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Models to Implement a Sustainable Forest Management – An Overview of the ModisPinaster Model

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1. Introduction

For a long period, practical recommendations for forest management were based upon experience gained through trial and error experimentation, observation and an understanding of density effects on tree growth within the stand. As stated by Zeide (2008), the limitations of the traditional empirical approach coupled with improvements on modelling efforts led to a change of procedures from forestry to forest science, this being defined by the author, as a new development relying on reasoning to produce the optimal system of forest management aimed at satisfying human needs and preserving nature at the same time (though not at the same place).

Nowadays, the use of mathematical models for tree and stand growth dynamics is the recommended scientific approach to test for alternative management options under a Sustainable Forest Management (SFM) concept and to help solve practical problems such as the appropriate range of stand densities, the thinning prescriptions and rotation ages that allow for a given goal. Assessment of volume and biomass growth, for a given period, or of yield and carbon stock at a point in time becomes a straightforward procedure as long as there are proper equations available, for the species and region of study.

Central to the successful implementation of research findings of sustainable forest management is their efficient transfer from the researcher to the manager (Farrell et al., 2000). In this context, there is a strong need for easily accessible programs to run various and numerous simulations in a convenient and flexible way. There are different possible approaches to build a simulation system, each having advantages and drawbacks. One is to build a specific tool for each model. Development can be fast when the objectives of the model are well defined, its structure remains simple and there is no need for complex outputs and interfaces. This approach nevertheless results in building many prototypes

which are generally not very flexible and are difficult to reuse. A second approach is to build one tool around a reusable model and adapt it to different species and situations by changing model parameters. The main drawback remains the limitation to one model with little possible modification. A more interesting option is given by Capsis (Computer-Aided Projection of Strategies In Silviculture, <http://www.inra.fr/capsis>). The Capsis software is a domain specific tool with a common methodology, but accepting models with different data structures, simulation steps and evolution methods.

This chapter will focus on a forest model developed for maritime pine (*Pinus pinaster* Ait.), the ModisPinaster model (Fonseca, 2004), as a supporting tool for Sustainable Forest Management that is freely available for use in the user-friendly Capsis platform. ModisPinaster (Model with Diameter Distribution for *P. Pinaster*) is a dynamic growth and yield (G&Y) model that applies to pure maritime pine stands. It is constituted by several components allowing the simulation of stand evolution through the rotation period and the simulation of interventions such as thinning and clear-cut. In the mortality component, abiotic and biotic variables are used to determine forest vulnerability to damages from wind and snow. This feature is invaluable in a climate change adaptation scenario. The level of detail of the output is the diameter class, with the diameter distributions being recovered by the 4-parameters Johnson S_B distribution (Johnson, 1949; Fonseca et al., 2009; Parresol et al., 2010). The model can be downloaded from the CAPSIS simulation platform web site.

This chapter has the following structure. Section 2, gives an overview of forest models that have been proposed for maritime pine (2.1), followed by a description of the Capsis platform (2.2) and its current uses. Section 3 is devoted to the description of the structure (3.1) and subcomponent models of the ModisPinaster model (3.2). A portrayal of ModisPinaster simulation capabilities within the Capsis interface is depicted in (3.3). Section 4 presents an example of simulation of three management scenarios for the species, using the CAPSIS environment. One scenario follows the traditional management guidelines in the study area. The second scenario follows density management criteria according to the self-thinning line theory. A third scenario provides a simulation that is compatible with the biodiversity promotion, under a SFM policy. Concluding remarks are presented in Section 5.

2. Use of forest models as a supporting tool for SFM

The sustainable management of the forests has been seen, for a long time, as a sustained yield of wood supply. Thus, it is not unexpected that until recently the great emphasis in the forest research domain has been towards stand volume predictions. Estimates on timber volume production originally come from spacing and thinning trials. The field experiments led to the creation of the first generation of yield tables, by German scientists, in the late 18th to the middle of the 19th century. From the experimental tables to the present G&Y models, different types were developed; although their main uses still are for timber management purposes.

The onset of the multi-functional forest paradigm caused the development of models for other purposes such as: management of non-wood products, the promotion of biodiversity, increasing the social benefits and aesthetic demands. For instance, according to the EU commission study (Nieto & Alexander, 2010), in Europe, 11% of the saproxylic beetle species are currently threatened. The main threat, relates to the loss and decline of their habitat either in relation to logging and wood harvesting in forests or due to a general decline in

veteran trees throughout the landscape. Management can help to conserve the biodiversity if done in a sustainable way (e.g. leaving dead wood material in the forest) and promoting the existence of older trees. Attention has also been focused on modelling natural disturbances as they can seriously affect timber production and other forest benefits. It is worthwhile to say that although simulations help to provide management guidelines for the forests, nature is not a virtual forest. Unexpected results might occur in a real forest under a real management process. Critical evaluation of results and adaptive management procedures that take risk into account are therefore advocated when using models for forest growth simulation purposes.

Contemporary studies in modelling extend to the use of the physiologic process based models. Nevertheless, process based models are generally not considered feasible for predicting G&Y under a SFM, as they require a great number of variables and parameters. Some of these variables (e.g. daily meteorological data, radiation absorption, transpiration rate) are hardly accessible or cannot be measured at all and their values have to be guessed, and the models are not capable of providing adequate predictions of tree growth (Zeide, 2008).

An overview of the model approaches for management of European forests is presented by Pretzsch et al. (2008), while a review of models employed to deal with the complexities associated with natural disturbance processes can be seen in Seidl et al. (2011).

Pretzsch et al. (2008), state that the objectives and structure of a model reflect the state of the art of the respective research area at the time, and document the contemporary approach to forest growth prediction. This does not mean that a new model is a better model than the previous existing ones. The selection of one model instead of a past one is strongly dependent on the reliability of the model and on the accuracy of the estimates, which are both dependent on the quality of the supporting data. From the model user's point of view, other useful features are the minimum input requirements; the ability for allowing simulations for diverse combinations of the state variables; and the ease of use. With the development of modelling software, this has become straightforward.

