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Growth and yield models in Spain: historical overview, contemporary examples and perspectives

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Abstract

In this paper we present a review of forest models developed in Spain in recent years for both timber and non timber production and forest dynamics (regeneration, mortality). Models developed are whole stand, size (diameter) class and individual-tree. The models developed to date have been developed using data from permanent plots, experimental sites and the National Forest Inventory. In this paper we show the different sub-models developed so far and the friendly use software. Main perspectives of forest modeling in Spain are presented.

Key words: timber production; non-wood production; recruitment; modeling; forest.

Resumen

Modelos de crecimiento y producción en España: historia, ejemplos contemporáneos y perspectivas

En el presente trabajo se presenta una revisión sobre los modelos forestales desarrollados en España durante los últimos años, tanto para la producción maderable como no maderable y, para la dinámica de los bosques (regeneración, mortalidad). Se presentan modelos tanto de rodal completo como de clases diamétricas y de árbol individual. Los modelos desarrollados hasta la fecha se han desarrollado a partir de datos procedentes de parcelas permanentes, ensayos y el Inventario Forestal Nacional. En el trabajo se muestran los diferentes submodelos desarrollados hasta la fecha,

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así como las plataformas informáticas que permiten utilizar dichos modelos. Se incluyen las principales perspectivas de desarrollo de la modelización forestal en España.

Palabras clave: producción maderable; productos no maderables; regeneración; modelización; forestal.

Introduction

Growth and yield studies began in Spain in the early 20th century when different permanent plots were established in *Pinus sylvestris* and *Pinus pinaster* stands in central Spain. The first forest growth models in Spain were yield tables developed in the 1940s for *Pinus radiata* and *Pinus pinaster* plantations in the Atlantic area (Echeverría, 1942; Echeverría and Pedro, 1948, respectively). In the second half of the 20th century there were new efforts at establishing permanent plots, which made it possible to construct new yield tables. However, in the last 15 years a new generation of forest researchers have combined previous data collection efforts with computer and statistics capabilities to revolutionize forest modeling in Spain. Advanced statistical approaches have been applied to develop models for different species, management purposes and regions (with the exception of the Macaronesic area) and at different scales (from whole stand to individual-tree models). Modelers have also developed a wide variety of models and tools based on forest diversity and end-user aims. Internationalization has been an important feature of Spanish forest modeling during the last 15 years. Great efforts have been made to integrate research from other countries into Spanish forest dynamics modeling and to participate in forest dynamics modeling overseas.

The aim of this article is to describe the current situation of forest growth and yield models in Spain and to give an overview of improvements made during the last century, from normal yield tables to the latest software. This will be followed by a reflection on future challenges, including suggestions for new lines of research and the need to include climate change and end-user needs in forest modeling. A detailed presentation of forest growth and yield models development in Spain is provided by Bravo *et al.* (2011). Readers are encouraged to review this book for complete information on forest and tree growth and yield modeling in Spain.

Driving processes

Forestry has been focused on timber productivity since it became a scientific discipline in the 17th century. The advent of empirical analysis along with a rationale-based interpretation of nature and the driving processes of forest productivity brought about a shift from tradition-based methods to sustained wood yield science-based methods (Gamborg and Larsen, 2003). Site productivity, density and competition are among the most important factors influencing forest growth. Growth modeling requires a good understanding of density/competition-growth relationships organized into indices that allow us to include them in growth functions.

The productive capacity of a site is often referred to as *site quality* and its estimation is a basic element of forest ecology and ecosystem management. Site quality can be evaluated directly using the mean annual volume increment from historical records of managed stands. However, data of this type is scarce and forest managers must find indirect methods. The most popular indirect method is the stand dominant height at a reference age or site index. Forest managers need to know the age and height of dominant trees in order to obtain the site index. However, these data are not always available, for example in young stands where crown differentiation is not apparent. In such situations, site index is usually related to climate or soil variables in a linear fashion (Sánchez-Rodríguez *et al.*, 2002; Romanyà and Vallejo, 2004; Afif-Khouri *et al.*, 2010; Álvarez-Álvarez *et al.*, 2011) or by discriminant rules (Bravo and Montero, 2001; Bravo-Oviedo and Montero, 2005).

