GROWTH AND YIELD MODELS IN SPAIN: HISTORICAL OVERVIEW, CONTEMPORARY EXAMPLES AND PERSPECTIVES

Coordinated by:

FELIPE BRAVO • JUAN GABRIEL ÁLVAREZ • MIREN DEL RÍO

2012

GROWTH AND YIELD MODELS IN SPAIN: HISTORICAL OVERVIEW, CONTEMPORARY EXAMPLES AND PERSPECTIVES

Felipe Bravo[1,2], Juan Gabriel Álvarez-González[3], Miren del Río[1,4], Marcos Barrio-Anta[5], José Antonio Bonet[6,11], Andrés Bravo-Oviedo[1,4], Rafael Calama[1,4], Fernando Castedo-Dorado[7], Felipe Crecente-Campo[3], Sonia Condés[8], Ulises Diéguez-Aranda[3], Santiago César González-Martínez[1,9], Iñigo Lizarralde[10], Nikos Nanos[8], Alberto Madrigal[8], Francisco Javier Martínez-Millán[8], Gregorio Montero[1,4], Cristóbal Ordóñez[1,2], Marc Palahí[11], Miriam Piqué[12], Francisco Rodríguez[10], Roque Rodríguez-Soalleiro[13], Alberto Rojo[3], Ricardo Ruiz-Peinado[1,4], Maria de la O Sánchez-González[1,4], Antoni Trasobares[14], Javier Vázquez-Piqué[15]

---

[1] Sustainable Forest Management Research Institute University of Valladolid-INIA Spain.
[2] Dpto. Producción Vegetal y Recursos Forestales, Universidad de Valladolid, Spain.
[3] Unidad de Gestión Forestal Sostenible. Departamento de Ingeniería Agroforestal. Universidad de Santiago de Compostela, Escuela Politécnica Superior. Campus Universitario s/n. 27002 Lugo, Spain.
[4] Dpto. Selvicultura y Gestión de Sistemas Forestales, CIFOR-INIA, Ctra. La Coruña, Km. 7.5, E-28040 Madrid, Spain.
[5] Departamento de Biología de Organismos y Sistemas, Escuela Politécnica de Mieres. Universidad de Oviedo, Mieres, Spain.
[6] Dept. Producción Vegetal y Ciencia Forestal, Universitat de Lleida, Spain.
[7] Departamento de Ingeniería y Ciencias Agrarias, Universidad de León. Escuela Superior y Técnica de Ingeniería Agraria, Ponferrada, Spain.
[8] Escuela Técnica Superior de Ingenieros de Montes, Universidad Politécnica de Madrid, Madrid, Spain.
[9] Dpto. Ecología y Genética Forestal, CIFOR-INIA, Ctra. La Coruña, Km. 7.5, E-28040 Madrid, Spain.
[10] Cesefor Foundation. Soria, Spain.
[11] European Forest Institute, Mediterranean Regional Office, Barcelona, Spain
[12] Centre Tecnològic Forestal de Catalunya, Ctra. Sant LLorenç de Morunys Km. 2. Solsona. Spain.
[13] Unidad de Gestión Forestal Sostenible. Departamento de Producción Vegetal. Universidad de Santiago de Compostela, Spain.
[14] Forest Ecology, Institute of Terrestrial Ecosystems. Department of Environmental Sciences. ETH Zurich. CH-8092 Zurich. Switzerland.
[15] Departamento de Ciencias Agroforestales. Escuela Politécnica Superior. Universidad de Huelva, Palos de la Frontera, Spain.

2012

Authors: Felipe Bravo, Juan Gabriel Álvarez-González, Miren del Río, Marcos Barrio-Anta, José Antonio Bonet, Andrés Bravo-Oviedo, Rafael Calama, Fernando Castedo-Dorado, Felipe Crecente-Campo, Sonia Condés, Ulises Diéguez-Aranda, Santiago César González-Martínez, Iñigo Lizarralde, Nikos Nanos, Alberto Madrigal, Francisco Javier Martínez-Millán, Gregorio Montero, Cristóbal Ordóñez, Marc Palahí, Miriam Piqué, Francisco Rodríguez, Roque Rodríguez-Soalleiro, Alberto Rojo, Ricardo Ruiz-Peinado, María de la O Sánchez-González, Antoni Trasobares, Javier Vázquez-Piqué.

Cover desing: Felipe Bravo
Cover pictures and graphs: Felipe Bravo, Irene Ruano, Iñigo Lizarralde and Antonio Muñoz

Edition: Insituto Universitario de Investigación en Gestión Forestal Sostenible (Universidad de Valladolid-INIA) and Unidad de Gestión Forestal Sostenible (Universidad de Santiago de Compostela)

Electronic versión available at:
http://sostenible.palencia.uva.es/document/gfs/publicaciones/Libros/2011_GrowthYield_Spain.pdf
http://www.usc.es/uxfs/Books

ISBN: 978-84-615-7145-1
Depósito legal: P-35-2012

Maquetación y Producción: Antonio Cristo, S.L. (cristosl@telefonica.net)

Imprime: Grafistaff, S.L. (grafistaff@yahoo.es)

Índice

Foreword 4
Abstract 5
1. Introduction 6
2. Driving processes 7
    a. Productivity 7
    b. Density and competition 8
3. Data and model requirements 9
    a. Data 9
    b. Auxiliary functions for estimating missing variables 10
4. Modeling approaches 13
    a. Empirical, Process and Hybrids 13
    b. Whole-stand models, size class models and individual-tree models 14
5. Model modules 21
    a. Increment, growth and yield 21
    b. Silviculture response functions 25
    c. Demography 27
    d. Output functions 30
6. Validation and calibration models 39
7. Interfaces 41
    a. Yield tables 41
    b. Stand density management diagrams 44
    c. Simulators and decision support systems 44
8. Perspectives 48
Acknowledgments 49
References 50

Foreword

This contribution summarized the development in forest modeling in Spain during the last fifteen years. By including information on the different modeling approaches conducted in Spain and the databased used, authors wish to show the diversity and the wide scope of the forest models. Edition has been funded by Sustainable Forest Management Research Institute (University of Valladolid-INIA), Sustainable Forest Management Unit (University of Santiago de Compostela) and the SELVIRED network (Spanish Ministry of Science and Innovation). We hope that this book will be found useful both for researches and managers and serve as inspiration to develop new ideas and approaches.

Abstract

This book presents a review of forest models developed in Spain in recent years for both, timber and non timber production and forest dynamics (regeneration, mortality,...). It reviews the key factors that regulate growth and demographic processes included in the described models with special emphasis on productivity, density and competition.

The models developed to date are based on data from permanent plots, silvicultural trials and the National Forest Inventory.

The book describes the main data network available in Spain and the auxiliary functions adjusted to estimate missing variables in the databases. After discussing, the different approaches (empirical, based on process or hybrid) used to date, the scales (whole stand models, class size and individual tree) commonly used in forest modeling are described. By describing the different submodels included in the models developed so far are presented indicating both, the species and the geographic area where it can be used. Validation and calibration of models is treated briefly while the ways of presenting the models (yield tables, charts or computer programs) are described in detail. The book ends with a set of perspectives from which emphasizes the need for integration of different methodologies and scales and underlines than an effort must be done to improve the evaluation and calibration of the models. Finally it highlights the need to facilitate the use of models by foresters by including visualization tools, integrating geographic information systems and facilitating the use different data formats and generate silvicultural scenarios.

Keywords: *timber production, non-wood forest products, recruitment, modelling, forest*

Resumen

Este libro presenta una revisión sobre los modelos forestales desarrollados en España durante los últimos años, tanto para predecir la producción maderable y no maderable, como para simular la dinámica de los bosques (regeneración, mortalidad,..). Se repasan los factores fundamentales que regulan los procesos de crecimiento y demográficos incluidos en los modelos expuestos, con especial énfasis en la productividad, la densidad y la competencia. Los modelos desarrollados hasta la fecha se han elaborado a partir de datos procedentes de parcelas permanentes, ensayos selvícolas y el Inventario Forestal Nacional. En el libro se describen las principales redes de datos disponibles en España y las funciones auxiliares ajustadas para estimar las variables ausentes en las bases de datos. Tras exponer las diferentes aproximaciones (empírica, de procesos o híbridas) utilizadas hasta la fecha se describen las escalas (modelos de rodal completo, de clases de tamaño y de árbol individual) habitualmente utilizadas en modelización forestal.

Mediante la descripción de los diferentes submodelos que los componen, se presentan los modelos indicando tanto la especie como el área geográfica donde se pueden utilizar. La validación y calibración de modelos se trata de forma sucinta, mientras que las formas de presentar los modelos (tablas de producción, diagramas o programas de ordenador) son descritas en detalle. El libro termina con un conjunto de perspectivas, derivadas de la reflexión sobre los requerimientos aún no cubiertos, entre las que resalta la necesidad de integración de diferentes metodologías y escalas, así como el esfuerzo que se debe hacer para mejorar la evaluación y calibración de los modelos. Finalmente se incide en la necesidad de facilitar el uso de los modelos por parte de los gestores forestales mediante la inclusión de herramientas de visualización, la integración con sistemas de información geográfica y la flexibilidad para poder usar diferentes formatos de datos y generar escenarios selvícolas.

Palabras claves: *producción maderable, productos forestales no maderables, regeneración, modelización, forestal*

1. Introduction

According to official statistics, forest lands cover 54.4% of the Spanish national territory. However, only 18.4 million ha (36% of the country) are true forests or plantations. Approximately 39.2% of Spanish forest lands are under different types of protection, such as national and regional parks or Natura 2000 areas. Three main forest ecoregions can be distinguished in Spain: Mediterranean, Atlantic and Subtropical (Macaronesic). Forestry in Spain has diverse objectives and the ecoregions present different forest management attributes corresponding to the importance of biodiversity conservation (higher in the Macaronesic area and lower in the Atlantic), timber production (higher in the Atlantic) or multifunctionality and non-timber products (higher in the Mediterranean). The harvest rate in Spain, expressed as the ratio between harvest volume and wood increment each year, reaches 64% in Galicia (NW Spain) and 30.2% for the country as a whole. The average harvest ratio in Europe (excluding of the Russian Federation) is 55%.

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 s developed in the 1940s for *Pinus radiata* and *Pinus pinaster* plantations in the Atlantic area (Echeverría, 1942 and 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 work 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.

2. Driving processes

a. Productivity

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).

Forest productivity can be placed within the broader field of Production Ecology. Although both disciplines have their own particular and aims (Pretzsch, 2009) the former can be viewed as the harvestable standing biomass of the latter, which is demanded by society. Forest scientists and managers deal with forest productivity in terms of growth or increment in volume of the stand and its integration in yield. Growth and yield are determined by four factors (Clutter *et al.*, 1983): the age or age distribution of the stand, the timber production capacity of the site, stand density or site occupancy, and silvicultural treatments.

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 (Barnes *et al.*, 1997). Consequently, the concept of site quality should not be relegated only to timber production as it involves multifunctionality. Alternative to traditional biomass allocation in the stem, cork production (Montero, 1987) or annual cone production (Mutke *et al.*, 2005) could be alternative site productivity proxies for traditional biomass allocation in the stem. However, wood volume is still one of the most valuable products in forest ecosystems and is highly correlated to forest productivity, so most growth and yield models are dedicated to it.

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. This value is usually extracted from a set of growth curves and is an indicator of the site potential for growing wood biomass. The main characteristics of these curves are inflection point, asymptote, polymorphism and base age invariance (Goelz and Burk, 1992).

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-Rodriguez *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). Some site-related variables commonly included in the models to reflect site quality are elevation (Trasobares and Pukkla, 2004b; Condés and Sterba, 2004, 2008), soil types and attributes (Bravo and Montero, 2001, Condés and Sterba, 2004 and 2008) or latitude (Trasobares and Pukkala, 2004b).

One successful way of incorporating site quality into diameter growth models has been to include the past growth index (GI). This was proposed by Trasobares and Pukkala (2004b) and used by Trasobares *et al.* (2004b). Other authors have incorporated different bioclimatic indexes for assessing the potential productivity of a particular area. For example, the bioclimatic index (IBL) proposed by Montero de Burgos and González Rebollar (1974) measures the capacity of trees to produce biomass after their cells have recovered from summer stress. It was used by Condés and Sterba (2008) to develop an individual-tree growth model for *Pinus halepensis*. In another case, the potential climatic productivity (MAI) index of Sánchez-Palomares and Sánchez-Serrano (2000) was included as an independent variable in an individual-tree growth model for *Pinus sylvestris* (Condés and Sterba, 2004). Adame *et al.* (2008a) utilised the biogeoclimatic strata of Elena-Roselló (1997). Calama *et al.* (2008b) used a land classification based on soil, physiografic and climatic attributes to model individual cone production.

b. Density and competition

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 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 (Munro, 1974). 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 (see Section 5.a.ii). In Mediterranean low-density forests, the number of trees per ha is a commonly used index (Calama and Montero, 2005; Sánchez-González *et al.*, 2006; Gea-Izquierdo and Cañellas, 2009) that reflects symmetric competition for water resources.

Distance-dependent indices are not often used in Spain, mainly because the inventory data does not include tree coordinates. When they were calculated, they were not found to be better than distance-independent indices (Álvarez Taboada *et al.*, 2003; Crecente-Campo, 2008; Gea-Izquierdo and Cañellas, 2009). This could be due to the small plot size used in forest modeling. Vázquez-Piqué *et al.* (2008) selected a onesided version (dominant trees are not affected by competition from dominated trees) of a distance-dependent index for a cork oak growth model. It indicated high asymmetry in the competition process, but no comparison was made using distance-independent indices.

Stand density reflects the average tree growing spaces 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.*, 2001a; 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 the stand density management diagrams for some Spanish forests, and Reineke's stand density index was used in the yield model of Bravo and Montero (2003). 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 (N) as state variables, so they do not include other stand density indices.

• 3. Data and model requirements

a. 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. When it is inadequate, a data collection process must also be designed (Rennolls, 1997).

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:

- Sample plots for resource inventory: The design is based on temporal plots, where the number of sample plots is calculated to achieve the desired precision for the analysed resource. The spatial distribution of the sample grid is usually oriented across environmental or physical gradients to maximize within-plot variation and thus reduce between-plot variance.
- Continuous Forest Inventory: The main objective is to assess and monitor the extent, state and sustainable development of forests at the national or regional level in a timely and accurate manner (e.g. Spanish National Forest Inventory). The design is based on permanent plots in different types of forest and stand conditions in proportion to area. Sampling is done by passive monitoring. As with resource inventory, precision is gained by reducing between-plot variance.
- Sample plots from field experiments: Growth data can be obtained from different field trials (spacing, thinning and pruning trials, fertilizer trials, growth trials, etc.). In Spain, these trials are established and maintained almost exclusively by government research organizations (Montero *et al.*, 2004a) or university research groups (Bravo *et al.*, 2004; Torres-Álvarez *et al.*, 2004; Diéguez-Aranda *et al.*, 2009). The design is based on permanent sample plots and the size, shape, number and distribution of sample plots depends on the objectives of the field experiment.
- 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 regional 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.

b. 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:

Bark thickness or bark percentage

Bark thickness (*bw*) or bark percentage (*b*%) equations usually act as auxiliary functions for growth models, which eliminates the need to calculate over-bark and under-bark volumes and facilitates correct estimates of diameter growth. Several bark models have been developed for Spain (Table 1).

Diameter-stump diameter and volume-stump diameter relationships

When a tree has been cut and only the stump remains as an indicator of its size, it sometimes becomes necessary to use the stump diameter (d_{st}) to estimate the tree diameter (*d*) or even the tree volume (*v*). Simple linear models are usually adequate for predicting *d* from d_{st}, whereas alometric or parabolic models are necessary for predicting *v* from d_{st}. In Spain, equations of this kind have been developed for *Betula alba*, *Eucalyptus globulus*, *Pinus pinaster*, *P. radiata*, *P. sylvestris* and *Quercus robur* in the region of Galicia (Diéguez-Aranda *et al.*, 2003; Diéguez-Aranda *et al.*, 2009).

Height-diameter relationships

The height of the trees in a stand is an important variable in forest management. It can be used to i) accurately predict total and commercial volume (together with *d*) using a volume equation, a tree taper equation, or a volume ratio equation, ii) estimate site quality in even-aged stands, and iii) characterize of the vertical structure of a stand (Gadow *et al.*, 2001). Local and generalized height-diameter (*h*-*d*) models are commonly used. Local *h*-*d* models are valid for a specific forest or stand, while generalized *h*-*d* models (local models that include stand variables in the formulation) are valid for a particular species in a particular region or regions (Table 2). Some generalized height-diameter models use a mixed-model approach that allows for model calibration when sample trees are available (Table 2).

Crown equations

Crown attributes are key components of growth and yield models (Soares and Tomé, 2001) but are also important for assessing wood quality (Kershaw *et al.*, 1990), competitive level (Mitchell, 1975), tree vigour (Hasenauer and Monserud, 1996), fire susceptibility (Keyes and O'Hara, 2002), mechanical stability (Wilson and Oliver, 2000), and microclimate (Grace *et al.*, 1987). The most typically measured tree attributes are i) height to the crown base (*hcb*), which, measured together with total height, makes it possible to estimate crown length (*cl*) and crown ratio (*cr*) or height to the base of the live foliage (*hblf*); ii) crown width, assessed as maximum potential width (*mcw*) or largest crown width (*lcw*), iii) height to the largest crown width (*hlcw*), in order to ascertain the competitive level of the lower part of the crown, and iv) crown radius which is used to develop the crown taper equations that are essential for estimating crown volume and cross-sectional areas (Table 1).