2.1 Available models to help for a SFM of *Pinus pinaster*

The maritime pine (*Pinus pinaster* Ait.), originally from the Mediterranean Basin, is an important conifer species in Portugal, Spain and France occupying an area greater than 3 500 thousand hectares (885 000 ha in Portugal, 1 684 000 ha in Spain and 1 100 000 ha in France). The first evidence of the species in Portugal, dates from the Pleistocenic, about 33 000 years ago. Now it is the leading softwood species in the country covering 27% of the mainland forested area. The major continuous cover is located in the central part of the country, in Mata Nacional de Leiria (MNL) and in the north of the country, in the Tâmega Valley region (TVR). The main uses of the species are related to wood for timber and pulp and to a lesser extent in resin production. On the poor sites it is used in afforestation programs for soil protection. The rotation age usually ranges from 40 to 50 years, although higher rotation ages do occur namely when aiming at high target diameters. To help with the management of the species, several G&Y models have been proposed. The earliest refers to the stand tables by Santos Hall (1931) for the even-aged stands in the MNL in Portugal. The tables by Echeverría & de Pedro (1948) for the pine stands in Pontevedra (Galicia), and the tables by Décourt & Lemoine (1969), for the pine stands in the South-West region, are the first references in Spain and in France, respectively.

Traditionally, the stand tables were based on a reference stand, originally of normal density or fully stocked, and site index, following predetermined average silviculture guidelines. The development of improved analysis methods has allowed for new types of models, which are not restricted to tabular forms or to fixed densities. For Portugal, the most recent include the diameter distribution models PBRAVO (Páscoa, 1987) and ModisPinaster (Fonseca, 2004), Dryads (Gonçalves, 2003) for mixed stands, and PBIRROL for uneven-aged structures (Alegria, 2003). For Spain, there are PINASTER (Soalleiro et al., 1994; Soalleiro, 1995) for even-aged stands in Galicia and the model developed by Diéguez-Aranda et al. (2009), included in the GesMO platform. Orois & Soalleiro (2002) proposed a model that applies to mixed stands. The platform SIMANFOR (Bravo et al., 2010), not being a model, integrates a set of modules for simulating and projecting stand conditions in Central Spain.

Available G&Y models for maritime pine in France, are one whole-stand model named PP1 (Lemoine, 1991) and two distance independent models, Afocelpp (Najar, 1999), and PP3 by B. Lemoine, P. Dreyfus and C. Meredieu (derived from Lemoine, 1991; Salas-Gonzalez et al., 2001) (<http://www.inra.fr/capsis/models>). The latter model presents several functionalities such as a dead wood estimation (Brin et al., 2008), windthrow risk through a connection to ForestGales (Cucchi et al., 2005), and wood quality assessment (Bouffier et al., 2009). The three French models and ModisPinaster are currently integrated in the Capsis platform.

2.2 The CAPSIS 4 platform

Software development can be very time-consuming and expensive. The Capsis project has undergone continuous development in France since 1994 with the aim to simulate the consequences of silvicultural treatments based on scientific knowledge, and to build an integration platform for forestry growth and yield models. One of the objectives of Capsis is to share this effort by organising the work around a small number of software developers, who concentrate on the technical aspects of the software and common tools, and modellers who concentrate on specific modules related to the scientific core of their models. Capsis relies on the JAVA environment. This choice of an object-oriented language promotes easier adaptation of common ancestor objects by the modellers, as well as modularity. Capsis has an open software architecture around a stable kernel, augmented with applicative and technical libraries. Different models are integrated in it as many modules, and various tools can be added at any time within flexible extensions. This “platform” runs either in interactive context to explore possibilities or in batch mode to run long or repetitive simulations (Dufour-Kowalski et al., 2012). Initially developed for forest modellers, the range of Capsis end-users very quickly expanded to a large number of stakeholders (Figure 1). It is used in an increasing number of applications for forest management and training. Stakeholder aims are now: to contribute to the development of models and test their sensitivity to model parameters by simulating managers' actions, to share tools and methods, to compare results of different models, to transfer models to managers and to develop training material.

Every component developed inside Capsis, except the Capsis modules (i.e. the model implementations) can be freely distributed under a free license (Lesser General Public Licence), meaning that the core application, including all the extensions, can be used by anyone.

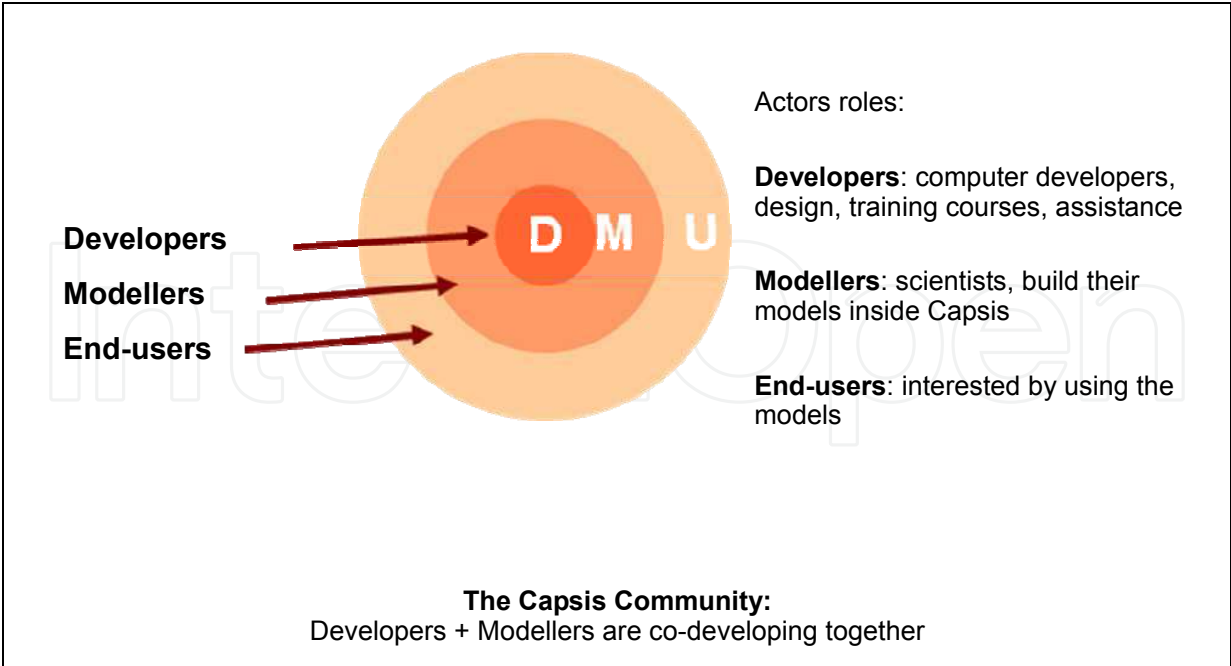


Fig. 1. The Capsis project organization.