The effect of competition on the growth of forest species has long been studied in order to increase the accuracy and precision of individual-tree models. A tree's competitive status is incorporated into the models using distance-dependent or distance-independent competition indices. In Spain, distance-independent competition expressions have been widely used to assess stand-level tree competition in individual-tree models. Number of trees per ha and basal area are the most commonly used distance-independent indices, but the crown competition factor or the basal area of larger trees have also been incorporated into different models. Distance-dependent indices are not often used in Spain, mainly because the inventory data does not include tree coordinates.

Stand density reflects the average tree growing space available or average competition among trees. At stand level, density-growth relationship for even-aged pure stands is described by the Wiedemann's hypothesis (Assmann, 1970) or Langsaeter's curve (Daniel *et al.*, 1979). These authors stated that stand volume increment does not vary across a wide range of densities. For Spanish forests, this curve has been analysed for *Pinus sylvestris* L. (Montero *et al.*, 2001; Río *et al.*, 2008), *P. pinaster* Ait. (Montero *et al.*, 1999), *Q. pyrenaica* Willd. (Cañellas *et al.*, 2004) and for mixed stands of *P. sylvestris* and *Q. pyrenaica* (Río and Sterba, 2009).

Density-induced mortality or self-thinning is another forest dynamic closely related to density and competition. Self-thinning based on Reineke's expression was modeled for Scots pine stands in central (Río *et al.*, 2001) and north-east Spain (Palahí *et al.*, 2003). Reineke's maximum density line concept was also applied in developing stand density management diagrams for some Spanish forests. Other density management diagrams rely on the Hart-Becking index, which was traditionally used in most Spanish yield tables to determine different thinning alternatives (Madrigal *et al.*, 1999). However, most of the Spanish dynamic whole-stand models are based on the state-space approach and use basal area and the number of trees per hectare as state variables, so they do not include other stand density indices.

Data and model requirements

Data

All the models developed in Spain for practical uses are parametric models and their parameters must be estimated from observations. Since estimate accuracy and a model's usefulness depend on the quality of data, the first step in growth model construction is to ensure that the available data is suitable for the model.

In recent decades, the automatic capture of forest state variables by various remote sensing techniques has substantially increased the amount of data available on stand dynamics. Even so, sample plots and stem analysis of felled sample trees continue to be the two basic data sources for developing growth models. Felled-tree sampling provides information similar to that obtained when re-measuring permanent sample plots. However, it is economically expensive and the development of some variables cannot be reconstructed by this method. Thus, the majority of the data used for growth modeling is obtained from sample plots. Examples of different networks of sample plots could be created for growth analysis and designed according to resource management needs are: (1) Sample plots for resource inventory, (2) Continuous Forest Inventory (*e.g.* Spanish National Forest Inventory), (3) Sample plots from field experiments (Bravo *et al.*, 2004; Montero *et al.*, 2004; Torres-Álvarez *et al.*, 2004; Diéguez-Aranda *et al.*, 2009) and (4) Permanent plot networks (PPN).

First attempts to establish a permanent plot network in Spain were made in 1915 when researchers from the former «*Instituto Central de Experiencias Técnico-Forestales*» established a set of plots to study timber production in Scots pine stands in the Central Range and to study resin yield in *Pinus pinaster* stands in the Northern Plateau. A second big effort to generate a PPN was made in the 1940s and another in the 1960s. Currently, different plot networks belonging to universities and research centers are maintained across the country.

Two aspects of PPNs are relevant for the future: *i*) a critical analysis of the utility of the permanent sample plot networks in light of the specific requirements for the next generation of growth models, and *ii*) development of open access historical data archives from different institutions for more extensive model development and validation.