Table 1. Crown and bark functions developed in Spain by species and area

Variable and Species	Area	Independent Variables	Goodness of fit (R^2)	References
Bark percentage				
Several species	*Whole country*	*d, h, bw*		Martínez Millán *et al.* (1993)
Bark thickness				
Pinus sylvestris	*Castilla y León*	*d, dib*	0.961	Lizarralde (2008)
Pinus pinaster	*Castilla y León*	*d, dib*	0.884	Lizarralde (2008)
Maximum crown width				
Several species	*Whole country*	*d*		Martínez Millán *et al.* (1993) Condés and Sterba (2005)
Largest crown width				
Pinus radiata	*Galicia*	*d, h, mcw*	0.730	Crecente-Campo *et al.* (2009a)
Pinus sylvestris	*Castilla y León*	*d, h, cr, cl*	0.700	Lizarralde (2008)
Pinus pinaster	*Castilla y León*	*d, h, cr, cl*	0.752	Lizarralde (2008)
Quercus suber	*Whole country*	*du, dg*	0.894	Sánchez-González *et al.* (2007c)
Several species	*Whole country*	*d, h*		Condés and Sterba (2005)
Height to largest crown width				
Pinus radiata	*Galicia*	*h, hblf*	0.866	Crecente-Campo *et al.* (2009a)
Pinus sylvestris	*Castilla y León*	*h, BAL, G*	0.898	Lizarralde (2008)
Pinus pinaster	*Castilla y León*	*h, BAL, G*	0.852	Lizarralde (2008)
Height to crown base				
Pinus radiata	*Galicia*	*d, h, t,* H_0	0.640	Crecente-Campo *et al.* (2009a)
Pinus sylvestris	*Castilla y León*	*hlcw, h, BAL,G,*	0.963	Lizarralde (2008)
Pinus pinaster	*Castilla y León*	*hlcw, h, BAL,G,*	0.921	Lizarralde (2008)
Upper crown radius (crown radius above largest crown width)				
Pinus radiata	*Galicia*	*lcw, h, hblf, hlcw*	0.901	Crecente-Campo *et al.* (2009a)
Lower crown radius (crown radius below largest crown width)				
Pinus radiata	*Galicia*	*lcw, h, hblf, hlcw*	0.859	Crecente-Campo *et al.* (2009a)

Where: *d* is diameter at breast height, *h* is total height, *bw* is bark thickness, *dib* is diameter inside bark, *mcw* is maximum crown width, *cr* is crown ratio, *cl* is crown length, *du* is diameter under cork, *dg* is quadratic mean diameter, *hblf* is height to the first living branch, *BAL* is the sum of basal areas of larger trees, *G* is basal area, *t* is age, H_0 is dominant height, *hlcw* is height at the largest crown width and *lcw* is largest crown width.

Table 2. Height-diameter functions developed in Spain by species and area

Species	Area	Independent Variables	Goodness of fit (R^2)	References
Eucalyptus globulus	*Galicia*	d, d_0, H_0 d, d_0, H_0	0.835 0.890	Diéguez-Aranda *et al.* (2009) Crecente-Campo *et al.* (2010a)- M.M
Populus sp. (Clone I-214, MC, Luisa Avanzo)	*North-east Spain*	d, d_0, H_0	0.97-0.99	Rodríguez (2005)
Quercus pyrenaica	*Castilla y León*	d, H_0, d_g d, H_0, G	0.756 0.823	Adame *et al.* (2005) Adame *et al.* (2008b)- M.M.
Quercus robur	*Galicia*	d, d_g, H_m d, d_0, H_0	0.778 0.753	Barrio-Anta *et al.* (2004) Diéguez-Aranda *et al.* (2009)
Quercus suber	*Whole country*	du, d_0, H_0	0.810	Sánchez-González *et al.* (2007c)
Pinus pinaster	*Southern Iberian Range*	d, d_g, H_0	0.866	Lizarralde (2008)
	Galicia	d, d_g, H_0, G d, d_0, H_0	0.919 0.938	Schröder and Álvarez González (2001) Castedo-Dorado *et al.* (2005)
Pinus pinea	*Central Range*	d, d_0, H_0	-	Cañadas *et al.* (1999)
	Valladolid	d, H_0	0.936	García Güemes *et al.* (2001)
	Whole country and by regions	d, H_0, P_{9010}	0.953	Calama and Montero (2004)- M.M.
Pinus radiata	*Galicia*	d, d_0, H_0, t, N d, d_0, H_0	0.918 0.933	López-Sánchez *et al.* (2003) Castedo-Dorado *et al.* (2006)- M.M.
	Asturias	d, d_0, H_0, N	0.900	Canga *et al.* (2007)
Pinus sylvestris	*Castilla y León* *Galicia* *Catalonia*	d, d_g, H_0 d, d_0, H_0 d, d_0, H_0, t	0.872 0.938 0.890	Lizarralde (2008) Diéguez-Aranda *et al.* (2005b) Palahí *et al.* (2003)
Pinus halepensis	*Middel Ebro Valley*	d, d_g, H_m	0.821	Cabanillas (2010)
Pseudotsuga menziesii	*Northern Spain*	d, d_0, H_0	0.873	López-Sánchez (2009)

Where: d is diameter at breast height, d_o is dominant diameter, H_o is dominant height, dg is quadratic mean diameter, G is basal area, du is diameter under cork, P_{9010} is the difference between the percentiles 90 and 10 of the diameter distribution, t is age, N is number of trees, and H_m is mean height. M.M. is mixed model.

• 4. Modeling approaches

a. Empirical, Process and Hybrids

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. Based on Vanclay (1995), Gadow and Hui (1999) and Davis *et al.* (2001), empirical growth and yield models can be grouped into three types of models that cover a wide spectrum: whole-stand models, size-class models and individual-tree models. The most appropriate model type varies according to intended use, stand characteristics, available resources and length of projection (Vanclay, 1994; Burkhart, 2003; García, 2003). These factors determine the data and precision required for the estimates. 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-León 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. Additionally, process-based models do not always provide interesting output that is easily applicable in forest management decision-making (see Landsberg *et al.*, 2003). 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. It also simulates forest carbon and water fluxes for different environments and tree species under changing environmental conditions.

Choosing between process-based and empirical models involves trade-offs between model realism (simulating system behavior based on a qualitatively realistic model structure), model accuracy (simulating system behavior in a quantitatively accurate manner), and model generality (Odenbaugh, 2006). However, most groups in Spain are currently working towards hybrid modeling that uses different approaches. Some are exploring climate variables to explain growth or site in empirical models (Mutke *et al.*, 2005, Bogino and Bravo, 2008, Bravo-Oviedo *et al.*, 2008, Martín-Benito *et al.*, 2008a and 2010, Bogino *et al.*, 2009 and Gea-Izquierdo *et al.*, 2009) and others are using physiologically-based growth models with empirical functions. An example of this is the 3PG model (Landsberg and Waring, 1997), which has been parametrized for eucalyptus (Rodríguez-Suárez *et al.*, 2010), *Pinus pinaster* and *Pinus radiata* plantations.

b. Whole-stand models, size class models and individual-tree models

Individual-tree growth models provide the most detailed information (García, 1994 and 2003) and usually perform better than whole-stand models for short term projections (Burkhart, 2003). Size class models offer a compromise between the other two approaches. Since aggregate outputs are usually required for forestry decision-making in Spain, individual-tree models can be overparamerized and too complicated for this purpose. Thus, whole-stand models continue to be an attractive alternative, at least for even-aged, single-species stands (including plantations).

It is useful to distinguish between static and dynamic whole-stand models. Static models attempt to directly predict the course of the quantities of interest (volume, mean diameter, etc) over time. Stand yield tables (SYT) and stand density management diagrams (SDMD) are included in static whole-stand models, and they are the most advanced tools that can be developed when research plot measurements are only available for one point in time. Dynamic models predict rates of change under different management approaches and stand conditions. Data on experimental rates of change are necessary for model development and are obtained by measuring research plots on at least two occasions. Dynamic whole-stand models are more flexible and accurate than static models, and therefore are preferred when they are available.

For more complex systems such as uneven-aged or mixed stands or for short-term projections, individual-tree models are sometimes preferred because they provide a more detailed description of stand structure and dynamics than whole-stand models. They can also be useful in assessing potential stand structures resulting from new silvicultural regimes (e.g., Condés and Sterba, 2008). Individual-tree growth models can be distance-dependent, if they include spatial competition indices in their formulation, or distance-independent if they do not.

The first growth and yield models developed in Spain were static 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 (see section 7.a). In recent years, 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 (See section 7.b.)

Dynamic whole-stand models and distance-independent individual-tree models have been developed for Spain in the last decade (see Tables 3a to 3e). To date, only two size-class models have been developed in Spain (Sánchez Orois and Rodríguez Soalleiro, 2002 and 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.

Table 3a. Atlantic pine plantations (yield tables and stand density management diagrams are not included)

Area	**Model type**	**Modules or submodels**	**Dependent variable**	**Independent variable**	**Goodness of fit (R^2)**	**Validation**	**References**
Pinus pinaster Ait.							
Galicia interior and coast	Dynamic stand	Diameter /Basal area	*IG* [m^2/ha·year]	*G* [m^2/ha], *t* [years]	0.57 (costa) and 0.60 (interior)	None	Álvarez González *et al.* (1999)
Galicia interior and coast	Dynamic stand	Diameter /Basal area	*IG* [m^2/ha·year]	G_1 [m^2/ha], t_1 [years], t_2 [years]	0.99	Cross-validation	Barrio-Anta *et al.* (2006b), Dieguez-Aranda *et al.* (2009)
North-west Spain: Pontevedra	Individual tree distance independent	Diameter /Basal area	*IG* [cm^2/year]	*ESD* (Effective soil depth) [cm], BALMOD, *CSR* (Crown spread ratio), *d* [cm]	0.78	None	Schröder *et al.* (2002)
Pinus radiata D. Don							
Basque country	Static stand (with diameter distribution estimation by parameter recovering technique)	Minimum Diameter/Basal area/P93/N_2	D*min* [cm]	*Unthined stands*: G_2 [m^2/ha], N_2 [trees/ha], t_2 [years] *Thinned stands*: G_1 [m^2/ha], t_1 [years], t_2 [years], N_1 [trees/ha] *Thinning effect*: $Dmin_1$ [cm]	0.72 0.86 0.88	None	Cantero *et al.*, 1995.
			G [m^2/ha]	*Unthined stands*: H_{02} [m], t_2 [years] *Thinned stands*: G_1 [m^2/ha], t_1 [years], t_2 [years], N_1 [trees/ha]	0.41 0.76		
			P93 [cm]	*Unthined stands*: H_{02}, t_2 [years] *Thinned stands*: G_1 [m^2/ha], t_1 [years], t_2 [years], N_1 [trees/ha] *Thinning effect*: $P93_1$ [cm]	0.89 0.89 0.99		
			N_2 [trees/ha]	*Thinning effect*: N_1 [trees/ha], G_1 [m^2/ha], G_2 [m^2/ha]	0.99		
Galicia	Dynamic stand	Diameter /Basal area	G_2 [m^2/ha]	G_1 [m^2/ha], t_1 [years], t_2 [years]	0.99	None	Castedo-Dorado *et al.* (2007a,b),
North-west Spain: Galicia	Individual tree distance independent	Diameter /Basal area	*IG* [cm^2/year]	BAR [(m^2)/(m^2/ha)], BALMOD, *t* [years], *G* [m^2/ha], *d* [cm]	0.62	None	Crecente-Campo (2008)

For variable description see Table 3e

Table 3b. Mediterranean Scots pine forests (yield tables and stand density management diagrams are not included)

Area	Model type	Modules or submodels	Dependent variable	Independent variable	Goodness of fit (R^2)	Validation	References
Pinus sylvestris L.							
Galicia	Dynamic stand	Diameter /Basal area	G_2 [m^2/ha]	SI [m], G_1 [m^2/ha], t_1 [years], t_2 [years]	0.93	Cross-validation	Diéguez-Aranda *et al.* (2006a)
Galicia	Individual tree distance	Basal area	ig [cm^2/year]	d [cm], G [m^2/ha], t [years], BAL		None	Crecente-Camp *et al.* (2010a)
High Ebro Basin	Multiplicative Static model	Volume/ Basal area	V[m^3/ha], G [m^2/ha]	H_0[m], SDI, N[trees/ha]	0.95/0.50	Calibration	Bravo (1999), Bravo and Montero (2003)
Central and Iberic Range	Dynamic stand	Volume/ Basal area/ Mortality	V_2 [m^3/ha], G_2 [m^2/ha], N_2 [tres/ha]	SI[m], G_1[m^2/ha], N_1[trees/ha], t_1[years], t_2[years]	0.97	None	Río and Montero (2001)
North-east Spain	Dynamic stand	Volume/ Basal area/ Mortality	V_2 [m^3/ha], G_2 [m^2/ha], N_2 [tres/ha]	V_1[m^3/ha], G_1[m^2/ha], N_1[trees/ha], H_{01}[m], H_{02}[m], t_1[years], t_2[years]	0.81/0.62/ 0.99	None	Palahí, *et al*. (2002)
North-east Spain	Individual tree distance independ.	Diameter /Basal area/Mortality	id[cm/5years], P(survive)	SI [m], BAL[m^2/ha], t [years], G[m^2/ha], d[cm]	0.24	None	Palahí *et al*. (2003)
Madrid	Individual tree distance independent	Diameter /Basal area	ig[cm^2/10years]	*Soil* [dummy], *Orig* [dummy], *MAI* [m^3/ha·year], *SLS*in *PERC*res [prop.], *BA*rem [m^2/ha], SKEW, CV [%], d [cm]	0.41	None	Condés and Sterba (2004)
Madrid (plantations)	Dynamic stand	Diameter /Basal area	V_2 [m^3/ha], G_2 [m^2/ha], N_2 [tres/ha]	SI[m], G_1[m^2/ha], N_1[trees/ha], t_1[years], t_2[years]	0.99	None	Río *et al*. (2005)
Central and Iberic Range	Individual tree distance independent	Diameter/ Height/ Mortality/ Ingrowth	id[cm/5years], ih[m/5years], P(survive), P(ingrowth), IG[m^2/ha]	SI[m], BAL[m^2/ha], CR[prop], G[m^2/ha], d[cm], *CV [%] Dg [cm]*	0.32/0.38/ 0.53	None	Bravo-Oviedo *et al.* (2006), Bravo *et al.* (2008), Lizarralde (2008)

For variable description see Table 3e

Table 3c. Black and Aleppo pine forests (yield tables and stand density management diagrams are not included)

Area	Model type	Modules or submodels	Dependent variable	Independent variable	Goodness of fit (R^2)	Validation	References
Pinus nigra Arn.							
North-east Spain: Lérida & Tarragona	Individual tree distance indepe.	Diameter /Basal area /Mortality	*id*[cm/5years], *P*(survive)	*SI* [m], *BAL*[m^2/ha], G *G*[m^2/ha], *t*[years],*d*[cm], *h*[m], H_0[m]	0.14	None	Palahí and Grau (2003).
Pinus halepensis Mill.							
North-east Spain: Catalonia	Individual tree distance independent	Diameter /Basal area/Mortality /Ingrowth	*id*[cm/10years], *P*(survive), *ING*[trees/ha], *DIN*[cm]	*GI*[(mm/5years)/(mm/5 years)], *BAL* [m^2/ha], *BALthin* [m^2/ha], *d*[cm], *SLO*[%], *ELE*[m], *G*[m^2/ha], G_{Ph}[m^2/ha]	0.25/0.04/ 0.08	None	Trasobares *et al.* (2004b).
Murcia	Individual tree distance independent	Diameter /Basal area/Height	*ig* [cm^2/year] *ih* [m/year]	*IBL* [b.u], *SLO*[prop], *ELE* [hm], *Soil* [dummy], *BAL*res[m^2/ha], h/H_0[prop], *CCF*res[prop],H_0[m], *d*[cm], *h*[m]	0.46/0.49	None	Condés and Sterba (2008).
Pinus sylvestris L. & *Pinus nigra* Arn.							
North-east Spain: Catalonia	Individual tree distance independent	Diameter /Basal area	*id*[cm/10 years	*GI* [(mm/5 years)/ (mm/5 5 years)], *ELE* [100 m], *SLO* [%], *CON* [km], LAT [100Km] *BAL*syl [m^2/ha], *BAL*nig [m^2/ha], *BAL*syl +acc [m^2/ha], *BAL*nig+acc [m^2/ha], *BAL*thin [m^2/ha] *d* [cm]	-	None	Trasobares and Pukkala (2004a, 2004b).