Concerning the modules (i.e. the models), the authors decide on the license they wish, free or not, and choose the way to distribute them outside the community. This framework relies on mutual confidence and favours multiple public and private partnerships. The current release of Capsis (Capsis 4) now contains more than 50 forest growth or dynamics models of different types: distance-independent tree models and individual tree models, as well as mixed models, developed by modellers worldwide (<http://www.inra.fr/capsis/models>). In addition, models within Capsis can be connected with other software (GIS, visualisation, architectural models, de Coligny, 2007). The potentialities of Capsis enhance the use of forest models for SFM through the ease of sharing the models with forest managers without charges and permitting the analysis of different scenarios. Simulations are easy to run and users can utilize and test different silvicultural scenarios for a sustainable forest management. It is used in an increasing number of applications for forest management and training. Capsis is particularly useful in situations where observation and experimentation is difficult. Many local and regional French National Forest Service offices have used the Capsis software to help define management operations for implementation by the field services (Meredieu et al., 2009). For example the silviculture handbook for the French northern Alps, applied to both public and private forests, is based on Capsis simulations, especially for mixed fir-spruce forests (Gauquelin & Courbaud, 2006).

3. A case study: the ModisPinaster model

Data used in the model development come from a large database on maritime pine (Data_Pinaster) created and maintained over the last two decades at the Department of Forest Sciences and Landscape Architecture of the University of Trás-os-Montes e Alto Douro. Data come from temporary and permanent plots and were collected in northern Portugal, more precisely in stands located in the Tâmega Valley (latitude range: 41° 15'N –

41°52'N; longitude range: 7° 20' W – 8° 00' W). The model addresses forest growth and yield, risks (wind related) and management procedures such as thinning and harvesting. Since its development, efforts have been made to promote its dissemination to potential users and to allow for a more effective use under a SFM vision. The implementation of ModisPinaster within the Capsis platform has improved its use as a tool for sustainable management of maritime pine forests. Details are given in the following sections.

3.1 Description of Modispinaster

ModisPinaster is constituted by six components: (i) dominant height growth; (ii) basal area growth; (iii) tree mortality; (iv) diameter distribution; (v) thinning algorithm and (vi) output functions for volume, biomass and carbon content assessment by diameter classes. The relationship among the components is shown in Figure 2.

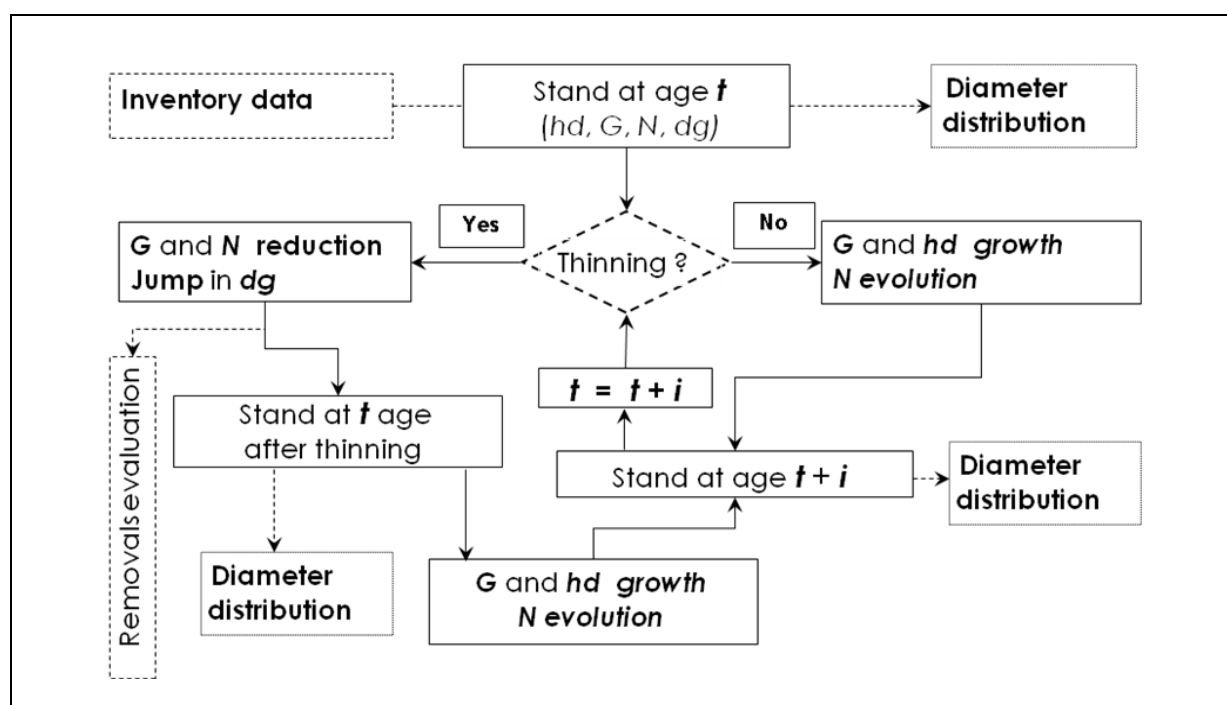


Fig. 2. Simplified structure of ModisPinaster.

The model initiates from a calibration point that requires data variables easily obtained from current inventories:

- Stand variables: stand age (t , yrs), the average height (m) of the 100 thickest trees per ha (hd , m) or the site index value (SI , m, base age 35 years), basal area (G , $\text{m}^2 \text{ha}^{-1}$), number of trees per hectare (N , trees ha^{-1}) and the average diameter of the dominant trees (dd , cm).
- Site variables: terrain slope (Inc , °) and terrain direction (Exp , °).
- Stand nature: specified as a qualitative variable (homogeneous or heterogeneous in terms of the uniformity of trees' age) or assessed through the diameter distribution in terms of the number of classes (5-cm wide) and the standard deviation of the diameters (sd , cm).
- Management variables (optional): number of trees recently cut (if any) (N_t , trees ha^{-1}).
- Historical details on tree mortality (optional): presence or absence of dead trees (0/1).

Other optional variables include: the median ($d_{0.50}$, cm), the average ($\bar{d}$, cm) and the minimum value of the diameter distribution (d_{min} , cm).

The input data coupled with the model components allow representing the stand growth and the management practices that are typical to the species, including the simulation of mechanical and selective thinnings and clear-felling. The maximum age allowed for the rotation term is 65 years. The minimum scale level admitted for prediction is the year.