Auxiliary functions for estimating missing variables

Several auxiliary functions are usually necessary for the application of growth and yield models. This is mainly due to the scarcity of input data or because some variables (*i.e.,* height) are only measured in a sample of the trees, or because some input variables can not be directly measured. The most important functions include: (1) Bark thickness or bark percentage, (2) Diameter-stump diameter and volume-stump diameter relationships, (3) Height-diameter relationships and (4) Crown equations. Most of the current models used in Spain include this type of auxiliary functions.

Modeling approaches

In Spain most modeling efforts have been aimed at developing empirical models as systems of interrelating equations that can use any desired combination of inputs to predict future stand development. Most

empirical models have a low model complexity, which makes them easier for managers and decision-makers to use in addressing forest management questions. In Spain, the regions of Galicia, Castille-and-Leon and Catalonia are already implementing some empirical models to develop forest management plans. However, with most empirical models there is an element of uncertainty due to the conditions for which the functions were calibrated, particularly when studying the impacts of environmental change on forest development.

As an alternative to empirical models, process-based models can provide more robust model projections under changing environmental conditions, but require more parameters, substantial calibration data, and increased simulation time. The «GOTILWA+» process-based model (Keenan *et al.*, 2008, www.creaf.uab.es/gotilwa+/) was developed in Spain to simulate growth processes and explore how they are influenced by climate, tree stand structure, management alternatives, soil properties and climate change.

Choosing between process-based and empirical models involves trade-offs between model realism, model accuracy, and model generality (Odenbaugh, 2006). However, most groups in Spain are currently working towards hybrid modeling that uses different approaches.

The first growth and yield models developed in Spain were static empirical whole-stand models (yield tables). Madrigal *et al.* (1999) elaborated a comprehensive compendium of the yield tables published in Spain since the end of the last century. In recent years, Stand Density Management Diagrams (SDMDs) have been replacing yield tables because they facilitate quick and easy comparisons among different thinning schedules and they graphically illustrate the relationships among stand variables.

Dynamic whole-stand models and distance-independent individual-tree models have been developed in Spain in the last decade. To date, only two size-class models have been developed in Spain (Sánchez Orois and Rodríguez Soalleiro, 2002; Escalante *et al.*, 2011), both based on a transition matrix growth model. Also, some of the whole-stand models developed in Spain can be mathematically disaggregated using a diameter distribution function, which provides more detailed information about stand structure and volume (*e.g.,* Río and Montero, 2001; Río *et al.*, 2005; Diéguez-Aranda *et al.*, 2006a; Castedo-Dorado *et al.*, 2007a; Cabanillas, 2010).

Most of the models have been developed for pure, even-aged and predominantly coniferous stands. Two relevant exceptions are the works by Sánchez Orois and Rodríguez Soalleiro (2002) for mixed stands of *P. pinaster* and broadleaf species in the coastal region of Galicia, and the work of Trasobares *et al.* (2004a) for mixed, uneven-aged stands of *P. sylvestris* and *P. nigra* in Catalonia. Calama *et al.* (2008a) has also adapted an individual-tree model of even-aged *Pinus pinea* stands for use with uneven-aged stands.

Model modules

Increment, growth and yield

Site index equations

Site index curves are the most commonly used technique for evaluating site productivity on single-pecies, even-aged stands. Nearly all sets of site index curves published in recent decades were elaborated using statistical curve-fitting procedures; most of them can be viewed as special cases of three general equation-development methods: the guide curve method, the parameter prediction method, and the difference equation method. Most of the site index research is focused on pine species but a few other species have also been studied.

Diameter and basal area growth functions

Individual growth models developed in Spain predict basal area or diameter increment based on growth as a function of site quality commonly characterized by site index, competition by using the basal area of large trees, *BAL* (Wykoff, 1990) and density variables, tree size (trees per ha or basal area) and even crown ratio as vigor variable in some models.