For variable description see Table 3e

Table 3d. Mediterranean Maritime and Stone pine forests (yield tables and stand density management diagrams are not included)

Area	Model type	Modules or submodels	Dependent variable	Independent variable	Goodness of fit (R^2)	Validation	References
Pinus pinaster Ait. (Mediterranean group)							
Spain	Dynamic stand	Volume/Basal area/Mortality	V_2 [m^3/ha], G_2 [m^2/ha], N_2 [tres/ha]	SI[m], G_1[m^2/ha], N_1[trees/ha], t_1[years], t_2[years]	0.95/0.97	Independent Sample	Bravo-Oviedo *et al.* (2004)
Central and Iberic Range	Individual tree distance independent	Diameter/Height/Mortality/Ingrowth	id[cm/5years], ih[m/5years], P(survive), P(ingrowth), IG[m^2/ha]	SI[m], BAL[m^2/ha], CR[prop], G[m^2/ha], d[cm], h[m] Dg[cm], d/Dg[prop]	0.40/0.43/0.51	None	Bravo-Oviedo *et al.* (2006), Bravo *et al.* (2008), Lizarralde (2008)
Pinus pinea L.							
Valladolid	Static stand	Diameter	Dg[cm]	H_0[m], N[trees/ha]	0.94	None	García-Güemes (1999)
Madrid	Individual tree distance independent	Diameter/Basal area	ir[mm/year]	H_0[m], BAL[m^2/ha], CR[prop], CCF	-	None	Cañadas (2000)
Spain	Individual tree distance independent	Diameter /Basal area	id [cm/5 years] years	SI [m], cat [dummy], H_0[m], N[trees/ha], d/Dg[prop], d[cm]	-	None	Calama and Montero (2005)

For variable description see Table 3e

Table 3e. Broadleaves forests (yield tables and stand density management diagrams are not included)

Area	Model type	Modules or submodels	Dependent variable	Independent variable	Goodness of fit (R^2)	Validation	References
Quercus pyrenaica Willd							
Castilla y León	Individual tree distance independent	Diameter/Basal area	*id* [cm/10 years]	*SI* [m], Biogeoclimatic stratum, *BAL* [m^2/ha], N [trees/ha], H_0 [m], *d* [cm]	0.44	Independent Sample	Adame *et al.* (2008a)
Quercus suber L.							
Whole country	Individual tree distance independent	Diameter /Basal area/Cork thickness	*idu* [cm/year] cc^2 [mm]	*SI* [m], *N* [trees/ha], *du* [cm], cc_1, t_1, t_2	0.12/0.99	Cross validation	Sánchez-González *et al.*, (2007b)
Populus sp. (clone I-214)							
Castilla y León y Madrid	Dynamic stand	Diameter /Basal area	G_2 [m^2/ha],	G_1[m^2/ha], t_1[years], $t_2$years]	0.99	None	Barrio-Anta *et al.* (2008)
Populus sp. (clones I-214, MC, Luisa Avanzo)							
North-east Spain	Dynamic stand	Diameter /Basal area	G_2 [m^2/ha]	G_1[m^2/ha], t_1[years],	0.99 for each clone	Cross-validation	Rodríguez *et al.* (2010)
Eucalyptus globulus Labill							
Galicia	Dynamic stand	Diameter /Basal area	*dG/dt*	*G*[m^2/ha], H_0 [m], *N* [trees/ha]	non specified	None	García and Ruiz (2003)

Where *d* is diameter at breast height, d_o is dominant diameter, d_{min} is minimum diameter, D_g is the quadratic mean diameter, *id* is individual tree diameter at breast height increment, H_o is dominant height, *h* is individual tree total height, *ih* is individual tree total height increment, *dg* is quadratic mean diameter, *G* is basal area, *IG* stand basal area increment, *ig* is individual tree basal area increment, *ir* is the radial increment, *du* is diameter under cork, P_{93} is the percentile 93 of the diameter distribution, *t* is age, *N* is number of trees, *BAL* is stand basal area in larger trees, *BALMOD* is modification of stand basal area in larger tree, *SI* is site index, *V* is stand volume, *P* is probability, *SDI* is Stand Density Index, *MAI* is mean annual increment, *SKEW* is skewness of the diameter distribution, *CV* is the coefficient of variation of diameter distribution, *CR* is crown ratio, *ING* is ingrowth, *GI* is Basal area growth index, *BALthin* is, the total basal area of trees larger than the subject tree and thinned during the next 10-year period, *ELE* is the elevation (100 m above sea level); *CON* is the continentality (linear distance to the Mediterranean sea, km), *LAT* i the latitude, *GPh* is the stand basal area of *P. halepensis, BALres* is the Basal area of larger trees measured in two consecutives inventories (before and after growth) and calculated with diameters before growth, *IBL* is bioclimatic index, CCFres is the Crown competition factor of residual trees between inventories (%). Subindices 1 and 2 denote the period of measurement.

5. Model modules

a. Increment, growth and yield

i. Site index equations

Site index curves are the most commonly used technique for evaluating site productivity on single-species, even-aged stands. A set of site index curves is a family of height (generally dominant height) development patterns with quantitative reference symbols or numbers associated with the curves. The most frequent referencing method uses the term *site index*, which is defined as the stand dominant height achieved at a specified *index age* or *base age*.

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 (Clutter *et al.*, 1983): the guide curve method, the parameter prediction method, and the difference equation method.

Most studies related to site index equations have used either the function proposed by von Bertalanffy (1949 and 1957) and studied by Richards (1959), or special log-logistic models, also known as the Hossfeld models (Cieszewski, 2000). The latter have a long history of describing a wide variety of population dynamics. The climate-based model developed by Bravo-Oviedo *et al.* (2008) is based on the GADA approach and includes climate attributes and parental material specific for each site. Bengoa (1999) and Bravo *et al.* (1996) used basal area-age functions as site productivity predictors in non-thinned stands. Most of the site index research is focused on pine species (Tables 4a and 4b) but a few other species have also been studied.

ii. Diameter and basal area growth functions

Individual growth models predict basal area or diameter increment based on growth as a function of site quality, competition and density variables, tree size and even vigor variables in some models. These growth models commonly use a site index to characterize the quality of the site (e.g., Palahí *et al.*, 2003; Sánchez-González *et al.*, 2006; Adame *et al.*, 2008a). However, when the stand age is unknown, the site index cannot be calculated and site-related variables must be used instead (see Section 2a).

Most of the individual growth models developed in Spain include the basal area of large trees, *BAL* (Wykoff, 1990), as a competition variable. This variable can be computed for all trees (Palahí *et al.* 2003; Palahí and Grau, 2003; Trasobares *et al.*, 2004b, Adame *et al.*, 2008a, Lizarralde, 2008), for thinned trees during the period between

Table 4.a. Site index equations for pine species in Spain

Species and area	Methodology[1]	Fitting procedure[2]	References
Pinus halepensis			
Whole country	GCM	ONLS	Erviti (1991), Montero *et al*. (2001b)
	ADA	DVM	Ruiz-Peinado *et al*. (2010)
Middle Ebro Valley	GADA	DVM	Cabanillas (2010)
Pinus nigra			
Catalonia	ADA	ONLS	Palahí and Grau (2003)
Rest of the Country	GADA	DVM	Martín-Benito *et al*. (2008b)
Castilla y León (Afforestations)	ADA	ONLS	Río *et al*. (2006)
Pinus pinaster			
Galicia	GCM	OLS	Bará and Toval (1983)
	GCM	OLS	Rodríguez-Soalleiro (1995)
	ADA	ONLS	Álvarez González *et al*. (2005)
	GADA	DVM	Diéguez-Aranda *et al*. (2009)
Mediterranean area	GCM	OLS	Pita (1967a)
	ADA	ONLS	Bravo-Oviedo *et al*. (2004)
	GADA	DVM	Bravo-Oviedo *et al*. (2007)
	Climate-based GADA	DVM	Bravo-Oviedo *et al*. (2008)
Castilla y León (Afforestations)	ADA	ONLS	Río *et al*. (2006)
Pinus pinea			
Northern Plateau	GCM	ONLS	García Güemes (1999)
Central Range	ADA	ONLS	Cañadas (2000)
Catalonia	ADA	ONLS	Piqué (2003)
Whole country	ADA	ONLS	Calama *et al*. (2003)
Whole country (afforestations)	GADA	DVM	Madrigal *et al*. (2007)
Pinus radiata			
Basque country	GCM	ONLS	Madrigal and Toval (1975)
Galicia	PPM	ONLS	Sánchez-Rodríguez *et al*. (2003)
	GADA	DVM	Diéguez-Aranda *et al*. (2005c)
Pinus sylvestris			
Whole country	GCM	OLS	Pita (1964)
Iberian Mountain	GCM	OLS	García Abejón (1981)
Central Mountain	GCM	OLS	García Abejón and Gómez Loranca (1984)
Pyrenees	GCM	OLS	García Abejón and Tella (1986)
Pyrenees, and Central and Iberian Mountain Ranges	ADA	ML	Ortega (1989)
Central Mountain	GCM	ONLS	Rojo and Montero (1996)
High Ebro Basin	PPM	ONLS	Bravo and Montero (2001)
Navarra	GCM	OLS	Puertas (2003)
Catalonia	ADA	ONLS	Palahí *et al*. (2004b)
Galicia	ADA	ONLS	Diéguez-Aranda *et al*. (2005a)
Castilla y León (Afforestations)	ADA	ONLS	Río *et al*. (2006)
Pinus uncinata			
Pyrenees	GCM	OLS	Pita (1967a)
	ADA	ONLS	Calama *et al*. (2004)

[1] GCM: Guide Curve Method (includes also some variants and previous methods); PPM: Parameter Prediction Method; ADA: Algebraic Difference Approach; GADA: Generalized Algebraic Difference Approach.

[2] DVM: Dummy Variables Method (Cieszewski *et al*., 2000); ML: Maximum Likelihood (García, 1983); OLS: Ordinary Least Squares; ONLS: Ordinary Nonlinear Least Squares.

Table 4.b. Site index equations for non pine species in Spain

Species and area	Methodology[1]	Fitting procedure[2]	References
Betula alba			
Galicia	GADA	DVM	Dieguez-Aranda *et al*. (2006c)
Eucalyptus globulus			
Galicia	ADA	OLS	Fernández López (1982)
	GCM	OLS	Fernández López (1985)
	ADA	ML	García and Ruiz (2003)
Juniperus thurifera			
Castilla y León	GADA	DVM	Alonso and Madrigal (2007)
Populus x euramericana			
Palencia and León	GCM	ONLS	González-Antoñanzas (1986)
Duero basin	GCM	OLS	Bravo *et al*. (1996)
Populus tremula			
Palencia and León	GCM	ONLS	Bravo *et al*. (2002)
Pseudotsuga menziesii			
Whole country	GADA	DVM	López-Sánchez (2009)
Quecus faginea			
Whole country	GADA	ONLS	López-Senespleda and Sánchez-Palomares (2007)
Quecus ilex			
Whole country (only dehesas)	GADA	DVM	Gea-Izquierdo *et al*. (2008)
Quercus pyrenaica			
León			Torre (1994)
La Rioja			Bengoa (1999)
Castilla y León	GADA	ONLS	Adame *et al*. (2006)
Galicia	GADA	ONLS	Diaz-Maroto *et al*. (2010)
Quercus robur			
Galicia	ADA	ONLS	Barrio-Anta and Diéguez-Aranda (2005)
Quercus suber			
Whole country	ADA	ONLS	Sánchez-González *et al*. (2005)
Fagus sylvatica			
Navarra	GCM	OLS	Madrigal *et al*. (1992)

[1] GCM: Guide Curve Method (includes also some variants and previous methods); PPM: Parameter Prediction Method; ADA: Algebraic Difference Approach; GADA: Generalized Algebraic Difference Approach.

[2] DVM: Dummy Variables Method (Cieszewski *et al*., 2000); ML: Maximum Likelihood (García, 1983); OLS: Ordinary Least Squares; ONLS: Ordinary Nonlinear Least Squares.

inventories, *BALthin* (Trasobares *et al.*, 2004b), for residual trees after thinning, *BALres* (Condés and Sterba, 2008) or for each species in uneven-aged mixed stands (Trasobares and Pukkala, 2004b). Transformations of this index are sometimes used as the ratio between BAL and total basal area (Condés and Sterba, 2004) or the *BALMOD* proposed by Schröder and Gadow (1999) (see also Schröder *et al.*, 2002; Crecente-Campo, 2008). Other competition variables include the crown competition factor developed by

Krajicek *et al.* (1961), which is calculated for residual trees after thinning and mortality by using open-grown equations (Condés and Sterba, 2005) fitted to the main Spanish forest species (Condés and Sterba, 2008). Competition has also been evaluated as the ratio between a tree and stand size indicators. Examples of this are the ratio between diameter at breast height and quadratic mean diameter (Calama and Montero, 2005), the ratio between total height and dominant height (Condés and Sterba, 2008), or the ratio between a section at breast height and stand basal area (Crecente-Campo, 2008).

Independent variables in models can also include stand density or size characteristics. Stand density is usually included as the number of trees per hectare or basal area (see Section 2.b). Dominant height (Calama and Montero, 2005; Adame *et al.*, 2008a; Condés and Sterba, 2008) and stand age (Palahí and Grau, 2003; Palahí *et al.*, 2003; Crecente-Campo, 2008) are the variables most frequently used to describe stand size. Variables such as the diameter distribution skewness and coefficient of variation (Condés and Sterba, 2004) are rarely included. Size is expressed as either untransformed or transformed (squared or logarithm) diameter, to ensure that basal area or diameter will not increase indefinitely. The under-bark diameter at breast height is used (Sánchez-González, 2006) for *Quercus suber* models.

Vigor is usually assessed by crown characteristics. Schröder *et al.* (2002) used the crown spread ratio CSR, calculated as crown width divided by total tree height, while Lizarralde (2008) used crown ratio (crown length divided by total height) as a proxy for tree vigor.

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. Dynamic models derived from the ADA or GADA approaches have been used to project basal area over time (e.g. Río, 1999; Rodríguez *et al.*, 2010). The initial condition values to be introduced into the dynamic equations are usually obtained from a common forest inventory. However, this is not always available, so some models include a basal area prediction equation function (e.g., Palahí *et al.*, 2002; Diéguez-Aranda *et al.*, 2005d and 2006a; Barrio-Anta *et al.*, 2006b; Castedo-Dorado *et al.*, 2007b). For Mediterranean maritime pine, Bravo-Oviedo *et al.* (2004) proposed a logarithmic function that projects basal area growth over a five-year period as a function of the initial basal area, initial age and site index. In some models, the expected variability in basal area growth has been analyzed by including regional and/or thinning effects as categorical dummy variables (e.g. Barrio-Anta *et al.*, 2006b; Castedo-Dorado *et al.*, 2007b; see also Section 5.b).

iii. 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 (see Section 3.b) 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. The two main model development strategies generally used for this (Huang and Titus, 1999) are: (i) equations that directly estimate height growth as a function of tree and stand attributes and other variables such as competition indexes, and (ii) "potential x modifier" equations; in which a simple equation serves as the estimator for the maximum potential value of height growth and is then modified by different variables.

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.*, 2010a) 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.

iv. Volume growth functions

Volume is impossible to measure directly in trees or stands and is therefore an estimated variable. Both current and increment tree or stand volumes must be estimated from tree or stand variables.

Most whole-stand growth models developed to date in Spain do not incorporate volume growth functions explicitly. A combination of three state variables (i.e. number of trees per hectare, stand basal area and dominant height) is usually found to be sufficient for obtaining an adequate stand state description (García, 2003), especially for pure and even-aged stands, which makes the use of stand volume unnecessary. The parsimony principle strengthens the argument for avoiding volume growth functions. Total (or merchantable) tree or stand volume is usually considered as an output variable. It is estimated by prediction functions that use the current or projected values of the state variables with the strongest correlation to tree or stand volume (see Barrio-Anta *et al.*, 2008; Crecente-Campo, 2008). However, some whole-stand growth models developed in Spain have included volume projection functions (Río *et al.*, 2001 and 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). These functions predict the mean annual volume increment as a function of diameter at breast height, total height and mean annual diameter increment.

b. 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 (Westfall *et al.*, 2004). 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. Examples of this approach include yield tables and specific models developed to represent a particular silvicultural regime, such as high-graded Scots pine stands (Bravo and Montero, 2003) and mixed pine-oak management (Sánchez Orois and Rodríguez Soalleiro, 2002). 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 (Section 7.a.). More recent growth models include thinning and fertilization functions to simulate different silvicultural regimes.

Thinning functions should be recognized as either thinning control functions or thinning response functions. The former evaluate immediate changes in forest conditions due to thinning, and the second consider the effects of thinning on growth, since stand growth characteristics and dynamics change after thinning. Several thinning control functions have been fitted for different species in Spain, usually by predicting the quadratic mean diameter after thinning from the same variable before thinning, along with the thinning weight (Río and Montero, 2001; Bravo-Oviedo *et al.*, 2004; Río *et al.*, 2005). In other cases the control function is determined by estimating the parameters of the diameter distribution after thinning (Espinel *et al.*, 1997; Álvárez González *et al.*, 2002). Álvarez González (1997) compared several methods for estimating the diameter distribution after thinning, and found the most accurate to be the prediction based on the Weibull parameters, which include parameters from before thinning as well as the percentage of trees and basal area removed.

Two approaches have commonly been used to estimate the thinning response effect: the development of different basal area growth functions for different types of stands (unthinned and thinned) or 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 first 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 to maritime and radiata pines (Barrio Anta *et al.*, 2006b; Castedo Dorado *et al.*, 2007b).

Castedo-Dorado *et al.* (2004) developed a thinning response function that serves as a reference for evaluating the effects of fertilization treatments after thinning. This has made it possible to analyze the separate effects of thinning and fertilization on basal area growth (Santalla, 2010).

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. Along with several natural (and somewhat unknown) factors, pruning response is also affected by the pruning height.

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. Parallel growth trends between treated and non-treated stands for a given age show the treated stands to be at a more advanced stage of development. A growth multiplier coefficient can be calculated from an existing model, as was suggested by Carson *et al.* (1999):

$$m = \frac{F^{-1}(C_2) - F^{-1}(C_1)}{t_2 - t_1} \qquad (1)$$

where: t_2 and t_1 are the final and initial ages at which the observations were made, $F^{-1}(C_2)$ is the age corresponding to a particular value of C_2, according to the model, $F^{-1}(C_1)$ is the age corresponding to a particular value of C_1, and m is the growth multiplier. 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). Other effects, such as the response to phosphorous fertilizer, are likely to be Type 2 responses, but long-term analyses of growth effects are needed to confirm this (Santalla, 2010).

c. Demography

i. 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. These require the establishment of seed traps (to estimate seed shadows) along with the spatial coordinates of the seed traps and seed sources. Inverse modeling relies on numerically intensive calculations of the likelihood of obtaining the observed seed shadow using a particular dispersal model. Popular models for kernel fitting are lognormal, 2Dt and two-parameter Weibull dispersal functions (see Greene *et al.*, 2004 for a comparison of these models). Tree fecundity can be estimated by the model itself, but is more frequently included in the model as a function of tree size (diameter) or direct seed counts. Alternatively, genetic markers, such as microsatellites, can be used to establish seed or seedling sources. In this case, two-parameter dispersal kernels from the exponential-power family are commonly used. This curve family is able to accommodate a wide range of functions (Gaussian, exponential) and also allows for fat-tailed long-distance dispersal.