Dominant height growth, for a given site index, is estimated using Marques (1987) model (equation 1). Site index value is calculated from Marques (1987, 1991) *SI* model (equation 2).

$$\widehat{hd} = e^{4.04764 - 8.75819t^{-0.56087}} + 1.19874(1 - e^{-0.081t})^{2.99578} (SI - 17.38) \quad (1)$$

$$SI = 17.38 - \left(e^{4.04764 - 8.75819t^{-0.56087}} - hd \right) \times (0.865685 - 0.00804747t + 0.000994305t^2 - 0.0000187066t^3) \quad (2)$$

Basal area at the projection age is estimated with equation 3. The growth model was originally presented in Svetz & Zeide (1996), and was refitted by T. Fonseca, after Fonseca (2004), using the Data_Pinaster dataset.

$$\hat{G}_2 = \left[G_1^{0.4090} + 7.4949e^{-0.0333t_1} (1 - e^{-0.0333(t_2 - t_1)}) \right]^{1/0.4090} e^{-0.8427(N_1 - N_2)/N_2} \quad (3)$$

In equation (1), *SI* refers to site index, defined as the stand dominant height (*hd*) at the reference age of 35 years whereas, in equation (3), G_i and N_i refer to the stand basal area and to the number of trees at age t_i , respectively ($i = 1, 2$ for actual and projection age, respectively). The other variables in equations 1-3 were already defined.

Evaluation of tree mortality is a two-phase process. In the first phase the model estimates the probability of mortality to occur during the projection period. In a second phase the number of survival trees is calculated for the projection age and then it is adjusted by the probability of mortality to occur.

Probability of mortality is predicted by two equations developed by Fonseca (2004), according to the major influences: wind (equation 4) and other causes (equation 5), these being mainly related to competition effects.

$$\hat{p}_1 = \left[1 + \exp \left(- \left(\frac{-30.4753 + 0.3725Qhdc + 21.1705RS_b \times BRS}{+4.2303BSExp + 0.1758Incl \times BF_1 + 5.5347BF_2} \right) \right) \right]^{-1} \quad (4)$$

$$\hat{p}_{oc} = \left[1 + \exp \left(- \left(\frac{-8.5235 - 0.3822N_t / 100 + (t_2 - t_1)(2.1449 + 1.5768BMA \times C + 39.2942BAMPD / dg_{MAX})}{(t_2 - t_1)(2.1449 + 1.5768BMA \times C + 39.2942BAMPD / dg_{MAX})} \right) \right) \right]^{-1} \quad (5)$$

In equation 4 and equation 5, the variable $Qhdc$ and the binaries BF_1 and BF_2 are related to the stability of the stand; the variable RS_b refer to relative spacing before thinning with BRS being a binary that makes a distinction of the average space conditions between the trees for the current stand; dg_{MAX} is the maximum values of tree diameter allowed according to the

self-thinning line for the species (Luis & Fonseca, 2004) and *BAMPD* is a binary variable used to differentiate the stands according to the proximity to the self-thinning line. These variables and the ones related to the occurrence of recent mortality (*BMA*) and to the intrinsic risk of damages occurrence, due to the terrain direction (*BSExp*) are defined as follows:

$$\begin{aligned}
 Qhdc &= 100 \times (hd - 1.30m) / dd \\
 BF_1 &= 1 \text{ if } Qhdc > 48; BF_1 = 0, \text{ otherwise.} \\
 BF_2 &= 1 \text{ if } 100 \times hd / dd \leq 54; BF_2 = 0, \text{ otherwise.} \\
 RS &= 100 / (\sqrt{N} \times hd) \\
 RS_b &= 100 / (\sqrt{N_b} \times hd) \\
 BRS &= 1 \text{ if } RS \leq 0.20; BRS = 0, \text{ otherwise.} \\
 C &= 1 \text{ for recent thinning; } C = 0, \text{ otherwise.} \\
 dg_{MAX} &= 25 (1859 / N)^{1/1.897} \\
 BAMPD &= 1 \text{ if } (dg_{MAX} - dg) \leq 17.5\text{cm}; BAMPD = 0, \text{ otherwise.} \\
 BMA &= 1 \text{ for recent mortality; } BMA = 0, \text{ otherwise.} \\
 BSExp &= 1 \text{ if direction } (^{\circ}) \text{ belongs to }]60, 120] \cup]180, 240] \cup]300, 360]; BSExp = 0, \\
 &\text{otherwise.}
 \end{aligned}$$

A join probability of mortality for the period $t_2 - t_1$ is estimated as

$$\hat{p} = \hat{p}_1 + \hat{p}_{OC} - \hat{p}_1 \hat{p}_{OC} \quad (6)$$

An initial assessment of the living trees at projection age t_2 is given by the survival model (equation 7), developed after Huang et al. (2001).

$$\hat{N}_2 = N_1 \left(\frac{1 + \exp[-5.2560293 + 1.81990161 \ln(1 + t_1) - 0.1532847SI + 0.86246466BE]}{1 + \exp[-5.2560293 + 1.81990161 \ln(1 + t_2) - 0.1532847SI + 0.86246466BE]} \right) \quad (7)$$

In equation 7 *BE* is a binary variable that characterizes the stand horizontal structure based on the heterogeneity of tree diameters. The stand is homogeneous in composition ($BE = 0$) for diameter distributions not exceeding 25 cm in range and 5.5 cm in standard deviation; otherwise it is heterogeneous ($BE = 1$).

The number of trees is adjusted according to equation 8.

$$\hat{N}_{2aj} = N_1 - \hat{p}(N_1 - \hat{N}_2) \quad (8)$$

ModisPinaster is a distribution model that presents output information at the detailed level of the diameter class. The diameter distribution is modelled by Johnson's S_B (Johnson, 1949), (equation 9).

$$\begin{aligned}
 f(d) &= \frac{\delta \lambda}{\sqrt{2\pi} (d - \xi)(\xi + \lambda - d)} \exp \left(-\frac{1}{2} \left[\gamma + \delta \ln \left(\frac{d - \xi}{\xi + \lambda - d} \right) \right]^2 \right) \quad \xi < d < \xi + \lambda \\
 &= 0, \text{ otherwise}
 \end{aligned} \quad (9)$$

where $\lambda, \delta > 0, -\infty < \xi < \infty, -\infty < \gamma < \infty$; λ is a range; ξ is a location parameter (lower bound), δ and γ are shape parameters, $\gamma = 0$ indicating symmetry.