Stand growth models estimate or predict basal area growth rates (*e.g.* Álvarez González *et al.*, 1999; García and Ruiz, 2003) or more frequently the basal area at a specific age, when basal area at any other age is known, using dynamic models. However, this is not always available, so some models include a static basal area prediction equation (*e.g.,* Palahí *et al.*, 2002; Castedo-Dorado *et al.*, 2007b; Diéguez-Aranda *et al.*, 2005a, 2006a; Barrio-Anta *et al.*, 2006).

Height growth functions

Two different approaches can be used to estimate height growth once the height of all the trees or the

diameter class has been determined, either by measurement of all the trees or estimation using a local or generalized height-diameter equation. The first approach is static and uses a height-diameter function to estimate future tree height. The estimated heights at two different moments are then subtracted to obtain height growth. The second approach requires the use of true height growth equations. Growth models developed in Spain generally do not contain height growth functions. The rare exceptions to this are the equations developed for radiata pine (Crecente-Campo, 2008) and Scots pine (Crecente-Campo *et al.*, 2010) in Galicia and those developed by Lizarralde (2008), which estimate height growth from tree and stand variables for Scots pine and Mediterranean maritime pine in Central Spain.

Volume growth functions

Most whole-stand growth models developed to date in Spain do not incorporate volume growth functions explicitly. The parsimony principle strengthens the argument for avoiding volume growth functions. However, some whole-stand growth models developed in Spain have included volume projection functions (Río *et al.*, 2001, 2005; Palahí *et al.*, 2002; Bravo-Oviedo *et al.*, 2004) in a system with at least two projection functions (for stand basal area and stand volume) that are fitted simultaneously to minimize the global sum of square error. Volume increment functions not included in individual-tree or whole-stand models have also been used in successive Spanish National Forest Inventories for the major Spanish timber species (Martínez-Millan *et al.*, 1993).

Silviculture response functions

Silviculture response functions are used to determine the effects of silvicultural practices, such as initial spacing, pruning, thinning and fertilization, on tree growth and stand development . Two main approaches are used in developing such models. The first is to fit regression equations separately to data derived from a particular silvicultural regime. The second approach is to develop models that can be applied to a set of silvicultural regimes. The first attempt at this in Spanish forestry was the development of variable-density yield tables. More recent growth models include thinning and fertilization functions to simulate different silvicultural regimes.

Three approaches have commonly been used to estimate the thinning response effect: *i*) modeling the effect of thinnings on the diameter distribution by relating the parameter of a probability density function after thinning with the thinning intensity (Espinel *et al.*, 1997; Álvarez González *et al.*, 2002); *ii*) developing different basal area growth functions for different types of stands (unthinned and thinned) and *iii*) the inclusion of a thinning response function that expresses the basal area growth of a thinned stand as a product of a reference growth value and the thinning response function. The second approach was applied in Spain by employing categorical dummy variables for detecting simultaneous homogeneity among parameters. The results showed that the same functions could be applied for thinned and unthinned stands in maritime and radiata pines (Barrio Anta *et al.*, 2006; Castedo Dorado *et al.*, 2007b). Based on this kind of thinning response functions, Santalla (2010), analyzes the separate effects of thinning and fertilization on basal area growth.

Models describing the response to pruning scarcely appear in the Spanish literature. Rodríguez (2005) compared several pruning methods for three different poplar clones, a study that may serve as a reference for evaluating the effects of pruning treatments on height, basal area and volume growth. Snowdon (2002) identified two basic long-term responses of plantations to fertilization and other silvicultural treatments. Type 1 responses show an initial increase in growth that is not sustained long-term, while Type 2 responses are sustained long-term and can be regarded as to the result of a change in site quality. The lack of long-term data and the need to avoid overestimation of silvicultural effects has led to the use of the first approach most of the time in Spain. This method has been used to evaluate the basal area or dominant height growth effect of ash fertilization for Douglas fir (Solla *et al.*, 2006), radiata pine and chestnut (Solla, 2004).