In Spain, there are different ongoing studies to determine seed dispersal kernel fittings for various forest trees and shrubs, such as English yew, *Prunus mahaleb*, oak, beech and pine. In *Prunus mahaleb*, the best-fitting dispersal kernels are very leptokurtic, resulting in large average seed dispersal distances of more than 100 m (Robledo-Arnuncio and García, 2007). Unpublished results using both inverse modeling and genetic markers for *Pinus pinaster* on the Castilian Plateau showed much shorter (about half) mean seed wind-dispersal distances. Models that best fitted the observed data were log-normal and fitted better in a sampling design consisting of many small seed traps rather than fewer but larger traps. Interestingly, five-fold variation in dispersal distances was found for different dates in the same dispersal season, probably due to local climate factors such as storms. In addition, dispersal kernels based on established regeneration in *Pinus pinaster* had larger average dispersal distances than those based on seed shadows, indicating Janzen-Connell effects (González-Martínez *et al.*, 2006). Such effects highlight the importance of post-dispersal mortality in tree population structure and dynamics.

There is a need to go beyond simple exponential curves and develop more explicit representation of dispersal kernels in growth and yield models. Along these lines, the integration of a recruitment behavior that includes dispersal functions into popular growth models such as SORTIE is promising. However, parametrization of the dispersal model for different forest trees would necessarily involve specific studies for selected model species, based on their reproductive system and life-history traits. It could be difficult to fit the distribution tails (i.e. long-distance dispersal) due to scarce and unreliable data.

ii. 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, Ávila (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, mainly for pine species in the Meditarrenean area. Results are available for *Pinus nigra* (Ordóñez *et al.,* 2004, Ordóñez and Retana, 2004), *Pinus halepensis* (de las Heras *et al.*, 2002, Pausas *et al.*, 2004, Broncano *et al.*, 2008), *Pinus sylvestris* (Nuñez *et al.*, 2003) and *Pinus pinaster* (Calvo *et al.*, 2008, Vega *et al.*, 2010). Data from these experiments and other monitoring studies will be used to develop multiplicative type models for predicting the number of seedlings established, by incorporating different independent variables such as seed production, primary and secondary dispersion, germination rate as a function of environmental conditions and establishment success as a funcition of environmental conditions and interaction with other species.

iii. Mortality models

Tree mortality plays a huge part in forest dynamics, as it reduces competition and leads to self-thinning. There are three types of stress factors that cause tree vigour to decline and affect tree survival (Manion, 1981 in Pedersen, 1998): predisposing factors, inciting factors, and contributing factors. Mortality has been divided in two categories: regular, non-catastrophic or competition-induced mortality and irregular or catastrophic mortality. The first category has been studied at both the stand and tree level. 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) adapted the model proposed by Clutter and Jones (1980) to estimate mortality in unthinned stands, 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.* (2005e) derived mortality functions from differential equations in Galicia for even-aged *Pinus radiata* and *Pinus sylvestris* plantations, respectively.

There are two possible status values for an individual tree at a certain point in time: the tree is either alive or dead, so the response is typically binary. This also happens at stand level and is demonstrated by the fact that a relatively high number of permanent sample plots have no occurrences of mortality, even over periods of several years (Monserud and Sterba, 1999; Eid and Tuhus, 2001). Woollons (1998) suggested a two-step modeling strategy to account for the binomial nature of mortality: a logistic function predicting the probability of survival using all sample plots and an equation to determine tree density reduction, fitted only with the sample plots where mortality occurs. The estimates derived from the tree-number reduction equation are modified using deterministic or stochastic approaches (Monserud and Sterba, 1999). Álvarez González *et al.* (2004) compared three of these approaches, while Diéguez-Aranda *et al.* (2005e) made an alternative comparison that estimates tree number reduction without considering the probability of survival (i.e., a function for predicting the reduction in tree number that was fitted to include all plots –with and without occurrence of mortality). Both of them found that the three methods of the two-step modeling strategy provided satisfactory predictions. Diéguez-Aranda *et al.* (2005e) suggest that the second approach may be a good alternative when natural mortality is very frequent.

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.* (2010b) used a multilevel logistic approach for predicting individual-tree mortality for *Quercus pyrenaica* from National Forest Inventory data. The application of these models requires the selection of a cut-off or threshold to determine if the tree is dead or alive. This threshold can be deterministic (survival rate or the point where sensitivity and specificity curves cross) or a random deviate. The logistic model can be used to classify trees according to their status (alive or dead) or to make predictions of survival rates. However, prediction and classification do not follow the same pattern (Bravo-Oviedo *et al.*, 2006) and model users should select the best option according to management objectives.

iv. 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-Soallerio, 2002), Scots pine and Mediterranean maritime pine in Central Spain (Bravo *et al.*, 2008) and *Quercus pyrenaica* (Adame *et al.*, 2010a) 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.

Sánchez-Orois and Rodríguez-Soallerio (2002) included basal area and number of stems per hectare as predictors for 10 year ingrowth projections for Maritime pine and accompanying broadleaf species. Bravo *et al.* (2008) used stand-level variables (basal area and quadratic mean diameter) as predictor variables, which together resulted in a model, that predicted 5 year basal area ingrowth equal to 63.5% for Scots pine and to 70.0% for Maritime pine. Finnally, Adame *et al.* (2010a) used quadratic mean diameter, average height, number of trees per hectare and average diameter as predictor variables. They obtained a 71.7% correct classification of ingrowth events but only a 0.358 coefficient of determination in the 10 year linear model for the amount of ingrowth.

d. Output functions

i. 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 (1967b). 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.*, 2009c), *P. radiata* (Castedo-Dorado and Álvarez González, 2007c), *Populus x 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 fire-wood) or with the greatest distribution area, as *Quercus ilex* (Ferres *et al.*, 1980; Canadell *et al.*, 1988; Canadell and Roda, 1991), *Q. pyrenaica* (González Doncel, 1989; Allué and San Miguel, 1991; San Miguel *et al.*, 1992; Gallego *et al.*, 1993), *Castanea sativa* (Leonardi *et al.*, 1996; Santa Regina, 2000), *Fagus sylvatica* (Santa Regina *et al.*, 1997), *Pinus radiata* (Merino *et al.*, 2003) or *P. sylvestris* (Santa Regina *et al.*, 1997; Montero *et al.*, 2004b). In addition to these studies, Montero *et al.* (2005) fitted biomass models for 32 forest species in order to estimate the amount of carbon fixed by Spanish forests. Later, using SUR (Seemingly Unrelated Regressions) methodology with the additivity property guaranteed and the efficiency increased (Parresol, 1999), individual-tree models were fitted for *Pinus pinaster* and *P. radiata* (Balboa-Murias *et al.*, 2006a), *Quercus robur* (Balboa-Murias *et al.*, 2006b) as well as *Betula alba*, *Eucalyptus globulus* and *E. nitens* (reported in Diéguez-Aranda *et al.*, 2009). Stand biomass models were developed for *Pinus pinaster* (Barrio-Anta *et al.* 2006a) and *P. radiata* (Castedo-Dorado *et al.*, 2009b) with this methodology, using stand variables as predictors. The biomass models proposed by Montero *et al.* (2005) are currently being revised to include the additivity property and incorporate tree diameter and height as independent variables (Ruiz-Peinado *et al.*, 2011).

ii. Taper equations

Accurate predictions involving wood products classified by merchantable sizes are a matter of interest for forest managers in Spain and many parts of the world. Volume prediction to any merchantable limit can be achieved by several methods, two of which are commonly applied. The first is to develop volume-ratio equations and the second involves elaborating an equation to describe the stem taper. Integration of the taper equation from the ground to any height provides an estimate of the merchantable volume to that height.

Taper functions provide forest managers with estimates of (i) diameter at any point along the stem, (ii) total stem volume, (iii) merchantable volume and merchantable height to any top diameter and from any stump height, and (iv) individual volumes for logs of any length at any height from the ground.

Data pairs of diameter and height along the stem are required for developing a taper function. This data was typically collected in Spain through destructive stem analysis, but now digital dendrometers are used (Rodríguez *et al.*, 2009). Most taper functions that have been developed in Spain can classified as single taper models, segmented taper models, and variable-form taper models. Ideally, a taper equation should also be *compatible*; in other words the volume computed by a taper equation from the ground to the top of the tree should be equal to that calculated by a total volume equation (Demaerschalk, 1972; Clutter, 1980). The existing research indicates that segmented models appear to be more accurate than the others for creating compatible systems (e.g., Jiang *et al.*, 2005).

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 (Table 5). Due

Table 5.a. Taper equations developed to the date for the major species in Spain, including the sample of trees used, the compatibility with a volume function and the implementation in growth simulators or specific programs

Species	Area	Goodness of fit (R^2)	Compatibility with a volume function	Implementation	Join validation	References
Eucalyptus globulus	Galicia[1]	0.985	YES	TCCP	None	Diéguez-Aranda *et al.* (2009)
Fagus sylvatica	Castilla y León	0.983	NO	cubiFOR	Cross-validation	Rodríguez (2010)
	Navarra	0.975	YES	WinCP Navarra	None	Dieguez-Aranda *et al.*(2007)
Juniperus thurifera	Castilla y León	0.96	NO	cubiFOR	Cross-validation	Rodríguez (2010)
Pinus canariensis	Canary Islands	0.906	NO	cubiFOR	Independent Sample	Martínez and Herranz (2006)
Pinus halepensis	Middle Ebro Valley	0.958	NO	cubiFOR	None	Cabanillas (2010)
Pinus nigra	Castilla y León	0.993	NO	cubiFOR	Cross-validation	Rodríguez (2010)
Pinus pinaster subsp. atlantica	Galicia[1]	0.989	NO	TCCP	Cross-validation	Rojo *et al.* (2005b)
Pinus pinaster subsp. mesogeensis	Castilla y León	0.977	NO	cubiFOR	Cross-validation	Rodríguez (2010)
	Southern Iberian Range	0.977	NO	SIMANFOR	Cross-validation	Lizarralde (2008)
Pinus pinea	Castilla y León	0.971	NO	cubiFOR	Cross-validation	Rodríguez (2010)
	Spain	0.954	YES	PINEA	None	Calama and Montero (2006)
Pinus radiata	Asturias	0.989	YES	-	None	Canga (2007)
	Basque Country	0.983	NO	cubiFOR	Cross-validation	Rodríguez (2010)
	Canary Islands	0.894	NO	cubiFOR	Split Sample	Martínez and Herranz (2006)
	Catalonia	0.995	NO	CUBICA	None	Badía *et al.* (2001)
	El Bierzo (León)	0.989	YES	-	None	Sevillano-Marco *et al.* (2009)
	Galicia[1]	0.989	YES	GesMO	None	Castedo-Dorado *et al.* (2007a)

[1] These models have been updated in Diéguez-Aranda et al. (2009),

[2] This model has been updated in Rodríguez (2010),

[3] It has been considered valid for the whole Spain but this work compares the main 6 mountain ranges in Spain (Northern Iberian Range, Central Range, Galician mountains, Southern Iberian Range, Soria and Burgos Mountains, Pyrenees) and an equation is obtained for each range.

Table 5.b. Taper equations developed to the date for the major species in Spain, including the sample of trees used, the compatibility with a volume function and the implementation in growth simulators or specific programs

Species	Area	Goodness of fit (R^2)	Compatibility with a volume function	Implementation	Join validation	References
Pinus sylvestris	Castilla y León[1]	0.982	NO	cubiFOR and SIMANFOR	Cross-validation	Lizarralde (2008)
	Galicia[2]	0.987	YES	GesMO	None	Diéguez-Aranda *et al.* (2006b)
	Spain[3]	0.982	YES	-	None	Crecente-Campo *et al.* (2009c)
Pinus uncinata	Spain[2]	0.970	NO	-	None	Calama *et al.* (2004)
Populus x euramericana cv. Canadá Blanco	Navarra	0.982	NO	-	None	Rodríguez and Molina (2003)
Populus x euramericana cv. I214	Navarra	0.989	NO	-	None	Rodríguez and Molina (2003)
	Aragón	0.992	NO	cubiFOR	Cross-validation	Rodríguez (2005)
	Central plateau	0.991	YES	-	None	Barrio-Anta *et al.* (2007b)
	Castilla y León	0.995	NO	cubiFOR	Cross-validation	Rodríguez (2010)
Populus x euramericana cv. Luisa Avanzo	Aragón	0.994	NO	cubiFOR	Cross-validation	Rodríguez (2005)
Populus x euramericana cv. MC	Aragón	0.995	NO	cubiFOR	Cross-validation	Rodríguez (2005)
	Navarra	0.983	NO	-	None	Rodríguez and Molina (2003)
Pseudotsuga menziesii	Spain[1]	0.988	YES	-	None	López-Sanchez (2009)
Quecus pyrenaica	Castilla y León	0.985	NO	cubiFOR	Cross-validation	Rodríguez (2010)
Quercus robur	Galicia	0.978	YES	TCCP	None	Barrio-Anta *et al.* (2007a)

[1] This model has been updated in Rodríguez (2010),

[2] These models have been updated in Diéguez-Aranda et al. (2009),

[3] It has been considered valid for the whole Spain but this work compares the main 6 mountain ranges in Spain (Northern Iberian Range, Central Range, Galician mountains, Southern Iberian Range, Soria and Burgos Mountains, Pyrenees) and an equation is obtained for each range.

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). They can also be submodels within complete growth and yield models for implementation in growth simulators such as GesMO (González-González *et al.*, 2009 available in Diéguez-Aranda *et al.*, 2009 and in www.usc.es/uxfs) or Simanfor (Bravo *et al.*, 2010 available at *www.simanfor.es*).

iii. 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; in fact their profitability sometimes exceeds that of timber products (Palahí *et al.*, 2009). Other indirect functions such as recreation can be included in forest production. Given their importance, information that aids prediction and clarifies requirements for optimal NWFP productivity should be integrated into forest management decisions and silvicultural practices. Several NWFP models have been developed in Spain in recent years (Table 6) for most non-timber production species (for example, *Pinus pinea*, *Quercus suber*, *Pinus pinaster* and *Pinus spp.*, for mushroom producing areas).

Most of the approaches to modeling stone pine cone production have evaluated the inclusion of different tree or forest stand parameters such as:

- tree size (Cañadas, 2000; Piqué, 2003; Calama and Montero, 2007), large trees are associated with greater production;
- tree level competition (Calama *et al.*, 2008b);
- stand density (GarcíaGüemes, 1999; Cañadas, 2000; Piqué, 2003; Calama *et al.*, 2008b), low density forest stands are recommended for fruit production;
- stand maturity (García Güemes, 1999);
- site index (Cañadas, 2000; Calama *et al.*, 2008b).

Site characteristics and soil attributes (Calama *et al.*, 2008b) are significant factors in predicting the cone yield for a given period. However, the effect of climate or other ecological factors on the variability of cone production is very important. Climatic factors such as rainfall and temperature before flowering explain much of the yearly variation in yield (Mutke *et al.*, 2005, Calama *et al.*, 2011).

Quercus suber is the most economically important NWFP species, and a few models have been elaborated for it (Table 6). In the model developed by Montero (1987), the independent variables selected were a compromise between simplicity of measurement and approximation to the real stripped surface. Three models have been developed using three different methodologies for estimating total cork thickness at the time of debarking: linear regression (González-Adrados *et al.*, 2000), ordinary kriging (Montes *et al.*, 2005) and mixed models (Sánchez-González *et al.*, 2007a). For cork thickness estimation by complete years, Sánchez-González *et al.* (2008) used the GADA formulation derived by Krumland and Eng (2005) from the Richards model, which has a reliability that ranges from almost 80% starting in the fourth year of cork rotation to nearly 90% from the eighth year onwards. 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.*, 2007d) using a taper equation.

Models have recently been developed (Bonet *et al.*, 2008; Bonet *et al.*, 2010) that attempt to estimate wild mushroom production in pine forests of the Central Pyrenees. Based on their own mushroom inventory (Bonet *et al.,* 2004) collected in 24 Scots pine plots over a three year period, Bonet *et al.* (2008) developed an empirical mixed model that established the relationship between species richness, the production of total, edible and marketable mushrooms, and stand and site factors. The results showed that production was greatest when stand basal area was approximately 20 m^2/ha, and species diversity (measured as number of species, Shannon index and Simpson index) was greatest when stand basal area varied between 15 and 25 m^2/ha. Using the same approach with new yearly mushroom inventories and a second set of 21 plots in *P. sylvestris*, *P. nigra* and *P. halepensis* forests (Martínez de Aragón *et al.*, 2007) in the county of Solsonès (Spain), Bonet *et al.* (2010) were able to establish new empirical models for pine forests. The results were similar to the previous studies, showing maximum mushroom productivity with 15-20 m^2/ha of stand basal area. Aspect, slope and elevation were also predictors of mushroom productivity.

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, using maximum likelihood to estimate resin-yield distribution parameters. 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. The need to use independent variables would be eliminated by employing spatial autocorrelation in conjunction with classical variogram analyses and a subsequent kriging interpolation. This geostatistical model can be used to identify stands with higher resin production capacity but it can not be extended to non-sampled stands.