The algorithm used to incorporate the S_B distribution in ModisPinaster was based on the parameter recovery method in combination with the parameter prediction proposed by Parresol (2003). Briefly, in his approach, Parresol assumed the minimum location parameter was pre-specified (set to 0.8 of minimum diameter in ModisPinaster). The range and two shape parameters were then recovered from the median and the first two noncentral moments of the diameter distribution (average diameter and quadratic mean diameter). A complete SAS code for the procedure is available in Parresol et al. (2010). The evolution of the stand structure in terms of diameter class distribution is provided for each year of the simulation and whenever an intervention is simulated.

The procedure to represent the stand structure after a thinning requires previous information on diameter distribution (actual or simulated using the S_B distribution). Trees to be removed from the diameter distribution are identified with a thinning algorithm (Alder, 1979). The procedure assumes a probability of survival to cut proportional to a tree's size, $l(F) = Fc$, with c given by N_t / N_a . The number of trees that remain in the diameter class j (N_{ja}) is then calculated as:

$$N_{ja} = N_b L \left[F(d_j)^{1/L} - F(d_{j-1})^{1/L} \right] \quad (10)$$

In equation 10, F represents the initial probability density function (PDF) and L corresponds to the proportion of the standing trees, comparing to the number of trees before thinning ($L = N_a / N_b$). The diameter distribution for the removed trees is obtained by subtraction.

The stand basal area after thinning is calculated with equation 11. This equation was refitted by T. Fonseca, after Fonseca (2004), using the Data_Pinaster dataset.

$$G_a = G_b \left(N_a / N_b \right)^{2.4979 N_b^{-0.1951}} \quad (11)$$

Stand variables after thinning are used to recalibrate stand variables at age t . That is, N becomes equal to N_a and G becomes equal to G_a .

Auxiliary functions, not presented here, were developed to allow for the estimation of the optional input variables. These include functions for the median, the average, the minimum and the maximum values of the diameter distribution, all required for the S_B recovery procedure. Additional functions appended to ModisPinaster refer to the height-diameter relationships, and to tree equations to calculate the volume and biomass content. At present, the model uses the height-diameter relationships by Almeida (1999), the volume equations from Fonte (2000), and the biomass equations from Lopes (2005).

3.2 ModisPinaster within the Capsis interface

The potentialities of Capsis enhance the use of ModisPinaster for SFM through the ease of permitting the analysis of different scenarios in a friendly environment. The extended outputs provide diverse information of stand growth and structure as well as of thinning intervention.

The simulations are easy to run and the users can utilize and test different silvicultural scenarios for a better choice under a sustainable forest management policy.

Figure 3 presents the ModisPinaster initializing scenario for a sampled stand (Stand_1) with the minimum input variables required for simulation purposes. By default, the stand is assumed to be of homogeneous structure (even-aged). For the example, a merchantability limit of a top diameter of 7 cm is specified for volume estimates. The state variables of the

stands, age (t , yrs), dominant height (hd , m), number of trees (N , trees ha^{-1}), and basal area (G , $m^2 ha^{-1}$), are projected on an annual basis until the end of the growth period, using the set of equations 1-8. A portrait of the Evolution dialog and of the appended output options is depicted in Figure 4. An automatic management procedure, based on the self-thinning theory is available in the Management/Self-thinning dialog. By default, the limits specified for the Stand Density Index (SDI , Reineke, 1933; Luis & Fonseca, 2004) are with respect to a stand that grows under high values of density. The occurrence of mortality by competition is expected whenever SDI reaches the threshold of 60%. The limits can be modified by the user, according to pre-determined management guidelines.

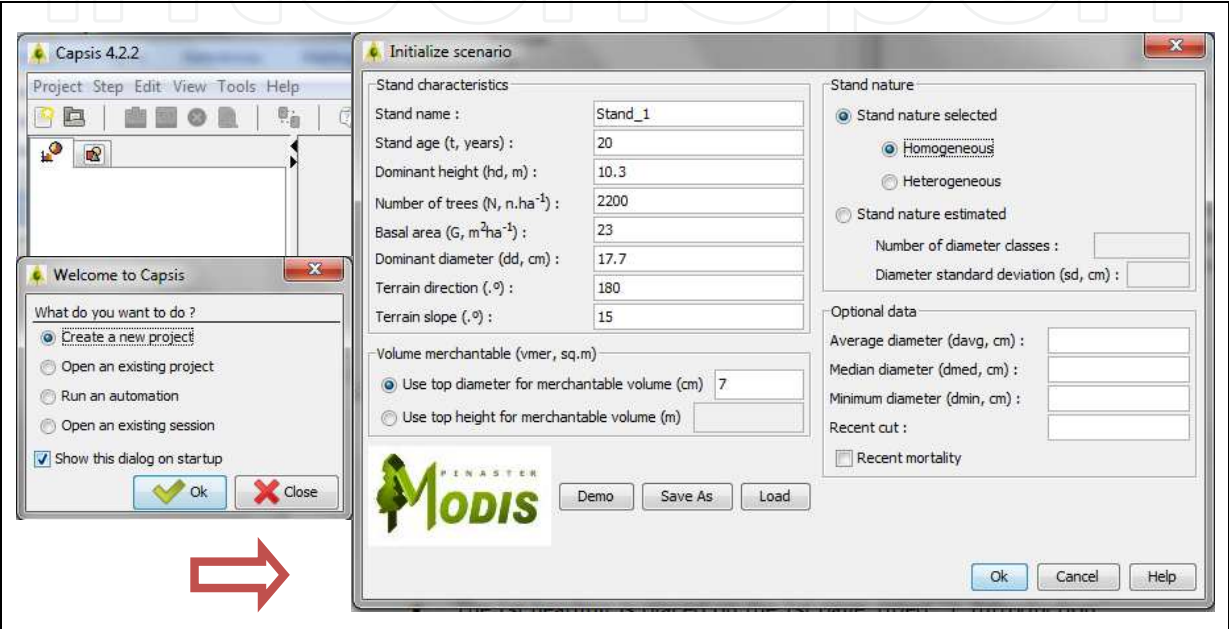


Fig. 3. The ModisPinaster input dialog in the Capsis platform.