Demography

Seed dispersal models

Seed dispersal patterns determine the potential area of plant recruitment. For most forest trees, seed density decreases as the distance to the seed source increases, following leptokurtic curves with extended tails of long-distance dispersal. Dispersal kernels, *i.e.* the

probability function of seed density decrease with greater distance, are normally fitted using either inverse modeling or genetic markers. Inverse modeling requires the establishment of seed traps (to estimate seed shadows) along with the spatial coordinates of the seed traps and seed sources while methods based on genetic markers are more flexible. In Spain, there are different ongoing studies to determine seed dispersal kernels for various forest trees and shrubs (*e.g.* González-Martínez *et al.*, 2006; Robledo-Arnuncio and García, 2007).

Regeneration models

Models for natural regeneration under different silvicultural methods are not well developed in Spain, mainly due the scarcity of long-term data. Only four main experimental sites have been established during the last decade, in Valsaín, Segovia (*P. sylvestris*), Cuéllar, Segovia and Navas del Marqués, Avila (both *P. pinaster*) and Viana de Cega, Valladolid (*P. pinea*). Experimental data regarding seed production, dispersion, predation, germination and establishment have been recorded for these sites. Post-fire recruitment has been also studied due to the importance of this perturbation, specially in Meditarrenean forests and even-aged stands in the northwestern of Spain.

Mortality models

Tree mortality plays a huge part in forest dynamics, as it reduces competition and leads to self-thinning. Stand regular mortality has generally been modeled in Spain using functions that describe the number of trees at projection age as an algebraic difference equation of previous surviving trees and age at the beginning of the projection interval. Espinel *et al.* (1997) modeled mortality for two thinning treatments using a linear regression for *Pinus radiata* in the Basque Country. Río and Montero (2001) estimated mortality in unthinned stands for *Pinus sylvestris*, and Bravo-Oviedo *et al.* (2004) fitted an exponential function for Mediterranean *Pinus pinaster*. Using data from plots where natural mortality had occurred, Álvarez-González *et al.* (2004) and Diéguez-Aranda *et al.* (2005b) derived mortality functions from differential equations in Galicia for even-aged *Pinus radiata* and *Pinus sylvestris* plantations, respectively.

At the individual tree level, the binomial nature of mortality makes Gaussian models inappropriate for expressing the probability of a tree dying or surviving. In Spain, logistic regression has been used to model individual-tree mortality for mixed-species, uneven-aged stands of *Pinus sylvestris* and *Pinus nigra* (Trasobares *et al.*, 2004a) and for single-species, uneven-aged stands of *Pinus halepensis* (Trasobares *et al.*, 2004b) in Catalonia; for separate single-species, even-aged stands of *Pinus pinaster* and *Pinus sylvestris* in continental and Mediterranean regions (Bravo-Oviedo *et al.*, 2006) and for *Pinus radiata* plantations in Galicia (Crecente-Campo *et al.*, 2009b). Adame *et al.* (2010a) used a multilevel logistic approach for predicting individual-tree mortality for *Quercus pyrenaica* from National Forest Inventory data.

Ingrowth models

Ingrowth, like other stochastic events, is a key component in long-term forest projection systems. However, most standard forest models do not include an explicit ingrowth submodel and assume that ingrowth is negligible or has no influence in any long-term silvicultural estimates. This assumption may be incorrect, at least for uneven-aged and highly structured stands (Vanclay, 1994) and low density forests. In Spain there are just a few exceptions that include an ingrowth submodel in growth and yield models. Two-step ingrowth models for maritime pine (Sánchez-Orois and Rodríguez-Soalleiro, 2002), Scots pine and Mediterranean maritime pine in Central Spain (Bravo *et al.*, 2008) and *Quercus pyrenaica* (Adame *et al.*, 2010b) have been developed. They include a logistic model to predict the probability of ingrowth occurrence in a specific stand and a linear model for quantifying ingrowth in terms of basal area (m^2/ha) or number of stems per ha.

