in Eastern Spain are showed in Figures 2 and 3.

One SDMD for each species was developed for each study area (Figs. 2 and 3) by superimposing fitted models trajectories on bivariate graph. In Aleppo pine graph (Fig. 2), quadratic mean diameter ranged from 8 to 44 cm, while density ranged from 100 to 2,400 stems per hectare. In Mediterranean maritime pine (Fig. 3), quadratic mean diameter ranged from 12 to 48 cm while density ranged from 100 to 2,400 stems per hectare.

Four practical examples showing the use of SDMD to develop a particular management regime for Aleppo pine (Fig. 4) and Mediterranean maritime pine (Fig. 5) have been developed. The management objective was optimizing tree growth in terms of volume. Thinning schedule consists in one or two operations and the target harvest age was defined by a dominant height of 22 m (both species and both alternatives) and different quadratic mean diameter (Figs. 4 and 5). Natural mortality was not considered so between thinning operation size-density trajectory was drawn parallel to x-axis. A similar assumption was also adopted to develop SDMD

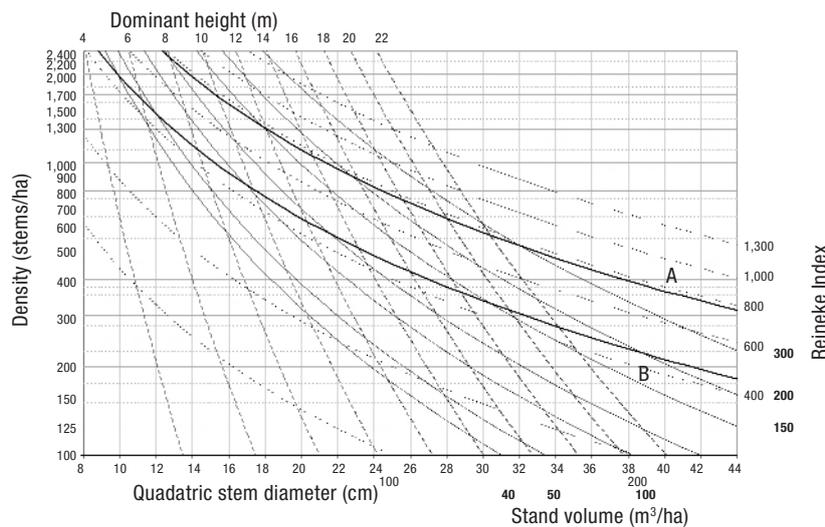


Figure 2. Stand Density Management Diagram for *Pinus halepensis* in Eastern Spain.

for other species (i.e., McCarter and Long, 1986; Dean and Baldwin, 1993; Barrio-Anta *et al.*, 2005).

Discussion

In this study, data from a single measurement plots were analyzed to develop stand density management diagram for Aleppo and Mediterranean Maritime pine stand. Continuing studies are needed to expand results to mixed irregular or structurally complex stands. By using appropriate conversion and expansion factors biomass and carbon pools estimations can be done.

Parameter signs agree with current silvicultural knowledge and adjusted coefficients of determination are over 0.69 in the quadratic mean diameter models and over 0.98 in the total volume models. Bravo and Montero (2003) showed that calibration factors improve estimation from whole stand models fitted using 2SFI data. Unfortunately, we have no permanent plots in Eastern Spain for the studied stands.

Forest managers can reach the maximum advantage of the density management diagrams by obtaining the necessary information (for example, to determine maximum and minimum density levels), to know the site occupancy situation of the stand, and decide if thinning is necessary or not, and the right intensity in that case.

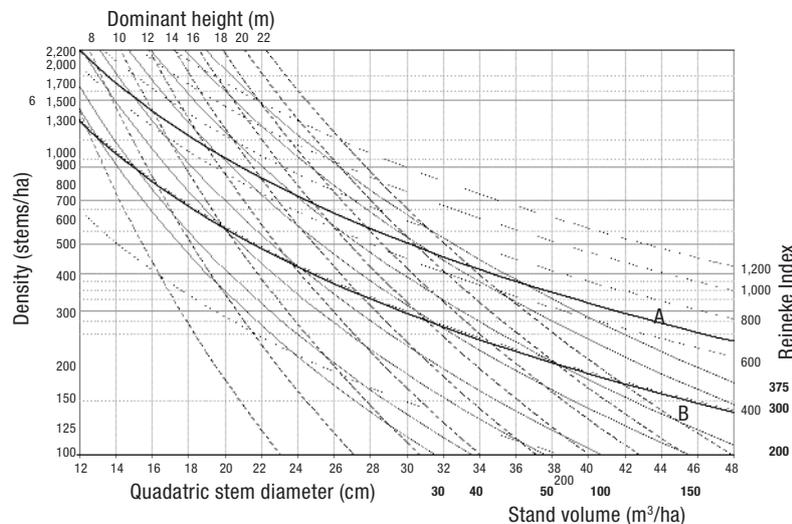


Figure 3. Stand Density Management Diagram for *Pinus pinaster* in Eastern Spain.