Selected outputs shown in Figure 4 refer to a stand table for the 5-year evolution period (bottom left) and to the number of trees, per diameter class, at the initial stand age (20 yrs) and at the end of the simulation (25 yrs) (bottom right). The diameter distribution is presented for each selected scene (year) according to the methodology described in section 3.1 and detailed in Parresol et al. (2010). Major improvements for the thinning simulation ability of ModisPinaster are available in the Capsis thinning interface (see Figure 5, to the left). Users can decide the thinning prescription based on the total number of trees to remove, or in density regulation rules, according to the stand density index (SDI) criteria based on the self-thinning theory, or according to the Wilson spacing factor, $Fw = 100N^{-0.5}hd$, where the variables N and hd had already been defined. In each of these cases, the selection of the trees to remove from the stand is made according to the algorithm of Alder, described in section 3.1, which assures a probability of a tree to survive to cut being proportional to the tree's size. Alternatively, the user can perform a selective thinning using the Capsis interactive diagram. With this option, the trees are cut by action on an interactive diameter distribution diagram. Figure 5 presents the intervention dialog with a simulation of a thinning at 20 years of age. In the example, a Wilson spacing factor of 0.23 was specified for the thinning criteria. At the bottom of the dialog, a summary of the variables N , G and dg , is presented for the initial

and for the residual stand, and for the thinned material. Results obtained for a growth series of 10 years, after the thinning, are presented to the right of the figure: a stand table in an annual basis, and the disaggregation by diameter classes of the total and merchantable volumes and of carbon content, per component, at the end age.

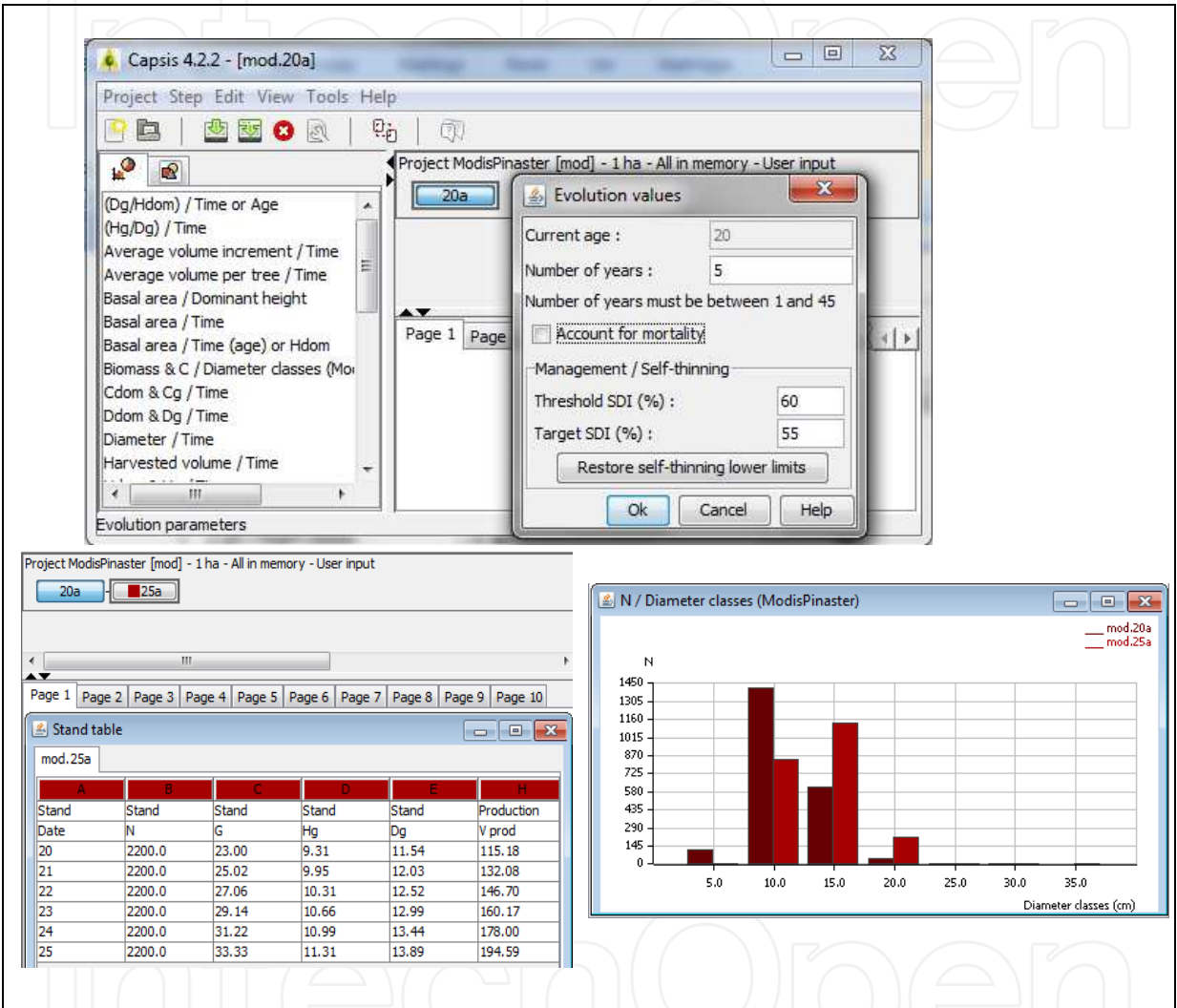


Fig. 4. The ModisPinaster evolution dialog and examples of the output information.

3.3 Analysis of different scenarios for a SFM

The majority of the maritime pine stands in Portugal are even-aged and are handled in a thinned managed regime. Density regulation is usually based on the Wilson spacing index. A typical value of $Fw = 0.23$ has been assumed in the maritime pine stands of the Tâmega Valley region (Moreira & Fonseca, 2002). The rotation age is defined by the age at which occurs the maximum annual increment of tree stem volume. Depending on site quality, stands attain their absolute explorability term for the volume variable when the stand reaches 35 (high quality) years to 45 (low quality) years (Marques, 1987; Moreira & Fonseca, 2002). In the area studied it is usual to set the lowest limit of stand age to harvest to 40-45 years.