Output functions

Volume and biomass equations

Volume equations are a fundamental part of individual-tree and whole-stand growth models, as they provide one of the key output variables for management plans. Until 1967, most of the published individual-tree volume equations with two variables were compiled by Pita (1967). The Spanish National Forest Inventory (SNFI) has published provincial, regional and

national individual-tree volume equations for the most representative forest species. Martínez Millán *et al.* (1993) have also developed tree equations for the most important forest species in Spain. Other works exist for *Pinus pinaster* (Bravo-Oviedo *et al.*, 2004), *P. sylvestris* (Bravo and Montero, 2003; Diéguez-Aranda *et al.*, 2006b; Crecente-Campo *et al.*, 2009a), *P. radiata* (Castedo-Dorado *et al.*, 2007a), *Populus* × *euramericana* (Barrio Anta *et al.*, 2007b) or *Quercus robur* (Barrio Anta *et al.*, 2007a).

Biomass equations are generally fitted in allometric form and have been developed for the different tree sections (stem, bark, branches of diverse sizes, crown, foliage, etc.) according to their importance in the nutrient cycle or for their use as bioenergy. In Spain, the species most studied are those with the highest economic value (wood or firewood) or with the greatest distribution area. Montero *et al.* (2005) fitted biomass models for 32 forest species in order to estimate the amount of carbon fixed by Spanish forests. These models have been revised to include the additivity property and incorporate tree diameter and height as independent variables (Ruiz-Peinado *et al.,* 2011)

Taper equations

Most taper functions that have been developed in Spain can classified as single taper models, segmented taper models, and variable-form taper models. Cervera (1973) made the first attempt at developing taper equations for major forest species in Spain. Since that time, many taper equations have been developed for particular regions and species, mainly for softwoods but also for some hardwoods. Due to their complicated formulations, most taper functions are implemented into specific programs for estimating total and merchantable volume from inventory data, such as cubiFor (Rodríguez *et al.*, 2008) or WinCP Navarra (Diéguez-Aranda *et al.*, 2007).

Non-timber product functions

Mediterranean forests are characterized by their multifunctionality and the diversity of both wood products and non-wood forest products (NWFP) they provide. Pine nuts, cork, edible fungi and resins are probably the most valuable non-wood products. Several NWFP models have been developed in Spain in recent years for most non-timber production species.

Models to estimate stone pine cone production have been developed including different tree or forest stand variables (García Güemes, 1999; Cañadas, 2000; Piqué, 2003; Calama and Montero, 2007; Calama *et al.*, 2008b). Climatic factors such as rainfall and temperature before flowering explain much of the yearly variation in yield (Mutke *et al.*, 2005; Calama *et al.*, 2010).

Quercus suber is the most economically important NWFP species, and a few models have been elaborated for it (González-Adrados *et al.*, 2000; Montes *et al.*, 2005; Sánchez-González *et al.*, 2007a, 2008). All the models described above deal with mature cork; the only model for virgin cork (the cork obtained from the first debarking) predicts virgin cork thickness at different heights (Sánchez-González *et al.*, 2007c) using a taper equation.

Models to estimate wild mushroom production in pine forests of different regions of Catalonia have recently been developed (Martínez de Aragón *et al.*, 2007; Bonet *et al.*, 2008, 2010).

Resin yield is affected by several natural (and partially unknown) factors, but also by the tapping method and height of the tapping-face above the ground. Resin yield models are scarce in the literature due to difficulties in finding reliable models for resin production and the reduced industrial demand for national resin products. However, Nanos *et al.* (2000) developed a model for stands of Spanish maritime pine based on probability distributions. However, they had no prediction method for the parameters of their model, since stand-level predictor variables (such as stem density or stand basal area) showed no significant correlation with resin yield (and, by extension, with the probability distribution parameters). Regression models predicting the average stand production for resin have never been reported, suggesting that the mean stand production capacity for this NWFP is not related to (and can not be predicted by) either climatic variables or classical independent variables such as site-index and stand basal area (Valero Moreno, 1998). Nanos *et al.* (2001) proposed the use of geostatistics to estimate the average resin yield of some stands in central Spain.