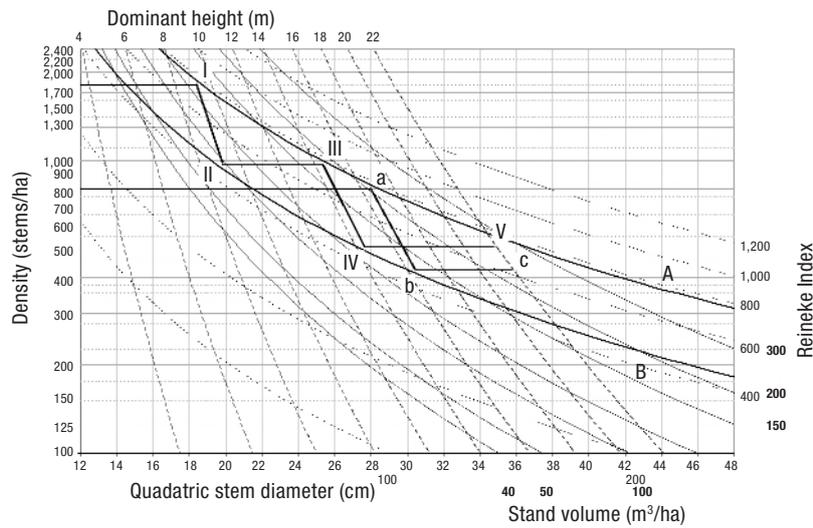


Figure 4. Density Management alternatives for *Pinus halepensis* in Eastern Spain.

As selection of upper and lower growing stock limits is a trade-off between maximum stand and tree growth (Long, 1985), the selection of the appropriate limits depends upon the silvicultural objectives.

From density (trees/ha) and quadratic diameter values for a stand we can obtain values of dominant height, stand volume and Reineke index in the diagram. With the values of two variables for a stand, we can obtain the other variables, for example, with dominant height and density, we can know the quadratic diameter, stand volume and Reineke index.

Maximum and minimum stand density limits can be described by the value of the Reineke index. Self thinning starts over the 60% of the maximum Reineke index

(Dean and Baldwin, 1993), so it can never be exceeded (line A in Figs. 4 and 5). Minimum level for Reineke index is the 35% to allow full site occupancy (line B in Figs. 4 and 5).

Figures 4 and 5 and Table 4 show two options of density management for the two species studied for a better comprehension of the silvicultural regimes, that represent a useful guideline that foresters can use under extensive and low-cost forestry in the studied area.

Whole-stand models, as SDMD, allow managers to adopt decisions in an effective-cost manner under low-economic return silvicultural systems. Other modelling approach as empirical individual-tree or process-based models can be more useful to understand ecosystem

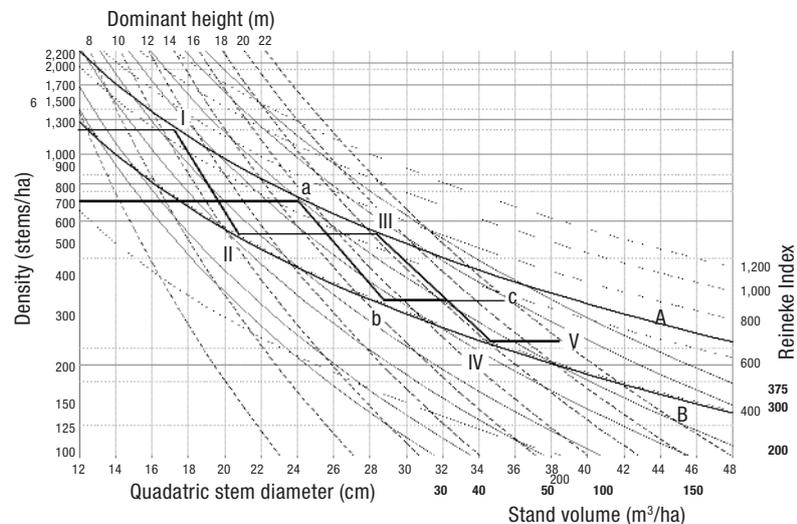


Figure 5. Density Management alternatives for *Pinus pinaster* in Eastern Spain.

Table 4. Alternative silvicultural density management options for Aleppo pine and Maritime pine in eastern Spain

Alternative	Cut	Quadratic stem diameter (cm)		Stand volume (m ³ /ha)		Density (stems/ha)	
		Before	After	Before	After	Before	After
<i>Pinus halepensis</i>							
1	I-II	14.5	16.0	125.0	100.0	1,800	950
	III-IV	21.5	22.7	175.0	130.0	950	500
	V	31.0	—	260.0	—	500	—
2	a-b	24.0	26.2	200.0	130.0	800	425
	c	31.7	—	220.0	—	425	—
<i>Pinus pinaster</i>							
1	I-II	17.5	21.3	125.0	70.0	1,200	550
	III-IV	28.6	34.5	250.0	175.0	550	230
	V	38.5	—	275.0	—	230	—
2	a-b	24.0	29.0	200.0	140.0	700	330
	c	35.5	—	300.0	—	330	—

dynamic. However, SDMD are practical tools basic in extensive silviculture applied in low productivity forests.

Conclusions

During the past fifteen years forest management has change, in some part of the world, from an oriented timber production focus to a biodiversity and multiple use forms. When forest management is oriented to develop structurally complex stands (i.e., Green tree retention practices) stand density management diagrams are too simple to help in thinning prescriptions. A new growth modelling approach using individual distance-independent models would be beneficial for modelling forest dynamic under these silvicultural schemes.

Mediterranean pine stands in Spain show high, aesthetic, biodiversity values that are key factors in forest management but have no market price, due to low productivity. Simple, cheap and easy-to-use tools are needed to help managers to fulfil society's demands and management objectives. In addition, the problem of forest fires is especially important in Mediterranean forests, and can be reduced in many cases with correct management.

These diagrams can be used as foundation to develop silvicultural strategies under economic constraints. Similar modelling strategies can help managers in other areas in the Mediterranean basin (northern Africa, Middle east...) to implement basic but effective silvicultural strategies.

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