Table 6a. Main existing models for NWFP in Spain

Area	**Model type**	**Dependent variable**	***Independent variables***				**Goodness of fit**	**Observations**	**References**
			Size	***Age***	***Dens***	***Site***			
Quercus suber									
Spain (divided in 6 areas)	Linear model without intercept	Fresh cork weight (Kg/tree)	$cuc \cdot sh$ $coc \cdot sh$				R^2=0.86-0.99	For each area two models (one using *cuc* and another using *coc*)	Montero (1987)
Spain	Linear model	Total cork thickness at the time of debarking (mm/tree)	cc_{-1} cc_{-2} cc_{-3}				R^2=0.92-0.99	Validation on a new sample	González-Adrados *et al.* (2000) Vázquez Piqué (2002)
Sestrica cork oak forest	Geostatistical model	Total cork thickness at the time of debarking (mm)					SE=3.90 CV=0.18	Ordinary kriging	Montes *et al.* (2005)
Spanish cork oak forests	Mixed model	Total cork thickness at the time of debarking (mm)					RMSE=4-8	Calibrable model for new locations	Sánchez-González *et al.* (2007a)
Spanish cork oak forests	GADA	Accumulated cork thickness in complete years (mm)	cc_{ti}	ti			R^2=0.99	Cross-validation	Sánchez-González *et al.* (2008)
Spanish cork oak forests	Non-linear model	Virgin cork dob_i thickness (mm)					R^2=0.72	Simultaneously fitted using SUR	Sánchez-González *et al.* (2007d)

Where cuc: circumference under cork (m); coc: circumference over cork (m); sh: stripping height (m); cc-1: accumulated cork thickness one year before debarking (mm); cc-2: accumulated cork thickness two years before debarking (mm); cc-3: accumulated cork thickness three years before debarking (mm); ccti: accumulated cork thickness at ti (mm); ti: any complete year of the cork rotation; dobi: diameter over virgin cork at height hi; G: stand basal area (m2/ha); Asp: aspect (rad); Slo: slope (%); Ele: elevation (m above see level); t: age of tree (years), t20.: dummy variable indicating if stand age is under 20; N: density (trees/ha); dg: quadratic mean diameter (cm); H0: dominant height (m); d: normal diameter of tree (cm); CCF: crown competition factor (%); Lcot: total longitude of tree crown (m); pp-3, T-3: different rainfall and temperature events occurring from three years before cone maturation; NU: soil stratification on Northern Plateau; RMSE: root mean square error; MSE: mean square error; SI: site index, EF: model efficacy

Table 6b. Main existing models for NWFP in Spain

Area	**Model type**	**Dependent variable**	***Independent variables***				**Goodness of fit**	**Observations**	**References**
			Size	***Age***	***Dens***	***Site***			
Pinus pinaster									
Meseta Castellana	Probability distribution model	Resin (Kg/tree)					Not reported	No predictive potential	Nanos *et al.* (2000)
Meseta Castellana	Geostatistical model	Resin(Kg/tree)					Not reported	Ordinary kriging	Nanos *et al.* (2000)
Pinus spp. Forests (*P. sylvestris, P. nigra, P. halepensis*)									
Central Pyrenees	Mixed model (linear/non-linear)	Mushrooms (Kg/ha) Mushrooms diversity (N species/100 m^2)			*G*	Slo Asp	Mixed models	Empirical model, including stand and site variables	Bonet *et al.* (2008)
Central Pyrenees	Mixed model (linear/non-linear)	Mushrooms (Kg/ha) Mushrooms diversity (N species/100 m^2)			*G*	Slo Asp Ele	Mixed models	Empirical models, with stand and site variables. Including plot and year factor models (Year factor correlating with autumn rainfall)	Palahí *et al.* (2009) Bonet *et al.* (2008)

Where cuc: circumference under cork (m); coc: circumference over cork (m); sh: stripping height (m); cc-1: accumulated cork thickness one year before debarking (mm); cc-2: accumulated cork thickness two years before debarking (mm); cc-3: accumulated cork thickness three years before debarking (mm); ccti: accumulated cork thickness at ti (mm); ti: any complete year of the cork rotation; dobi: diameter over virgin cork at height hi; G: stand basal area (m2/ha); Asp: aspect (rad); Slo: slope (%); Ele: elevation (m above see level); t: age of tree (years), t20.: dummy variable indicating if stand age is under 20; N: density (trees/ha); dg: quadratic mean diameter (cm); H0: dominant height (m); d: normal diameter of tree (cm); CCF: crown competition factor (%); Lcot: total longitude of tree crown (m); pp-3, T-3: different rainfall and temperature events occurring from three years before cone maturation; NU: soil stratification on Northern Plateau; RMSE: root mean square error; MSE: mean square error; SI: site index, EF: model efficacy

Table 6c. Main existing models for NWFP in Spain

Area	Model type	Dependent variable	*Independent variables*				Goodness of fit	Observations	References
			Size	*Age*	*Dens*	*Site*			
Pinus pinea									
Northern Plateau	Linear/Non-linear model	Cones (Kg/ha)	*dg*	*t*	*N* *G*		R^2=0.53 R^2=0.63 R^2=0.94	4 descriptive models (each one using just one independent variable)	García- Güemes (1999)
Central Range	Linear/Non-linear model	Cones (Kg/tree)	*d*		*N* *CCF*	H_0	MSE= 12.74-13.34	2 descriptive models (one using N and another using CCF)	Cañadas (2000)
Northern Plateau	Linear model	Weight of nuts (kg/tree)	*d*		*1/N*	Plot	R^2=0.80	Descriptive model for genetic selection Five year average value	Mutke *et al.* (2001)
Catalonia	Linear/Non-linear model	Weight of cones ln (Kg/tree)+1	*d* *Lcot* *dg*		*N*	H_0	EF=0.38-0.43	2 descriptive models (one using Lcot and another only using d as a tree level variable)	Piqué (2003)
Northern Plateau	Mixed model (linear/non-linear)	Weight of cones (kg/tree)	*g* *d/dg*		*N*	NU	EF=0.39 RMSE= 4.002	Five year average tree scale	Calama *et al.* 2008b
Northern Plateau	Zero inflated-log normal	Weight of cones (kg/tree.year)	*d* *d/dg*	t_{20}	*N*	NU pp_3 T_3	EF=36% tree x year EF=51% Plot x year	Annual scale. Two models: presence-absence and abundance. Independent validation set	Calama *et al.* 2011
Northern Plateau	Linear model	Weight of cones (kg/ha)				pp_3 T_3	R^2=0.708	Regional scale	Mutke *et al.* (2005)
Central range	Mixed model (linear / non-linear)	Nut weight Nut yield	Average cone weight			SI	EF=43% EF=39%	Simultaneous models	Calama and Montero (2007)

Where cuc: circumference under cork (m); coc: circumference over cork (m); sh: stripping height (m); cc-1: accumulated cork thickness one year before debarking (mm); cc-2: accumulated cork thickness two years before debarking (mm); cc-3: accumulated cork thickness three years before debarking (mm); ccti: accumulated cork thickness at ti (mm); ti: any complete year of the cork rotation; dobi: diameter over virgin cork at height hi; G: stand basal area (m2/ha); Asp: aspect (rad); Slo: slope (%); Ele: elevation (m above see level); t: age of tree (years), t20.: dummy variable indicating if stand age is under 20; N: density (trees/ha); dg: quadratic mean diameter (cm); H0: dominant height (m); d: normal diameter of tree (cm); CCF: crown competition factor (%); Lcot: total longitude of tree crown (m); pp-3, T-3: different rainfall and temperature events occurring from three years before cone maturation; NU: soil stratification on Northern Plateau; RMSE: root mean square error; MSE: mean square error; SI: site index, EF: model efficacy

6. Validation and calibration models

Model evaluation is the process of qualitative and quantitative examination of the model to ensure that model predictions reflect the most likely real outcome (Soares and Tomé, 2007). According to Vanclay (1994), part of this process should be to expose any errors and deficiencies in the model by establishing: i) whether the equations used adequately represent the processes involved; ii) if the equations have been combined correctly in the model; iii) whether the numerical coefficients obtained in fitting the model are the best estimates; iv) whether the model provides realistic predictions throughout the likely range of application; v) if the model satisfies specified accuracy requirements; vi) how sensitive model predictions are to errors in estimated coefficients and input variables.

Based on these six principles, a model evaluation should provide as much information as possible about the model's behaviour and predictive ability. This allows the people affected by the decisions based on these models to decide whether or not the models represent the real world accurately enough for their intended uses. Soares *et al.* (1995) pointed out that "model evaluation should not be a mere afterthought to model construction, but should be considered at every stage of model design and construction, when component functions are formulated and fitted to data, and when these components are assembled to provide the completed model".

There is no universal approach to model evaluation, but it usually includes qualitative and quantitative aspects. Qualitative evaluation examines the structure and properties of the model to verify that it is logically consistent and biologically realistic. Types of analyses can vary according to the modeling approach used, the purpose of the model, its complexity, and its generality. According to Oderwald and Hans (1993) a qualitative evaluation should at least confirm: i) the absence of contradictions within the complete model and among submodels; ii) that the variables included and omitted from the model meet expectations; iii) the signs and values of parameters; iv) that estimates outside the range of the development data are reasonable and v) that limits and derivatives (maxima, minima, inflexion points) are in agreement with current forestry growth theories. The first three features are included in most of the forest growth models developed in Spain, but the last two are not usually addressed.

Quantitative evaluation is based on the comparison of model results with observations. Graphical analysis and the use of statistical indices and tests are the usual methods for comparison and should include an analysis of the model performance and robustness as well as a detailed characterization of errors (bias and precision of the model and its components, distribution of residuals, dependencies of residuals on initial stand conditions and length of projection, correlations over time and between components, confidence intervals and critical errors, contributions by each model component to total error, etc.).

The data used for quantitative evaluation should be independent from the observations used to structure the model and estimate its parameters. Unfortunately, such observations are not usually available, and foresters generally use one of two alternatives: i) to randomly split the data set into model estimation and model testing subsets; ii) to use re-sampling techniques. However, some researchers have questioned whether these methods (especially the first one) actually provide relevant information for quantitative model evaluation, when compared to error characterization from the entire data set (Kozak and Kozak, 2003). Both approaches have been widely used in Spain for modeling forest dynamics. The use of re-sampling techniques for double cross-validation is currently the most commonly used criterion for model evaluation, until a new and independent data set for assessing the true quality of the predictions becomes available. Finally, Vanclay and Skovsgaard (1997) emphasized that the validity of conclusions drawn from all these model evaluation procedures depends on the validity of the assumptions underlying both the model and the evaluation.

Growth and yield model calibration to geographical areas or forestry practices different from those in which the original data were obtained is one of the most challenging situations for end-users. In practice, calibration of a normal yield table prediction based on the ratio between actual basal area and basal area from the table is routinely done by assuming that the model is correct in shape but not in value, and then applying the necessary scalar modification. However, this method relies on the hypothesis that there are no differences between the silvicultural treatments applied in the stands used to elaborate the model and the stands where the model is going to be used. This leaves room for alternative calibration systems. Bravo and Montero (2003) proposed adding to their static volume model a simple linear component that included dominant height as an independent variable. The model efficiency increased from 0.4964 to 0.9856 with this approach.

7. Interfaces

a. 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.

Yield tables are static models because they are elaborated from a single measurement. Occasionally they use data from plots inventoried more than once, but unlike dynamic models they disregard growth when applying methodologies for adjusting the equations used. Therefore, yield tables must be differentiated from numerical tables or charts generated from dynamic growth models (see Section 7.c). Dynamic growth models have a format similar to that of the yield tables but describe evolution using the age of the variables of an even-aged stand.

To understand and apply yield tables correctly, it is essential to bear in mind that they are based on stands in which trees uniformly cover the entire surface, which is not always true. The yield and growth values of the tables must be adapted for each stand by using correction factors to account for their different characteristics (see Section 6). Vannière (1984) indicated that yield tables are “an idealized model, valid as an average for a given region and that must be used with caution. They are a certain number of reference points, of average values, but in no case lead to reliable and certain values.” This fact, however, does not diminish their usefulness as a management and planning tool, which is why it has enjoyed such a long tradition of use by so many European foresters (Madrigal, 1991).

A set or family of yield tables is generally used for a species in a given geographical area. The number of tables included in the set is determined by the number of site quality classes that are usually established for the study area (a table is constructed for each site index) and by the number of silvicultural regimes represented in the sample plots used (a table is constructed for each silvicultural treatment within each site quality class). Thus, site index (see Section 5.a-i) is a fundamental variable that must be known in order to use growth and yield models.

Rojo and Montero (1994) elaborated the first comprehensive review of yield tables

Table 7a Spanish yield tables[1]. Broadleaves

Species and area	**Silviculture regimes**	**Observations**	**References**	**Others yield tables**
Betula alba				
Galicia (NW Spain)	MTS	-	Diéguez *et al.* (2009)	Rojo *et al.* (2005a)
Castanea sativa				
Asturias (N Spain)	MOS & TIS	Coppice stands	Cabrera (1997)[2]	Cabrera and Ochoa (1997)
Eucalyptus globulus				
Galicia (NW Spain)	NTC	Different tables for first and second rotation	Fernández López (1982)[2]	-
Galicia (NW Spain)	NTC	Different tables for initial spacing 2x2, 2.5x2.5 and 3x3 m	Fernández López (1985)[2]	-
Northern Spain	NTC	Different tables for initial spacing 1.80x1.80 and 2x2 m	Pita (1966)	-
SW Spain	NTC	Different tables for sandy and slaty soils	Madrigal *et al.* (1977)[2]	Echeverría (1952); Pardo (1980)
Fagus sylvatica				
Navarra	MOS & TIS	-	Madrigal *et al.* (1992)	-
La Rioja	MOS	-	Ibáñez (1989)[3]	-
Populus x euramericana				
Duero Basin	NTC	For 8x5 m initial spacing plantations	Bravo *et al.* (1996)	González Antoñanzas (1986)
Quercus pyrenaica				
León province	NTC	Coppice stands	Torre (1994)[2]	-
Quercus robur				
Galicia (NW Spain)	MOS	Different tables for two possible density evolutions	Diéguez *et al.* (2009)	Barrio-Anta (2003)
Quercus suber				
Spain (whole country)	MOS	Dehesas and open woodlands with basal area < 14 m^2/ha	Montero *et al.* (1996)	-
Spain (whole country)	MTS	Even-aged and full stocked stands with 12 to 23 m^2/ha of basal area	Montero and Cañellas (1999)	-

MOS: Mean Observed Silviculture, MTS: Mean Theoretical Silviculture (theoretic evolution of stems number), TIS: Theoretical Intensive Silviculture (theoretic evolution of stems number), RIS: Real Intensive Silviculture, NTC: No Thinnings are Considered, SD: Silviculture in Demand.

[1] Numerical tables or charts generated from dynamic growth models, which describe the evolution with age of the variables of an even-aged stand with a format similar to that of the yield tables (see section 7.c), are not included.

[2] Unpublished. Available in Madrigal *et al.* (1999).

[3] Unpublished.

Table 7b Spanish yield tables[1]. Conifers

Species and area	Silviculture regimes	Observations	References	Others yield tables
Pinus halepensis				
Spain (whole country)	MOS& TIS	-	Montero *et al.* (2001b)	Montero *et al.* (2000)
Pinus nigra				
IIberian Mountain Range	MOS & TIS	-	Gómez Loranca (1996)	-
Navarra Region	MOS & TIS	*Pinus nigra* ssp. *austriaca*	Eraso *et al.* (1996) [3]	-
Pyrenees	SD	-	González Molina *et al.* (1999)	-
Sierra de Cazorla, Segura y las Villas (S Spain)	MOS & TIS	-	Bautista *et al.* (2005)	Bautista *et al.* (2001)
Pinus pinaster				
Central Mountain Range	MOS & TIS	-	García Abejón and Gómez Loranca (1989)	-
Galicia (NW Spain)	MOS & TIS	-	Martínez Millán and Madrigal (1992) [3]	Echeverría and De Pedro (1948); Molina and Ruiz (1976)
León province	MOS	Different tables for three possible density evolutions	Santamaría *et al.* (2009)	-
Pinus pinea				
Catalonia (NE Spain)	MOS & TIS	Different tables for two possible density evolutions	Piqué (2003)	-
Pinus radiata				
Basque Country (N Spain)	MOS	-	Madrigal and Toval (2009)	-
Basque Country (N Spain)	MOS & TIS	-	Muñoz (1985)	-
Galicia (NW Spain)	MOS	Different tables for three possible density evolutions	Sánchez Rodríguez *et al.* (2003)	Echeverría (1942); Sánchez Rodríguez (2001)
Asturias (N Spain)	MOS	Different tables for three possible density evolutions	Canga (2007)	-
Pinus sylvestris				
Sierra de Guadarrama (Central Mountain Range)	MOS & RIS	Different tables for two possible density evolutions in the intensive silviculture	Rojo and Montero (1996)	García Abejón and Gómez Loranca (1984); Picardo (1985); Rojo (1994)
Iberian Mountain Range	MOS & TIS	-	García Abejón (1981)	-
Pyrenees	MOS	-	García Abejón and Tella Ferreiro (1986)	-
Galicia (NW Spain)	MOS & TIS	Different tables for two possible density evolutions	Martínez Chamorro (2004)	-
Navarra	MOS & TIS	Different tables for two possible density evolutions	Puertas (2003)	
Pseudotsuga menziesii				
Spain (whole country)	MOS	-	López-Sánchez (2009)	López-Sánchez *et al.* (2009)

For variable description and notes see table 7a 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. Since then, numerous yield tables have been elaborated in Spain and are available for these species. The yield tables currently available in Spain are briefly described in Tables 7a and 7b, showing only the most recent tables when several works are available for the same species and regions.

b. 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 (Newton and Weetman, 1994). Two different types of SDMDs have been developed in Spain according to the density indices used for characterizing the growing stock level: *i*) SDMDs based on the relative spacing index (RS) (Hart, 1928, cited in Clutter *et al.*, 1983) and *ii*) SDMDs based on the Reineke index (SD) (Reineke, 1933). SDMDs provide information on the main relationship between average tree size, density or yield and a productivity indicator. All the variables included in those equations are graphically represented in a two-axis diagram from which density management outcomes can be evaluated by mean tree size and stand-level volumetric yields.