Interfaces

Yield tables

Yield tables are numerical tables that show the evolution over time of the variables of a coetaneous or

even-aged forest stand of a given species, within a given geographical area, for different site quality indices and for one or several silvicultural treatments (Madrigal, 1991). Yield tables can be classified as static models of growth and yield for even-aged forest stands. They have been, and still are, frequently used worldwide, although their use is declining as more reliable and flexible dynamic models for the same species and geographic areas become available.

Rojo and Montero (1994) elaborated the first comprehensive review of yield tables in Spain. Later, Madrigal *et al.* (1999) studied the definition, classification, structure, construction and operational use of the yield tables. They included a compilation of all tables existing in Spain up to that time, as well as some foreign tables for species that yield tables had not yet been developed for with data collected in Spanish forests.

Stand density management diagrams

Stand density management diagrams (SDMDs) are average and static stand-level models that graphically illustrate the relationship between yield and density-dependent mortality at all stages of stand development. Two different types of SDMDs, based on the relative spacing index or on the Reineke index, have been developed in Spain for pine and broadleaf species in Atlantic forests and a few Mediterranean forests.

Simulators and decision support systems

The first forest growth and yield model software developed in Spain was the PINASTER program (Rodríguez Soalleiro *et al.*, 1994), which included a dynamic stand growth model for even-aged *Pinus pinaster* stands in Galicia. PINASTER provides three «Pre-established silvicultural model» options for simulating stand growth and silvicultural treatments, according to site quality and product destination. The program can run trial-and-error or target objective simulations of silvicultural treatments.

Another forest growth and yield simulator was elaborated by Cantero *et al.* (1995) for *Pinus radiata* stands in the Basque Country. It projects stand development and describes the products that can be obtained with different thinning intensities based on diameter distributions (reviewed in Espinel *et al.*, 1997). The SILVES program (Río and Montero, 2001) is based on a stand growth model with diameter distribution disaggregation. It was designed to model thinning in *Pinus sylvestris* L. even-aged stands, and thinning age, intensity and rotation can be selected for analysis. In the SILVES2 version, the model was adapted for *P. sylvestris* reforestation sites in Central Spain (Río *et al.* 2005).

The GesMO© simulator was designed as a standard platform from which different stand growth models can be implemented. GesMO 1.0 (Castedo-Dorado, 2004; Diéguez-Aranda, 2004) and GesMO 2.0 (González González *et al.,* 2009 available in Diéguez-Aranda *et al.*, 2009 and http://www.usc.es/uxfs/) simulate different forest stand types and include dynamic stand growth models developed for even-aged stands of coastal and inland *Pinus pinaster* as well as *Pinus radiata* and *Pinus sylvestris* in Galicia. GesMO© makes it possible to simulate and evaluate different user-generated silvicultural alternatives according to the type, intensity and age of thinning and the rotation age. Tables, graphs and reports can be created to show the evolution of the main stand variables for each alternative analyzed. A disaggregation module distributes the stand yield, biomass (total and partial) and fixed CO_2 by diameter class for each stand stage. There is a classification module for wood products obtained and an economic evaluation module for the simulated silvicultural alternatives.

One software package available at the individual tree level is the integrated PINEA2 model, developed for the multifunctional management of even-aged Stone pine (*Pinus pinea* L) stands (Calama *et al.*, 2007). Growth and yield (wood products, wood quality, cone production, biomass fractions and fixed CO_2) can be predicted in five-year increments and under different management scenarios. These are defined by thinning and rotation length and by simulating the evolution of each individual tree within the stand. PINEA2 is an inter-regional stochastic model that allows for the calibration of new locations. The PINEA2 (Madrigal *et al.*, 2009) software application only incorporates the model parameterized for the Northern Plateau and Central Range of Spain, but maintains its stochastic character by adding single-tree and stand-level random components into the diameter increment function.