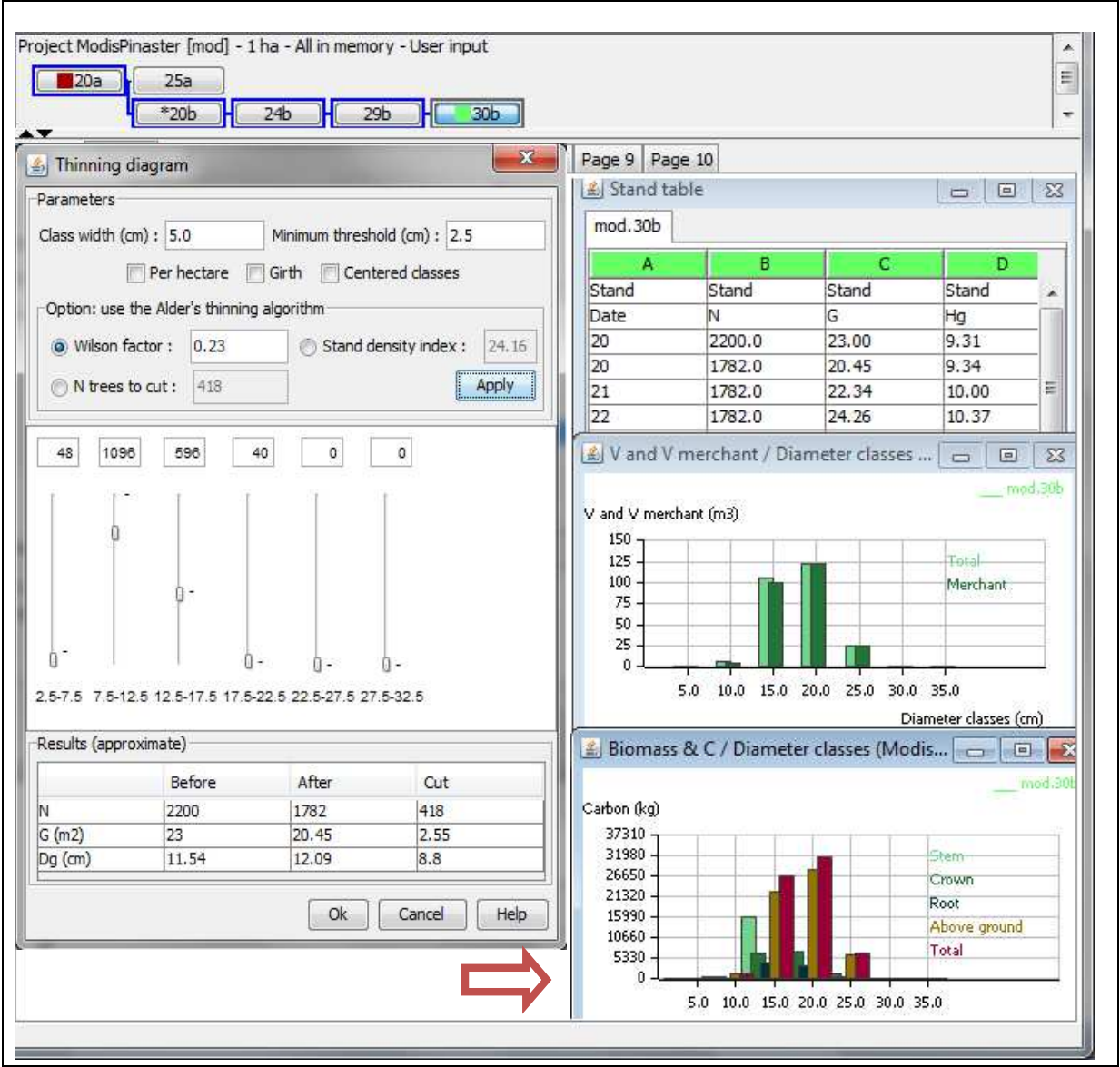


Fig. 5. The thinning dialog and some of the possible results available for ModisPinaster in the Capsis environment.

Three scenarios are proposed for comparison:

- Typical forestry guidelines (TYF). This scenario focuses on timber production, according to the traditional silviculture guidelines followed in the Tâmega Valley region. That is, cyclic thinning with an average silviculture compatible with a strong to moderate grade with $Fw = 0.23$; and a rotation age of 45 years.
- Low competition forestry (LCF). This scenario also focuses on the single purpose of timber. The management is made in accordance to the self-thinning line theory. The stand has a window for density between 25-35%, as measured by the stand density index, to keep the inter-tree competition at lower levels. The rotation age is maintained at 45 years.
- Combined objectives forestry (COF). Here, emphasis is done on maximizing the total volume yield and on promotion of the biodiversity. This scenario can be viewed as landowner absence where natural mortality is expected to occur. An old-stand situation is promoted. Rotation age is extended to 65 years.

The data used for the simulations refer to a 20 year old stand with the characteristics depicted in Figure 3.

For each scenario the following indicators were selected for comparison: yield in volume and in carbon in the aboveground component; products obtainable from the thinning practices (volume and average tree size). Dead wood was quantified in scenarios **TYF** and **LCF** as downed woody debris produced by thinning, considering that the tip of the trees (top diameter of 7 cm) are kept in the stand. For scenario **COF**, dead wood was quantified as the total volume of the stem for the trees that die during the rotation period. Table 1 presents the results obtained by following the current silviculture guidelines and the strategy of allowing the stand to grow in lower levels of competition. In the first case, a total of four thinnings, with a cycle of 5 years, starting at age 20, were considered until the stand reaches 35 years. Simulations of the thinning were made using the thinning dialog with specification of the target value for the Wilson factor (see Figure 5). After each thinning, the stand growth was simulated with the evolution dialog. For the **LCF** scenario, the simulation was made in an automatic mode using the facilities given in the evolution dialog (see Figure 4), setting a threshold of *SDI* equal to 35% and a target value of *SDI* equal to 25%. The first thinning occurs at the age of 24 years, a second at 30 years and a third and last one when the stand age is 37 years.

Sim.	<i>t</i> (yrs)	<i>hd</i> (m)	<i>dg_b</i> (cm)	<i>N_b</i> (trees ha ⁻¹)	<i>C_b</i> (ton ha ⁻¹)	<i>V_b</i> (m ³ ha ⁻¹)	<i>V_t</i> (m ³ ha ⁻¹)	Debris (m ³ ha ⁻¹)
TYF	20	10.3	11.5	2200	28.5	115.2	14.6	3.2
	25	12.9	14.7	1782	41.1	176.9	45.6	4.2
	30	14.8	18.9	1136	49.0	212.6	37.9	1.1
	35	16.5	22.6	859	58.1	255.8	37.6	0.5
	45	19.4	28.2	693	82.2	374.1		
LCF	20	10.3	11.5	2200	28.5	115.2	-	-
	24	12.5	13.4	2200	41.0	178.0	61.8	7.6
	30	14.8	18.9	1146	49.4	214.2	71.4	1.9
	37	17.1	25.2	648	57.4	252.5	79.3	0.6
	45	19.4	31.8	401	65.7	293.4		

Table 1. Characteristics of the stand, at age *t* (years), according to the simulation results of the management scenarios focused on timber production: typical forestry guidelines (TYF) and low competition forestry (LCF). The presented variables refer to dominant height (*hd*), quadratic mean diameter (*dg*), number of trees (*N*), carbon (*C*) and volume (*V*) of the standing trees before (*b*) the thinning practice. The products of the thinning operation refer to the volume of the removed trees (*V_t*) and to the tip debris.