If information about any other stand variable related to other aspects of resource management is available (e.g. non-timber resources, carbon pools, biotical and abiotical hazards, wild life management, etc), these variables can also be included in the diagram by fitting new equations and overlaying the information, which facilitates the decision-making process. In Spain, SDMDs have been developed for pine and broadleaf species (Table 8) in Atlantic forests and a few Mediterranean forests.

c. 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 inten-

Table 8.- Stand density management diagrams published Spain

Species and area	Density index	Yield estimation	Risk assessment	Reference
Pinus pinaster				
Central Range	SD	Total volume	No	del Peso *et al.* (2005)
Galicia	RS	Total volume, total and stem biomass and total aboveground carbon	No	Barrio-Anta *et al.* (2006a)
Ourense (NW Spain)	RS	Total volume	Windthrow and Crown fire hazard	Castedo-Dorado *et al.* (2009a)
Eastern Spain	SD	Total volume	No	Valbuena *et al.* (2008)
Pinus halepensis				
Catalonia and Aragón	SD	Total volume	No	Valbuena and Bravo (2005)
Eastern Spain	SD	Total volum	No	Valbuena *et al.* (2008)
Ebro medium valley (NE Spain)	RS	Total volume	No	Cabanillas *et al.* (2009)
Pinus radiata				
Basque country	SD	Total basal area	No	Chauchard and Olalde (2004)
Galicia	RS	Commercial volume, total and stem biomass and total aboveground carbon	Windthrow hazard	Castedo-Dorado *et al.* (2009b)
Quercus robur				
Galicia	RS	Commercial volume	No	Barrio-Anta and Álvarez-González (2005)
Betula alba				
Galicia	RS	Total volume	No	Diéguez-Aranda *et al.* (2009)
Pseudotsuga menziesii				
Spain	RS	Total volume, total aboveground biomass	Windthrow and Crown fire hazard	López-Sánchez and Rodríguez-Soalleiro (2009)
Eucalyptus nitens				
Galicia	RS	Total volume, total biomass and total aboveground carbon	No	Pérez-Cruzado *et al.* (2009)

RS: Relative Spacing index, SD: Stand Density index.

sities 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). Bravo (2001) integrated a model developed for Scots pine in the High-Ebro basin into a Microsoft Excel spreadsheet from which static yield tables can be generated for the economic evaluation of silviculural paths.

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 diferent 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. Models for other species such as for *Betula alba* and *Quercus robur* are being developed and will be added in the future. 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. There is also the possibility of creating and applying "pre-defined silvicultural schemes". 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.*, 2007a and 2007b). 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. Future development of the software will include more regions (Andalucia and Catalonia), extensions of the growth model to uneven-aged stands and afforestations (Calama *et al.*, 2008a; 2009), simultaneous prediction of different stands and simulation schedules and other complements such as annual cone production and pine nut production modules.

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). Its model interface is very similar to PINEA2, since it was programmed using the same environment. 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. It uses the parameterization for two of the most important cork-producing areas in Spain (the Natural Park of Los Alcornocales and Catalonia), and can be considered representative of Spanish cork oak forests. This version is also stochastic, so that a single tree random component can be added into the cork thickness function. Subsequent versions will include a module for low-density cork oak forests (dehesas) and a function that defines site index based on ecological factors.

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. MONTE is organized into various subsystems: 1) database management system; 2) simulation system, based on growth and yield models, fire risk models, etc. (Palahí *et al.*, 2003; Trasobares *et al.*, 2004a; 2004b; González *et al.*, 2006; 2007; Bonet *et al.*, 2008; Blasco *et al.*, 2009); 3) planning system that formulates and solves problems using an optimisation tool (mathematical programming or heuristics) (Pukkala, 2002); 4) sensitivity analysis system. RODAL is a similar information system that supports decision-making at the stand level. It can be applied to even-aged and uneven-aged management, as well as to pure and mixed stands. The optimisation algorithm automatically finds a management schedule for the stand that maximises the user-defined objective function. Multiple management objectives may be included in the planning model, such as land expectation value (Trasobares and Pukkala, 2004a), wood production, net income, biodiversity (Palahí *et al.*, 2004a), mushroom production (Palahí *et al.*, 2009), or fire risk (González *et al.*, 2008).

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. SIMANFOR is under permanent development and three new features will be included in the near future: (*i*) new models, (*ii*) improvement of user-friendly interface and (*iii*) translation into other languages, starting with English and then Portuguese and French. 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.

8. 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.

Vanclay (1994) recommends that information provided by models should be accurate, complete, concise, relevant, appropriate and timely. However, the long time required for developing models, the lack of adequate data sets or the chronic understaffing in universities and research centers all add to the time it takes for forest models to reach a forester's computer. 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 enhace 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 favourable to using models as they develop.

Acknowledgments

The models described in this book were funded by different regional, national and European projects, and some of them were elaborated by the authors. This work was funded by the Spanish Government by the SELVIRED network (code AGL2008-03740) and the strategic project 'Restauración y Gestión Forestal' (code PSE-310000-2009-4).

References

ADAME P., CAÑELLAS I., RÍO M., 2005. Modelo de la relación altura-diámetro para rebollares en Castilla y León. Actas del IV Congreso Forestal Español 4CFE05-365-T1, 320. [In Spanish].

ADAME P., CAÑELLAS I., RÍO M., 2008b. A mixed nonlinear height-diameter model for pyrenean oak (*Quercus pyrenaica* Willd.). For Ecol Manage 256, 88-98.

ADAME P., CAÑELLAS I., RÍO M., 2010a. Ingrowth model for pyrenean oak stands in north-western Spain using continuous forest inventory data. Eur J Forest Res 129(4), 669-678.

ADAME P., CAÑELLAS I., RÍO M., 2010b. Modeling individual-tree mortality in Pyrinean oak (*Quercus pyrenaica* Willd.) stands. Ann For Sci 67, 810 DOI: 10.1051/forest/2010046.

ADAME P., CAÑELLAS I., RÍO M., ROIG S., 2006. Modelling dominant height growth and site index curves for rebollo oak (*Quercus pyrenaica* Willd.). Ann For Sci 63, 929-940.

ADAME P., CAÑELLAS I., HYNYNEN J., RÍO M., 2008a. Individual-tree diameter growth model for rebollo oak (*Quercus pyrenaica* Willd.) coppices. For Ecol Manage 255, 1011-1022.

AFIF-KHOURI E., CÁMARA-OBREGÓN M.A., CANGA-LÍBANO E., OLIVEIRA-PRENDES J.A., GORGOSO-VARELA J.J., 2010. Relationships among soil parametrs, tree nutrition and site index of *Pinus radiata* D. Don in Asturias, NW Spain, Forest Systems 19, 77-88.

ALLUÉ M., SAN MIGUEL A., 1991. Estructura, evolución y producción de tallares de *Quercus pyrenaica* Willd. en el centro de España. Invest Agrar: Sist Recur For 0, 35-48. [In Spanish].

ALONSO R., MADRIGAL G., 2007. Modelo de crecimiento e índice de sitio para *Juniperus thuriphera* en España. Cuadernos SECF 23, 99-106. [In Spanish].

ÁLVAREZ-ÁLVAREZ P., AFIF-KHOURI E., CÁMARA-OBREGÓN A., CASTEDO-DORADO, F., BARRIO-ANTA, M., 2011. Effects of foliar nutrients and environmental factors on site productivity in *Pinus pinaster* Ait. stands in Asturias (NW Spain) *Ann For Sci* 68(3):497-509.

ÁLVAREZ GONZÁLEZ J.G., 1997. Análisis y caracterización de las distribuciones diamétricas de *Pinus pinaster* Ait en Galicia. Doctoral thesis. Universidad Politécnica de Madrid. [In Spanish].

ÁLVAREZ GONZÁLEZ J.G., RODRIGUEZ-SOALLEIRO R., VEGA G., 1999. Elaboración de un modelo de crecimiento dinámico para rodales regulares de *Pinus* *pinaster* Ait en Galicia. Invest Agrar: Sist Recur For 8(2), 319-334. [In Spanish].

ÁLVAREZ GONZÁLEZ J.G., BARRIO ANTA M., RODRÍGUEZ SOALLEIRO R., RUÍZ GONZÁLEZ A.D., 2005. Ecoregional site index models for *Pinus pinaster* in Galicia (northwestern Spain). Ann For Sci 62, 115-127.

ÁLVAREZ GONZÁLEZ J.G., RODRÍGUEZ SOALLEIRO R., RUÍZ GONZÁLEZ A.D., SCHRÖDER J., 2002. Modelling the effect of thinnings on the diameter distribution of even-aged Maritime pine stands. For Ecol Manage 165, 57-65.

ÁLVAREZ GONZÁLEZ J.G., CASTEDO DORADO F., GADOW K.V., LÓPEZ SÁNCHEZ C.A., RUIZ GONZÁLEZ A.D., 2004. A two-step mortality model for even-aged stands of *Pinus radiata* D. Don in Galicia (northwestern Spain). Ann For Sci 61, 439-448.

ÁLVAREZ TABOADA M.F., ÁLVAREZ GONZÁLEZ J.G., BARRIO ANTA M., GORGOSO VARELA J., 2003. Influencia de la competencia en el crecimiento en sección en *Pinus radiata* D. Don. Invest Agrar: Sist Recur For 12(2), 25-36. [In Spanish].

ASSMANN E., 1970. The principles of forest yield study. Pergamon Press, Oxford.

BADÍA M., BROTO M., RODRÍGUEZ F., 2001. Modelos del perfil del árbol. Aplicación al pino radiata (*Pinus radiata* D. Don). III Congreso Forestal Español. Granada, septiembre 2001. Mesa 5: 478-486. [In Spanish].

BALBOA-MURIAS M.A., ÁLVAREZ-GONZALEZ J.G., MERINO A., RODRIGUEZ-SOALLEIRO R., 2006a. Temporal variations and distribution of carbon stocks in aboveground biomass of radiata pine and maritime pine pure stands under different silvicultural alternatives. For Ecol Manage 237, 29-38.

BALBOA-MURIAS M.A., ÁLVAREZ J.G., MERINO A., ROJO A., 2006b. Carbon and nutrient stocks in mature *Quercus robur* L. stands in NW Spain. Ann For Sci 63, 557-565.

BARÁ S., TOVAL G., 1983. Calidad de estación de *Pinus pinaster* Ait, en Galicia. Comunicaciones INIA, Serie Recursos Naturales nº 24. 166 p. Madrid. [In Spanish].

BARNES B.V., DENTON S.R., SPURR S.H., ZAK D.R., 1997. Forest Ecology. John Wiley and Sons, New York. 774 pp.

BARRIO-ANTA M., 2003. Crecimiento y producción de masas naturales de *Quercus robur* L. en Galicia. Doctoral thesis. University of Santiago de Compostela, Lugo. [In Spanish].

BARRIO-ANTA M., ÁLVAREZ-GONZÁLEZ J.G., 2005. Development of a stand density management diagram for even-aged pedunculate oak stands and its use in designing thinning schedules. Forestry 78, 209-216.

BARRIO-ANTA M., DIÉGUEZ-ARANDA U., 2005. Site quality of pedunculate oak (*Quercus robur* L.) stands in Galicia (northwest Spain). Eur J For Res 124, 19-28.

BARRIO ANTA M., ÁLVAREZ GONZÁLEZ J.G., DÍAZ-MAROTO I.J., LOPEZ SÁNCHEZ C.A., 2004. Relación altura-diámetro generalizada para *Quercus robur* L. en Galicia. Cuadernos SECF 18, 141-146. [In Spanish].

BARRIO-ANTA M., CAÑELLAS I., CASTEDO-DORADO F., SIXTO-BLANCO H., 2008. Dynamic growth model for I-214 poplar plantations in the northern and central plateaux in Spain. For Ecol Manage 255, 1167-1178.

BARRIO-ANTA M., ÁLVAREZ-GONZÁLEZ J.G., BALBOA-MURIAS M., CASTEDO-DORADO F., DIÉGUEZ-ARANDA U., 2006a. An ecoregional model for estimating volume, biomass and carbon in maritime pine stands in Galicia (northwestern Spain). For Ecol Manage 223, 24-34.

BARRIO ANTA M., ÁLVAREZ GONZÁLEZ J.G., CASTEDO-DORADO F., DIÉGUEZ-ARANDA U., GADOW K.v., 2007a. Merchantable volume system for pedunculate oak in northwestern Spain. Ann For Sci 64, 511–520.

BARRIO-ANTA M., ÁLVAREZ-GONZÁLEZ J.G., CASTEDO-DORADO F., DIÉGUEZ-ARANDA U., PARRESOL B., RODRÍGUEZ-SOALLEIRO R., 2006b. Development of a basal area growth system for maritime pine in northwestern Spain using the generalized algebraic difference approach. Can J For Res 36(6), 1461-1474.

BARRIO-ANTA M., CAÑELLAS I., GONZÁLEZ-ANTOÑANZAS F., SIXTO-BLANCO H., 2007b. Sistema de cubicación con clasificación de productos para plantaciones de *Populus x euramericana* (Dode) Guinier cv. ‘I-214’ en la meseta norte y centro de España. Invest Agrar: Sist Recur For 16(1), 65-75. [In Spanish].

BAUTISTA R., ALONSO A., GÓMEZ LORANCA J.A., GRAU J.M., 2001. Tablas de producción de selvicultura media para las masas de *Pinus nigra* Arn. de la Sierra de Cazorla, Segura y Las Villas. III Congreso Forestal Nacional, Granada, Septiembre 2001. Mesa 5, 854-859. [In Spanish].

BAUTISTA R., MONTERO G., RÍO M., GRAU J.M., 2005. Tablas de producción de selvicultura varibale para las masas de *Pinus nigra* Arn. de la Sierra de Cazorla, Segura y Las Villas. In: Los pinares de *Pinus nigra* Arn. En España: Ecología, uso y gestión (Grande-Ortíz M.A., García-Abril A. eds.). Fundación Conde del Valle de Salazar, Madrid, pp. 559-584.[In Spanish].

BENGOA J.L., 1999. Análisis de un modelo de crecimiento en altura de masas forestales. Aplicación a las masas de *Quercus pyrenaica* de La Rioja. Doctoral thesis. Universidad Politécnica de Madrid. [In Spanish].

BERTALANFFY L.v., 1949. Problems of organic growth. Nature 163, 156-158.

BERTALANFFY L.v., 1957. Quantitative laws in metabolism and growth. Quarterly Review of Biology 32, 217-231.

BLASCO E., GONZÁLEZ-OLABARRIA J.R., KOLEHMAINEN O., PALAHÍ M., PUKKALA T., RODRIGUÉZ-VEIGA P., 2009. Predicting scenic beauty of forest stands in Catalonia (North-east Spain). J For Res 20(1), 73−78.

BOGINO S.M., BRAVO F., 2008. Growth response of *Pinus pinaster* Ait. to climatic variables in central Spanish forest. Ann For Sci 65, 506-518.

BOGINO S.M., BRAVO F., FERNÁNDEZ NIETO M.J., 2009. Climate effect on radial growth of *Pinus sylvestris* at its southern and western distribution limits. Silva Fennica 43(4), 623-609.

BONET J.A., COLINAS C., FISCHER C.R., 2004. The relationship between forest age and aspect on the production of sporocarps of ectomycorrhizal fungi in *Pinus sylvestris* forests of the central Pyrenees. For Ecol Manage 203, 157-175.

BONET J.A., COLINAS C., FISCHER C.R., MARTÍNEZ DE ARAGÓN J., PALAHÍ M., PUKKALA T., 2008. Empirical models for predicting the production of wild mushrooms in Scots pine forests in the Central Pyrenees. Ann For Sci 65(2), 206. DOI: 10.1051/forest: 2007089.

BONET J.A., COLINAS C., FISCHER C.R., MARTÍNEZ DE ARAGÓN J., MIINA J., PALAHÍ M., PUKKALA T., 2010. Modelling the production and species richness of wild mushrooms in pine forests of Central Pyrenees in north-eastern Spain. Can J For Res 40, 347-356.

BRAVO, F. 2001. Whole Stand Simulator "Alto Ebro" (freely available at *http://sostenible.palencia.uva.es/gfs/rinv/List/Software+de+inter%C3%A9s/3/List.aspx*)

BRAVO F., MONTERO G., 2001. Site index estimation in Scots pine (*Pinus sylvestris* L.) stands in the High Ebro Basin (northern Spain) using soil attributes. Forestry 74, 395-406.

BRAVO F., MONTERO G., 2003. High-grading effects on Scots pine volume and basal area in pure stands in northern Spain. Ann For Sci 60, 11-18.

BRAVO F., GONZÁLEZ ANTOÑANZAS F., GRAU J.M., 1996. Curvas de calidad y tablas de producción para *Populus x euramericana* en la cuenca del Duero. Montes 44, 43-46. [In Spanish].

BRAVO F., ORDOÑEZ A.C., RODRÍGUEZ F., 2010. SimanFor: Sistema de apoyo para la simulación de alternativas de manejo forestal sostenible. Available in www.simanfor.es (last access 15th april 2010). [In Spanish].

BRAVO F., LIZARRALDE, I., ORDOÑEZ, C., PANDO, V., 2008. Modelling ingrowth in mediterranean pine forests: A case study from scots pine (*Pinus sylvestris* L.) and mediterranean maritime pine (*Pinus pinaster* Ait.) stands in Spain. Invest Agrar: Sist Recur For 17(3), 250-260.

BRAVO, F., FÉLIZ DE VARGAS, J.M., LUCAS, A.I., PESO, C. del, RÍO, M. del, 2002. Estructura de los rodales de Populus tremula en la vertiente meridional de la Cordillera Cantábrica Sierra, R. (Coordinator) El álamo temblón (Populus tremula L.) Bases para su cultivo, gestión y conservación, 135-150 Mundi-Prensa ISBN: 84-8476-096-0.