Another software package available for individual trees is ALCORNOQUE 1.0 (Sánchez-González *et al.*, 2007b), an integrated growth and yield model for high-

density cork oak forests (as opposed to lower-density woodlands). ALCORNOQUE 1.0 consists of a system of mathematical functions for simulating growth and yield (cork growth, cork thickness, cork weight) under different silvicultural regimes, thus providing important information for sustainable management of cork oak forests in the Natural Park of Los Alcornocales and Catalonia. This version is also stochastic, so that a single tree random component can be added into the cork thickness function

Some growth models are integrated into more complex software with optimisation options, such as the MONTE and RODAL software designed for Catalonian forests. MONTE is an information system for forest-level planning (see www.forecotech.com), designed to optimise forest resources and maximise forest owner benefit and includes: 1) a database management system; 2) a simulation system 3) a planning system that formulates and solves problems using an optimisation tool and 4) a sensitivity analysis system. RODAL is a similar information system that supports decision-making at the stand level according to multiple objectives. It can be applied to even-aged and uneven-aged management, as well as to pure and mixed stands.

SIMANFOR (Bravo *et al.*, 2010) is a web-based platform that allows foresters to develop sustainable forest management alternatives. It integrates different modules for managing forest inventories, simulating and projecting stand conditions and maintaining systems security and integrity. SIMANFOR outputs are compatible with an Office environment (Microsoft or Open), allowing users to exchange data and files between SIMANFOR and their own software. It is freely available for use by the world-wide forestry community (foresters, scientists, students, etc.) through the www.simanfor.org web page and can be instrumental for research, teaching and developing new silvicultural scenarios. Currently, SIMANFOR includes modules for simulating Scots pine and Mediterranean maritime pine stands in Central Spain, but it is open to incorporating models from different ecosystems around the world and is supported by a server that can be scaled up to respond to future demands.

In spite of the advances in forest growth simulators and decision support systems during the last decade, software development is still needed for many forest systems. This kind of software has become essential for forest managers and technicians in developing forest growth and yield models.

Perspectives

Model development in Spain during the last decade has been dramatic. However, several challenges lie ahead. The gap between scientific evidence and practical relevance is increasing (Pretzsch, 2009) and models will have to fill this gap by providing accurate and useful information to stakeholders. Currently, this information is available in a disjointed manner, where not all the relevant factors are properly addressed by each model independently. Process models are far from operative, but hybrid models that incorporate tactical planning, climatic drivers and physiological responses could provide more realistic long-term predictions. The development of dynamic site productivity models based on environmental change is a key issue. In Spanish forestry, advances in the area of silvicultural response functions are limited.

Models that include branch size, angle and distribution and other technological issues such as free knot bole size are lacking. There is a need for long-term trials that would provide information to adapt current models and, especially, for models that account for pre-crown closure growth changes derived from site preparation, herbaceous weed control and fertilization at establishment.

Integration is one of the main tasks for the future. Seed dispersal models and regeneration models are not integrated with growth and yield models, for example.

Special care should be taken to ensure that models are flexible enough to meet manager and stakeholder demands while maintaining the desired generality (in terms of species, areas and management options), biological foundations, focus on available data and modularity for obtaining different outputs. Models must also be well documented and user-friendly.

An effort at model evaluation and calibration must be made in the next few years. Integration of models to support decision-making and simulation tools at different scales will help to disseminate scientific output to the end-users. The use of tree- and stand-level variables based on standard forest inventory procedures as proxy variables for relevant services (carbon sequestration, recreation...) and non-timber products in currently available models could help to enhance the decision-making process. However, new models should be developed to address these specific needs. By improving decision support systems to include visualization tools, geographical information systems output, more flexible data input and silvicultural scenarios,

end-users will be more favorable to using models as they develop.

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