The current silvicultural guidelines with a 4 thinning management regime through the rotation period produce a 25% greater yield, in terms of volume and carbon content, than the yield achieved with the low competition management. In terms of total volume (with the thinning removals included) the difference reduces to just 3.9 m³ ha⁻¹, because the **TYF** scenario presents thinning removals of 135.7 m³ ha⁻¹, while for the **LCF** scenario 212.5 m³ ha⁻¹ are harvested by thinning. These results could lead to an undifferentiated selection between both management options, or even to the preference of the **LCF** scenario as it provides timber of great size (31.8 cm of diameter, for the mean tree, at age 45). Nevertheless, under a

SFM other issues, such as the assessment of risk, need to be taken into consideration. For the example, the ratios of the mean height to mean diameter of the dominant trees vary between 0.57 and 0.60, during the rotation. This indicates a potential problem of stability of the trees under windy conditions and a high risk of wind damages. Therefore, to perform a thinning at age 24, with a density of 1054 trees ha⁻¹, might not be a secure option.

Also shown in Table 1 are the dead wood estimates from downed woody debris, ranging from 9 to 10.1 m³ ha⁻¹. This is a part of the material obtained by thinning. Other values could be estimated depending on the specification of the merchantability limits and of accounting, for instance, additionally for the mass of the branches. For a complete assessment of the debris produced in the stand, it is suggested to evaluate the debris material using as an indicator the biomass (or carbon content) of the entire crown component (branches and leaves, instead of restricting the evaluation to the tip volume of the trees). Independently of the indicator chosen, the ModisPinaster features allow for the quantification of debris by diameter classes (not shown in Table 1). This might be of importance in some studies, such as when evaluating for the wood decay.

Although dead wood and decaying trees were considered for a long time as being of less or null commercial value, they do have considerable ecological value. The dead wood has a major influence on biodiversity. Many forest species, such as forest floor vertebrates and insects benefit or depend on dead wood material for habitat or resources. The scenario **COF** is presented as an example of a potential scenario to promote habitat and resources for the conservation of biodiversity. A comparison between the three scenarios is shown in Table 2.

Sim.	<i>t</i> (yrs)	d classes range (cm)	<i>dg</i> (cm)	Total volume (m ³ ha ⁻¹)	Harvested volume (m ³ ha ⁻¹)	Deadwood volume (m ³ ha ⁻¹)
TYF	45	20 - 35	28.2	509.8	135.7	9.0
LCF	45	20 - 35	31.8	505.9	212.5	10.1
COF	45	15 - 35	24.0	582.4	-	183.8
COF	65	25 - 40	31.5	920.1	-	350.7

Table 2. Characteristics of the stand at the end of the rotation age according to the simulation results achieved for the management scenarios of typical forestry guidelines (TYF), low competition forestry (LCF) and of combined objectives forestry (COF). In the TYF and LCF scenarios, the rotation age is fixed at 45 years while in the COF scenario an extended rotation age of 65 years is promoted. The characteristics refer to the diameter distribution (range and quadratic mean diameter, *dg*) and to the total volume of the standing trees at age *t*; to the removals obtained by thinning for the management options TYF and LCF; and to the accumulated volume of the trees that die during the simulation period for the three scenarios.

In Table 2, the total volume includes the volume from thinning practices, for the scenarios **TYF** and **LCF**, and the volume of the dead trees, for the **COF** scenario. As expected, a maximum value is achieved when there is no interference in the stand growth. This is consistent with the current consensus about the effect of stand density on growth (Zeide, 2001). The objective of thinning is to anticipate mortality and to provide better growth conditions for the remaining trees. Other goals might be added, such as, to obtain a target

value for diameter at the thinning ages and at the final rotation. For the examples presented, the management according to a window for density between 25-35%, presents material distributed by 4 diameter classes (5 cm of amplitude) with average dimension slightly higher than the material obtained with the typical silviculture. When combined objectives are required, other guidelines need to apply. The growth under high densities (55-60% of *SDI*) and the extension of the rotation age, as presented in the **COF** scenario, allow for exploitation of wood, although of minor size, and guarantees better habitat conditions for the promotion of the fauna biodiversity.

4. Conclusion

The use of forest models has undoubtedly enhanced the scientific knowledge about forest dynamics and about the effects of alternative silvicultural options in the stand evolution. Taking as example the ModisPinaster model, it was shown how essential the models are for management decisions and planning purposes. The managers are facing challenges in terms of selecting the most appropriate management guidelines that assure the management goals, which might combine timber and other forest benefits, and increasingly of accounting for risk. Different scenarios are permitted for simulation, leading to better-quality choices under a Sustainable Forest Management guiding principle. From a user's point of view, other needs, such as an easy and free use of the models, are additionally mandatory. Software simulators of forest growth and stand dynamics should favour re-use and share methods and algorithms, promote integration and encourage partnerships. Capsis was delineated to follow these criteria. The examples provided here for ModisPinaster prove how an efficient software simulator can improve capabilities of models and encourage their use by the stakeholders for guidance in decision making.

The involvement in Capsis of different actors, developers, modellers and end-users, brings to the top the desirable features of "easy-to-use" models, allowing for a prompt search of guiding principles while securing the scientific validity of the simulation estimates.

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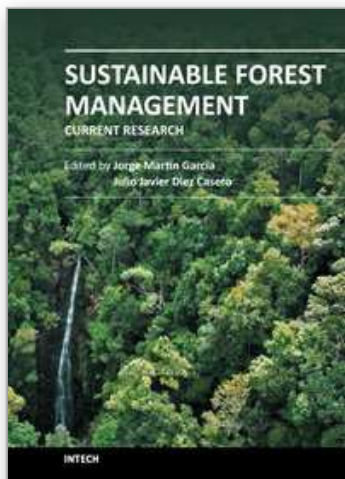
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Sustainable forest management (SFM) is not a new concept. However, its popularity has increased in the last few decades because of public concern about the dramatic decrease in forest resources. The implementation of SFM is generally achieved using criteria and indicators (C&I) and several countries have established their own sets of C&I. This book summarises some of the recent research carried out to test the current indicators, to search for new indicators and to develop new decision-making tools. The book collects original research studies on carbon and forest resources, forest health, biodiversity and productive, protective and socioeconomic functions. These studies should shed light on the current research carried out to provide forest managers with useful tools for choosing between different management strategies or improving indicators of SFM.

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