BRAVO F., BRAVO-OVIEDO A., DOMÍNGUEZ DOMÍNGUEZ M., GUERRA BURTON B., LIZARRALDE I., ORDÓÑEZ C., OSORIO VÉLEZ L.F., DEL PESO TARANCO C., 2004. Red de parcelas y experimentos del grupo de investigación sobre gestión forestal sostenible de la ETS de ingenierías agrarias de Palencia (Universidad de Valladolid). Cuadernos SECF 18, 237-242. [In Spanish].

BRAVO-OVIEDO A., MONTERO G., 2005. Site index in relation to edaphic variables in stone pine (*Pinus pinea* L.) stands in south west Spain. Ann For Sci 62, 61-72.

BRAVO-OVIEDO A, MONTERO G, RÍO M, 2004. Site index curves and growth model for Mediterranean maritime pine (*Pinus pinaster* Ait.) in Spain. For Ecol Manage 201, 187-197.

BRAVO-OVIEDO A., MONTERO G., RIO M., 2007. Geographic variation and parameter assessment in generalized algebraic difference site index modeling. For Ecol Manage 247, 107-119.

BRAVO-OVIEDO A., BRAVO F., DEL RIO M., STERBA H., 2006. Competition-induced mortality for Mediterranean *Pinus pinaster* Ait. and *P. sylvestris* L. For Ecol Manage 222, 88-98.

BRAVO-OVIEDO A., BRAVO F., MONTERO G., RÍO M., TOMÉ M., 2008. Dominant height growth equations including site attributes in the generalized algebraic difference approach. Can J For Res 38, 2348-2358.

BRAVO-OVIEDO, A., BRAVO, F., MONTERO, G., RÍO, M., ROIG. S., 2011. Environmental variability and its relationship to site index in Mediterrean Maritime pine. Forest Systems 20(1): 50-64.

BRONCANO M.J., RETANA J., RODRIGO A., 2008. Post-dispersal seed pretaion in *Pinus halepensis* and consequences on seedling establishment after fire. Int J Wildland Fire 17(3), 407-414.

BURKHART H.E., 2003. Suggestions for choosing an appropriate level for modelling forest stands, In: Modelling Forest Systems (Amaro A., Reed D., Soares P., eds.). CAB International, Wallingford, Oxfordshire, UK, pp. 3-10.

CABANILLAS A., 2010. Bases para la gestión de masas naturales de *Pinus halepensis* Mill. en el Valle del Ebro. Doctoral thesis. Universidad Politécnica de Madrid. [In Spanish]. Available at http://oa.upm.es/4960/

CABANILLAS A., BARRIO-ANTA M., ROJO ALBORECA A., NOTIVOL PAÍNO E., 2009. Diagrama de manejo de la densidad para masas naturales de pino carrasco (*Pinus halepensis* Mill.) en la Depresión del Ebro. Actas del V Congreso Forestal Español. 21-25 de septiembre. Ávila. Ref: 5CFE01-213. [In Spanish].

CABRERA M., 1997. El monte bajo de castaño en Asturias: alternativas selvícolas. Doctoral thesis. Universidad Politécnica de Madrid. [In Spanish].

CABRERA M., OCHOA F., 1997. Tabla de producción de castaño (*Castanea sativa* Mill.) tratado a monte bajo, en Asturias. Actas del II Congreso Forestal Español, Irati, septiembre 1997. Mesa 4, 131-136. [In Spanish].

CALAMA R., MONTERO G., 2004. Interregional nonlinear height-diameter model with random coefficients for stone pine in Spain. Can J For Res 34, 150-163.

CALAMA R., MONTERO G., 2005. Multilevel Linear Mixed Model for tree diameter increment in Stone Pine (*Pinus pinea*): a calibrating approach. Silva Fenica 39(1), 37-54.

CALAMA R., MONTERO G., 2006. Stand and tree level variability on stem form and tree volume in *Pinus pinea* L: a multilevel random components approach. Invest Agrar Sist Recur For 15(1), 24-41. [In Spanish].

CALAMA R., MONTERO G. 2007. Cone and seed production from stone pine (*Pinus pinea* L.) stands in Central Range (Spain). Eur J Forest Res 126, 23-35.

CALAMA R., CAÑADAS N., MONTERO G., 2003. Inter-regional variability in site index models for even-aged stands of stone pine (*Pinus pinea* L.) in Spain, Ann For Sci 60, 259-269.

CALAMA R., MONTERO G., SÁNCHEZ-GONZÁLEZ M., 2007b. Management oriented growth models for multifunctional Mediterranean Forests: the case of Stone Pine (*Pinus pinea* L.). EFI Proceedings 56, 57-70.

CALAMA R., GORDO F.J., MONTERO G., MUTKE S., 2008b. An empirical ecological-type model for predicting stone pine (*Pinus pinea* L.) cone production in the Northern Plateau (Spain). For Ecol Manage 255, 660-673.

CALAMA R., BARBEITO I., MONTERO G., PARDOS M., RÍO M., 2008a. Adapting a model for even-aged *Pinus pinea* L. stands for complex multi-aged structures. For Ecol Manage 256, 1390-1399.

CALAMA R., CAÑELLAS I., COQUILLAS V., MONTERO G., RÍO M., 2004. Modelos de calidad de estación y de perfil de fuste para masas de *Pinus uncinata* Ram. en el Pirineo español. Invest Agrar: Sist Recur For Fuera de serie, 176-190. [In Spanish].

CALAMA R., BACHILLER A., FINAT L., GARRIGA E., GORDO J., MONTERO G. 2007a. PINEA2: Un modelo integrado para la gestión de las masas regulares de *Pinus pinea* L. en la Meseta Norte. Cuadernos SECF 23, 147-152. [In Spanish].

CALAMA R., GORDO J., MONTERO G., MUTKE S., TOME J., TOME M., 2011. Modelling spatial and temporal variability in a zero-inflated variable: The case of stone pine (*Pinus pinea* L.) cone production. Ecol Model 222(3):606-618 doi:10.1016/j.ecolmodel.2010.09.020.

CALAMA R., GARRIGA E., MADRIGAL G., MONTERO G., MORO J., RÍO M., SÁNCHEZ-GONZÁLEZ M., 2009. Modelo para la gestión multifuncional de repoblaciones de *Pinus pinea* L. en Sierra Morena y Meseta Sur. 5º Congreso Forestal Español. Ávila, septiembre 2009. [In Spanish].

CALVO L., SANTALLA S., VALBUENA L., MARCOS E., TARREGA R., LUIS-CALABUIG E. 2008. Post-fire natural regeneration of a *Pinus pinaster* forest in NW Spain. Plant Ecol 197(1), 81-90.

CANADELL J., RODA F., 1991. Root biomass of *Quercus ilex* in a montane Mediterranean forest. Can J For Res 21, 1771-1778.

CANADELL J., RIBA M., ANDRÉS P., 1988. Biomass equations for *Quercus ilex* L. in the Montseny Massif, northeastern Spain. Forestry 61, 137-147.

CANGA E., 2007. Crecimiento y producción de pinares regulares de *Pinus radiata* D. Don en Asturias. Doctoral thesis. Universidad de Oviedo. [In Spanish].

CANGA E., AFIF KHOURI E., CÁMARA OBREGÓN A., GORGOSO VARELA J., 2007. Relación altura-diámetro generalizada para *Pinus radiata* D. Don en Asturias (Norte de España). II Reunión sobre aspectos prácticos de la Modelización Forestal. Cuadernos SECF 23, 153-158. [In Spanish].

CANTERO A., ESPINEL S., SÁENZ D., 1995. Un modelo de gestión para las masas de *Pinus radiata* en el País Vasco. Cuadernos SECF 1, 193-198. [In Spanish].

CAÑADAS M.N., 2000. *Pinus pinea* L. en el Sistema Central (Valles del Tiétar y del Alberche): Desarrollo de un modelo de crecimiento y producción de piña. Doctoral thesis. Universidad Politécnica de Madrid. [In Spanish].

CAÑADAS M.N., GARCÍA GÜEMES C., MONTERO G., 1999. Relación altura-diámetro para *Pinus pinea* en el Sistema Central. Congreso de Ordenación y Gestión Sostenible de Montes Tomo I, 139-154. [In Spanish].

CAÑELLAS I., MONTERO G., RÍO M., ROIG S., 2004. Growth response to thinning in *Quercus pyrenaica* Willd. coppice stands in Spanish Central Mountain. Ann For Sci 61(3), 243-250.

CARSON S.D., GARCIA O., HAYES J.D., 1999. Realized gain and prediction of yield with genetically improved *Pinus radiata* in New Zealand. For Sci 45, 186-200.

CASTEDO-DORADO F., 2004. Modelo dinámico de crecimiento para las masas de *Pinus radiata* D. Don en Galicia. Simulación de alternativas selvícolas con inclusión del riesgo de incendio. Doctoral thesis. Universidad de Santiago de Compostela, Lugo. [In Spanish].

CASTEDO-DORADO F., ÁLVAREZ-GONZÁLEZ J.G., 2000. Construcción de una tarifa de cubicación con clasificación de productos para *Pinus radiata* D. Don en Galicia basada en una función del perfil del tronco. Invest Agrar: Sist Recur For 9(2), 253-268. [In Spanish].

CASTEDO-DORADO F., ÁLVAREZ-GONZALEZ J.G., DIÉGUEZ-ARANDA U., 2007a. A growth model for *Pinus radiata* D. Don stands in north-western Spain. Ann For Sci 64, 453-465.

CASTEDO-DORADO F., ÁLVAREZ-ÁLVAREZ P., BARRIO-ANTA M., CRECENTE-CAMPO F., 2009b. Development a stand density management diagram for radiate pine stands including assessment of stand stability. Forestry 82, 1-16.

CASTEDO DORADO F., ÁLVAREZ GONZÁLEZ J.G., BARRIO ANTA M., DIÉGUEZ-ARANDA U., 2007b. Modelling stand basal area growth for radiata pine plantations in Northwestern Spain using the GADA. Ann For Sci 64, 609–619.

CASTEDO-DORADO F., ÁLVAREZ GONZÁLEZ J.G., BARRIO M., PARRESOL B.R., 2005. A stochastic height–diameter model for maritime pine ecoregions in Galicia (northwestern Spain). Ann For Sci 62, 455-465.

CASTEDO-DORADO F., ÁLVAREZ-ÁLVAREZ P., BARRIO-ANTA M., QUINTAIROS R., 2009a. Inclusión de riesgos abióticos en diagramas de manejo de la densidad. Un caso de estudio en masas de *Pinus pinaster* Ait. 5º Congreso Forestal Español, Ávila, Septiembre 2009. Ref: 5CFE01-190. [In Spanish].

CASTEDO-DORADO F., BARRIO ANTA M., DIÉGUEZ-ARANDA U., GADOW K.v., SÁNCHEZ RODRÍGUEZ M., 2006. A generalized height–diameter model including random components for radiata pine plantations in northwestern Spain. For Ecol Manage 229, 202-213.

CERVERA J.M., 1973. El área basimétrica reducida, el volumen reducido y el perfil. Montes: 415-418. [In Spanish].

CHAUCHARD L.M., OLALDE M., 2004. Diagrama de manejo de la densidad de masas de pino radiata en el País Vasco. Cuadernos SECF 18, 161-166.

CIESZEWSKI C.J., 2000. Analytical solution to the generalized log-logistic equation. For Sci 46, 291-296.

CIESZEWSKI C.J., HARRISON M., MARTIN S.W., 2000. Practical methods for estimating non-biased parameters in self-referencing growth and yield models. University of Georgia PMRC-TR 2000-7.

CLUTTER J.L., 1980. Development of taper functions from variable top merchantable volume equations. For Sci 26: 117–120.

CLUTTER J.L., JONES E.P., 1980. Prediction of growth after thinning in old-field slash pine plantations. USDA Forest Service, Res Pap SE-217, 19pp.

CLUTTER J.L., BAILEY R.L., BRISTER G.H., FORTSON J.C., PIENAAR L.V., 1983. Timber management: a quantitative approach. Wiley, New York, Chichester, Brisbane, Toronto, Singapore. 333 pp.

CONDÉS S., STERBA H., 2004. Modelo de crecimiento individual para *Pinus sylvestris*, con datos de los inventarios forestales nacionales 2º y 3º, en la provincia de Madrid. Cuadernos SECF 18, 211-217. [In Spanish].

CONDÉS S., STERBA H., 2005. Derivation of compatible crown width equations for some important tree species of Spain. For Ecol Manage 217(2-3), 203-218.

CONDÉS S., STERBA H., 2008. Comparing an individual tree growth model for *Pinus halepensis* Mill. in the Spanish region of Murcia with yield tables gained from the same area. Eur J Forest Res 127, 253-261.

CRECENTE-CAMPO F., 2008. Individual-tree basal area and height growth models for *Pinus radiata* D. Don in Galicia. Modelo de crecimiento de árbol individual para *Pinus radiata* D. Don en Galicia. Doctoral thesis. Universidad de Santiago de Compostela, Lugo. [In Spanish and English].

CRECENTE-CAMPO F., DIÉGUEZ-ARANDA U., ROJO A., 2009c. A merchantable volume system for *Pinus sylvestris* L. in the major mountain ranges of Spain. Ann For Sci 66 (8) 808. DOI: 10.1051/forest/2009078.

CRECENTE-CAMPO F., MARSHALL P., RODRIGUEZ-SOALLEIRO R., 2009b. Modeling non-catastrophic individual-tree mortality for *Pinus radiata* plantations in northwestern Spain. For Ecol Manage 257, 1542-1550.

CRECENTE-CAMPO F., DIÉGUEZ-ARANDA U., MARSHALL P., LEMAY V., 2009a. A crown profile model for *Pinus radiata* D. Don in northwestern Spain. For Ecol Manage 257, 2370-2379.

CRECENTE-CAMPO F., DIÉGUEZ-ARANDA U., SOARES P., TOMÉ, M., 2010a. Modelling anual individual-tree growth and mortality of Scots pine with data obtained at irregular measurement intervals and containing missing observations. For Ecol Manage 260, 1965-1974.

CRECENTE-CAMPO F., DIÉGUEZ-ARANDA U., SOARES P., TOMÉ M., 2010b. A generalized nonlinear mixed-effects height-diameter model for *Eucalyptus globulus* L. in northwestern Spain. For Ecol Manage 259, 943-952.

DANIEL T.W., BAKER F.S., HELMS J.A., 1979. Principles of silviculture, 2nd edition, McGraw-Hill Book Co., New York.

DAVIS L.S., BETTINGER P.S., HOWARD T.E., JOHNSON K.N., 2001. Forest Management: To Sustain Ecological, Economic, and Social Values. McGraw-Hill, New York.

DE LAS HERAS J., FERRANDIS P., GONZÁLEZ-OCHOA A.I., HERRANZ J.M., MARTÍNEZ-SÁNCHEZ J.J., 2002. Establishment of *Pinus halepensis* Mill. Saplings following fire: effects of competition with shrub species. Acta Oecol - Int J Ecol 23(2), 91-97.

DEL PESO C., BRAVO F., ORDOÑEZ C., VALBUENA P., 2005. Diagramas para el manejo de la densidad de rodales de pino negral (*Pinus pinaster* Ait.) en el Sistema Central. Actas del IV Congreso Forestal Español. 26-30 de septiembre. Zaragoza. [In Spanish].

DEMAERSCHALK J., 1972. Converting volume equations to compatible taper equations. For Sci 18, 241–245.

DIAZ-MAROTO I.J., BARCALA-PÉREZ E., FERNANDEZ-PAJARES J., VILA-LAMEIRO P., 2010 Site index model for natural stands of Rebollo oak (*Quercus pyrenaica* Willd.) in Galicia, NW Iberian Peninsula. Ciência Florestal, 20(1), 57-69.

DIÉGUEZ-ARANDA U., 2004. Modelo dinámico de crecimiento para masas de *Pinus sylvestris* L. procedentes de plantación en Galicia. Doctoral thesis. Universidad de Santiago de Compostela. [In Spanish].

DIÉGUEZ-ARANDA U., ÁLVAREZ-GONZALEZ J.G., CASTEDO-DORADO F., 2005d. Funciones de crecimiento en área basimétrica para masas de *Pinus sylvestris* L. procedentes de repoblación en Galicia. Invest Agrar: Sist Rec For 14(2), 253-266. [In Spanish].

DIÉGUEZ-ARANDA U., BARRIO ANTA M., CASTEDO DORADO F., 2005b. Relación altura-diámetro generalizada para masas de *Pinus sylvestris* L. procedentes de repoblación en el noroeste de España. Invest Agrar: Sist Recur For 14, 229-241. [In Spanish].

DIÉGUEZ-ARANDA U., BURKHART H.E., RODRÍGUEZ-SOALLEIRO R., 2005c. Modeling dominant height growth of radiata pine (*Pinus radiata* D. Don) plantations in north-western Spain. For Ecol Manage. 215, 271-284.

DIÉGUEZ-ARANDA U., ÁLVAREZ-GONZÁLEZ J.G., BARRIO ANTA M., ROJO ALBORECA A., 2005a. Site quality equations for *Pinus sylvestris* L. plantations in Galicia (northwestern Spain). Ann For Sci 62, 142-152.

DIÉGUEZ-ARANDA U., ÁLVAREZ-GONZÁLEZ J.G., CASTEDO-DORADO F., RODRÍGUEZ-SOALLEIRO R., 2005e. Modelling mortality of Scots pine (*Pinus sylvestris* L.) plantations in the northwest of Spain. Eur J Forest Res 124, 143-153.

DIÉGUEZ-ARANDA U., ÁLVAREZ-GONZÁLEZ J.G., CASTEDO-DORADO F., ROJO A., 2006a. Dynamic growth model for Scots pine (*Pinus sylvestris* L.) plantations in Galicia (north-western) Spain. Ecol Model 191, 225-242.

DIÉGUEZ-ARANDA U., ÁLVAREZ-GONZÁLEZ J.G., CASTEDO-DORADO F., ROJO A., 2006b. Compatible taper function for Scots pine plantations in north-western Spain. Can J For Res. 36, 1190-1205.

DIÉGUEZ-ARANDA U., ÁLVAREZ-GONZÁLEZ J.G., GADOW K.v, GRANDAS-ARIAS J.A., 2006c. Site Quality Curves for Birch Stands in North-Western Spain. Silva Fennica 40(4), 631-644.

DIÉGUEZ-ARANDA U., BALBOA-MURIAS M., BARRIO-ANTA M., CASTEDO-DORADO F., 2003. Estimación del diámetro normal y del volumen del tronco a partir de las dimensiones del tocón para seis especies forestales comerciales de Galicia. Invest Agrar: Sist Rec For 12(2), 131-139. [In Spanish].

DIÉGUEZ-ARANDA U., ÁLVAREZ-GONZÁLEZ J.G., CRECENTE-CAMPO F., GONZÁLEZ GONZÁLEZ J.M., ROJO ALBORECA A., 2007. Aplicación informática para la cubicación con clasificación de productos de *Fagus sylvatica* L. en Navarra. Gobierno de Navarra. [In Spanish].

DIÉGUEZ-ARANDA U., ÁLVAREZ GONZÁLEZ J.G., BALBOA-MURIAS M.A., BARRIO-ANTA M., CASTEDO-DORADO F., CRECENTE-CAMPO F., GONZÁLEZ GONZÁLEZ J.M., GORGOSO VARELA J.J., LÓPEZ-SÁNCHEZ C.A., PÉREZ-CRUZADO C., RODRÍGUEZ SOALLEIRO R., ROJO ALBORECA A., SÁNCHEZ RODRÍGUEZ F., 2009. Herramientas selvícolas para la gestión forestal sostenible en Galicia. Consellería do Medio Rural, Xunta de Galicia. 268 pp. + CD-Rom. . [In Spanish].

ECHEVERRÍA I., 1942. Ensayo de tablas de producción del *Pinus insignis* en el norte de España. Boletines del I.F.I.E., nº 22, Madrid. 67 pp. [In Spanish].

ECHEVERRÍA I., 1952. Producción del *Eucalyptus globulus*. Estudio de las leyes de crecimiento en la zona forestal de Huelva del Patrimonio Forestal del Estado. Boletines del I.F.I.E., nº 62, Madrid. 39 pp. [In Spanish].

ECHEVERRÍA I., DE PEDRO S., 1948. El *Pinus pinaster* en Pontevedra. Su productividad normal y aplicación a la celulosa industrial. Boletines del I.F.I.E., nº 38, Madrid. 147 pp. [In Spanish].

EID T., TUHUS E., 2001. Models for individual tree mortality in Norway. For Ecol Manage 154, 69-84.

ELENA-ROSELLÓ R., 1997. Clasificación biogeoclimática de España Peninsular y Balear. MAPA. Madrid. [In Spanish].

ERASO E., OLABE F., PUERTAS F., 1996. Tablas de producción de selvicultura media y de referencia para masas artificiales de *Pinus nigra* ssp. austriaca en la Comunidad Foral de Navarra. [Unpublished]. [In Spanish].

ERVITI J.J., 1991. Desarrollo de Modelos de crecimiento y producción de las masas de *Pinus halepensis* Mill. en España. Doctoral thesis. Universidad Politécnica de Madrid. [In Spanish].

ESCALANTE E., BRAVO F., ORDÓÑEZ C., PANDO V., 2011. Multinomial logit estimation of a diameter growth matrix model of two Mediterranean pine species in Spain. Ann For Sci 68(4), 715-726.

ESPINEL S., SÁENZ D., CANTERO A., 1997. Un modelo de simulación para rodales de *Pinus radiata* D. Don en el País Vasco. II Congreso Forestal Español- Irati 97, vol. IV, pp. 201–206. [In Spanish].

FERNÁNDEZ LÓPEZ A.B., 1982. Evaluación del crecimiento y productividad del monte bajo de *Eucalyptus globulus* en rotaciones sucesivas. Premio Excma. Diputación de Pontevedra. 70 pp. [Unpublished]. [In Spanish].

FERNÁNDEZ LÓPEZ A.B., 1985. Efecto del espaciamiento inicial en la producción de *Eucalyptus globulus*. Departamento Forestal de Lourizán. 45 pp. [Unpublished]. [In Spanish].

FERRES L., RODA F., TERRADAS J., VERDÚ A.M.C., 1980. Estructura y funcionalismo de un encinar montano en el Montseny. Mediterranea 4, 23-36. [In Spanish].

GADOW K.v., HUI G.Y., 1999. Modelling forest development. Kluwer Academic Publishers, Dordrecht. 213 pp.

GADOW K.v., ÁLVAREZ-GONZÁLEZ J.G., REAL P., 2001. Modelización del crecimiento y la evolución de bosques. IUFRO World Series vol. 12, Vienna. [In Spanish].

GALLEGO H. A., RICO M., SANTA REGINA I., 1993. Biomass equations and nutrient distribution for *Quercus pyrenaica* forests. Mesogee 53, 75-82.

GAMBORG G., LARSEN J.B., 2003. "Back to nature" -a sustainable future for forestry?. For Ecol Manage 179, 559-571.

GARCÍA ABEJÓN J.L., 1981. Tablas de producción de densidad variable para *Pinus sylvestris* L. en el Sistema Ibérico. Comunicaciones I.N.I.A. Serie: Recursos Naturales, 10. 47 pp. [In Spanish].

GARCÍA ABEJÓN J.L., GÓMEZ LORANCA J.A., 1984. Tablas de producción de densidad variable para *Pinus sylvestris* L. en el Sistema Central. Comunicaciones I.N.I.A. Serie: Recursos Naturales, 29. 36 pp. [In Spanish].

GARCÍA ABEJÓN J.L., GÓMEZ LORANCA J.A., 1989. Tablas de producción de densidad variable para *Pinus pinaster* Ait. en el Sistema Central. Comunicaciones I.N.I.A. Serie: Recursos Naturales, 47. 45 pp. [In Spanish].

GARCÍA ABEJÓN J.L., TELLA FERREIRO G., 1986. Tablas de producción de densidad variable para *Pinus sylvestris* L. en el Sistema Pirenaico. Comunicaciones I.N.I.A. Serie: Recursos Naturales, 43. 28 pp. [In Spanish].

GARCÍA GÜEMES C., 1999. Modelo de simulación selvícola para *Pinus pinea* L. en la provincia de Valladolid. Monografía INIA. Serie forestal: nº 6. [In Spanish].

GARCÍA GÜEMES C., CAÑADAS N., MONTERO G., 2001. Modelo de estimación de alturas en *Pinus pinea* L. para la provincia de Valladolid. III Congreso Forestal Español, Granada, Septiembre 2001. 3CFE03-121-T3, 794-799. [In Spanish].

GARCÍA O., 1983. A stochastic differential equation model for the height growth of forest stands. Biometrics 39, 1059-1072.

GARCÍA O., 1994. The state-space approach in growth modelling. Can J For Res 24, 1894-1903.

GARCÍA O., 2003. Dimensionality reduction in growth models: an example. FBMIS 1, 1-15.

GARCÍA O., RUIZ F., 2003. A growth model for eucalypt in Galicia, Spain. For Ecol Manage 173, 49-62.

GEA-IZQUIERDO G., CAÑELLAS I., 2009. Analysis of Holm Oak intraspecific competition using gamma regression. For Sci 55, 310-322.

GEA-IZQUIERDO G., CAÑELLAS I., MONTERO G., 2008. Site index in agroforestry systems: age-dependent and age-independent dynamic diameter growth models for *Quercus ilex* L. in Iberian open oak woodlands. Can J For Res 38, 101-113.

GEA-IZQUIERDO G., CAÑELLAS I., CHERUBINI P., MARTÍN-BENITO D., 2009. Climate-growth variability in *Quercus ilex* L. west Iberian open woodlands of different stand density. Ann For Sci 66, 802. DOI: 10.1051/forest/2009080.

GOELZ J.C.G., BURK T.E., 1992. Development of a well-behaved site index equation: jack pine in north central Ontario. Can J For Res 22, 776-784.

GÓMEZ LORANCA J.A., 1996. *Pinus nigra* Arn. en el Sistema Ibérico: tablas de crecimiento y producción. Monografías I.N.I.A. 93. 106 pp. [In Spanish].

GONZALEZ F., 1986. Crecimiento y producción, en la meseta central, según calidades de estación, de plantaciones de *Populus x euroamericana* (Dode) Guinier "Campeador". Comunicaciones INIA, Serie Recursos Naturales, nº 44. [In Spanish].

GONZÁLEZ ADRADOS J.R., CALVO HARO R., GONZÁLEZ HERNÁNDEZ R., 2000. La predicción del calibre de corcho al final del turno y su aplicación al muestreo de la producción. Invest Agrar: Sist Recur For 9, 363-373. [In Spanish].

GONZÁLEZ ANTOÑANZAS F., 1986. Crecimiento y producción, en la Meseta Central, según calidades de estación, de plantaciones de *Populus x euramericana* (Dode) Guinier "Campeador". Comunicaciones I.N.I.A. Serie: Recursos Naturales 44. 56 pp. [In Spanish].

GONZÁLEZ DONCEL I., 1989. Tablas ponderales para la estimación de la biomasa de rebollo (*Quercus pyrenaica* Willd.) en la provincia de León. INIA-MAPA, Madrid, 56 pp. [In Spanish].

GONZÁLEZ GONZÁLEZ J.M., ÁLVAREZ GONZÁLEZ J.G., CASTEDO-DORADO F., DIÉGUEZ-ARANDA U., ROJO ALBORECA A., 2009. GesMO 2009. Simulador de crecimiento y producción de rodales forestales. Universidad de Santiago de Compostela. (available at *www.usc.es/uxfs*).

GONZÁLEZ J.R., PALAHÍ M., PUKKALA T., TRASOBARES A., 2006. A fire probability model for forest stands in Catalonia. Ann For Sci 63, 169-176.

GONZÁLEZ J.R., PALAHÍ M., PUKKALA T., TRASOBARES A., 2007. Predicting tree survival in burned forests in Catalonia (North-East Spain) for strategic forest planning. Ann For Sci 64, 733-742.

GONZÁLEZ J.R., PALAHÍ M., PUKKALA T., TRASOBARES A., 2008. Optimising the management of *Pinus nigra* Arn. Stands under endogenous risk of fire in Catalonia. Invest Agrar: Sist Recur For 17(1), 10-17.

GONZÁLEZ MOLINA J.M., ARRUFAT D., MEYA D., 1999. Primeras tablas de selvicultura a la carta para masas regulares de *Pinus nigra* Arn. del Prepirineo catalán. Invest Agrar: Sist Recur For 8(1), 49-61. [In Spanish].

GONZÁLEZ-MARTÍNEZ S.C., ALÍA R., BURCZYK J., GIL L., NANOS N., NATHAN R., 2006. Effective gene dispersal and female reproductive success in Mediterranean maritime pine (*Pinus pinaster* Aiton). Mol Ecol 15, 4577-4588.

GRACE J.C., JARVIS P.G., NORMAN J.M., 1987. Modelling the interception of solar radiant energy in intensively managed stands. New Zeal J For Sci 17, 193-209.

GREENE D.F., CANHAM C.D., COATES K.D., LEPAGE P.T., 2004. An evaluation of alternative dispersal functions for trees. J Ecol 92, 758-766.

HASENAUER H., MONSERUD R.A., 1996. A crown ratio model for Austrian forests. For Ecol Manage 84, 49-60.

HUANG S., TITUS S.J., 1999. Estimating a system of nonlinear simultaneous individual tree models for white spruce in boreal mixed-species stands. Can J For Res 29, 1805-1811.

IBÁÑEZ J.I., 1989. El haya (*Fagus sylvatica* L.) en la Rioja. Selvicultura y ordenación. Doctoral thesis. Universidad Politécnica de Madrid. [In Spanish].

JIANG L., BROOKS J.R., WANG J., 2005. Compatible taper and volume equations for yellow-poplar in West Virginia. For Ecol Manage 213, 399–409.

KEENAN T., GRACIA C.A., SABATE S., 2008. Forest Ecophysiological Models and Carbon Sequestration. In: Managing forest ecosystems: The Challenge of Climate Change, (Bravo F., LeMay V., Jandl R., Gadow K.v., eds). Springer, Berlin, 83-102.

KERSHAW J.A., HANN D.W., MAGUIRE D.A., 1990. Longevity and duration of radial growth in Douglas-fir branches. Can J For Res 20, 1690-1695.

KEYES C.R., O'HARA K.L., 2002. Quantifying stand targets for silvicultural prevention of crown fires. West J Appl For 17, 101-109.

KOZAK A., KOZAK R., 2003. Does cross validation provide additional information in the evaluation of regression models? Can J For Res 33, 976-987.

KRAJICEK J.E., BRINKMAN K.A., GRINGRICH S.F., 1961. Crown competition: a measure of density. For Sci 7, 35-42.

KRUMLAND B.E., ENG H., 2005. Site index systems for major young-growth forest and woodland species in northern California. Cal. Dept. Forestry and Fire Protection. Cal. For. Rep. No. 4.

LANDSBERG J., LEMAY V.M., MARSHALL P.L., 2003. Modelling forest ecosystems: state of the art, challenges, and future directions. Can J For Res 33, 385-397.

LANDSBERG, J.L., WARING, R.H., 1997. A generalised model of forest productivity using simplified concepts of radiation-use efficiency, carbon balance and partitioning. For Ecol Manage 95, 209-228.

LEONARDI S., GALLEGO H.A., RAPP M., RICO M., SANTA REGINA I., 1996. Biomass, litterfall and nutrient content in *Castanea sativa* coppice stands of southern Spain. Ann Sci For 53, 1071-1081.

LIZARRALDE I., 2008. Dinámica de rodales y competencia en las masas de pino silvestre (*Pinus sylvestris* L.) y pino negral (*Pinus pinaster* Ait.) de los Sistemas Central e Ibérico Meridional. Doctoral thesis. Universidad de Valladolid, Palencia. [In Spanish].

LÓPEZ-SÁNCHEZ C.A., 2009. Estado selvícola y modelos de crecimiento y gestión de plantaciones de *Pseudotsuga menziesii* (Mirb.) Franco en España. Doctoral thesis. Universidad de Santiago de Compostela, Lugo. [In Spanish].

LÓPEZ SÁNCHEZ C.A., ÁLVAREZ GONZÁLEZ J.G., CASTEDO DORADO F., DIÉGUEZ-ARANDA U., RIBOT DE PORTA E., RODRÍGUEZ SOALLEIRO R.J. 2009. Tablas de producción de plantaciones de abeto Douglas en España. 5º Congreso Forestal Español, Ávila, Septiembre 2009. [In Spanish].

LÓPEZ-SÁNCHEZ C., RODRÍGUEZ-SOALLEIRO R. 2009. A density management diagram including stand stability and crown fire risk for *Pseudotsuga menziesii* (Mirb.) Franco in Spain. Mt Res Dev 29(2),169-176.

LÓPEZ-SÁNCHEZ C.A., ÁLVAREZ GONZÁLEZ J.G., CASTEDO F., GORGOSO J.J., RODRÍGUEZ R., ROJO A., SÁNCHEZ F., 2003. A height-diameter model for *Pinus radiata* D. Don in Galicia (Northwest Spain). Ann For Sci 60, 237-245.

LÓPEZ-SENESPLEDA E., SÁNCHEZ-PALOMARES O., 2007. Modelo de calidad de estación y altura dominante para *Quercus faginea* Lam. en España. Cuadernos SECF 23, 199-206. [In Spanish].

MADRIGAL A., 1991. Tablas de producción. Seminario sobre inventario y ordenación de montes, Valsaín, Segovia (Spain), Vol. II: 32-70. [In Spanish].

MADRIGAL A., TOVAL G., 1975. Tablas de producción, cubicación y tarifas de *Pinus radiata* D. Don. en las Provincias Vascongadas. Dirección General de la Producción Agraria. Mº de Agricultura. Madrid. 75 pp. [In Spanish].

MADRIGAL A., MARTÍNEZ MILLÁN F.J., PUERTAS F., 1992. Tablas de producción para *Fagus sylvatica* L. en Navarra. Serie Agraria, nº 3. Departamento de Agricultura, Ganadería y Montes. Gobierno de Navarra. Pamplona, 122 pp. [In Spanish].

MADRIGAL A., ÁLVAREZ-GONZÁLEZ J.G., RODRÍGUEZ-SOALLEIRO R., ROJO ALBORECA A. 1999. Tablas de producción para los montes españoles. Fundación Conde del Valle de Salazar. Escuela Técnica Superior de Ingenieros de Montes, Madrid. 253 pp. [In Spanish].

MADRIGAL G., CALAMA R., GORDO J., MONTERO G., 2009. PINEA2 v1.0: aplicación informática para la gestión de las masas regulares de *Pinus pinea* L. en la Meseta Norte. 5º Congreso Forestal Español. Mesa 2. Ávila, septiembre 2009. [In Spanish].

MADRIGAL A., HERRANZ J., LÓPEZ M., MOSQUERA R., 1977. Tablas de producción de *Eucalyptus globulus* Labill. en el Sudoeste de España. Dirección General de la Producción Agraria. Ministerio de Agricultura. Madrid, 109 pp. [Unpublished]. [In Spanish].

MADRIGAL G., ALONSO R., CALAMA R., MONTERO G., MORO J., 2007. Patrón de crecimiento en altura dominante en masas naturales y artificiales de *Pinus pinea* L.: comparación a través de modelos dinámicos. Cuadernos SECF 23, 207-214. [In Spanish].

MANION P.D., 1981. Tree disease concepts. Prentice-Hall, Englewood cliffs, New Jersey, USA.

MARTÍN-BENITO D., CAÑELLAS I., RÍO M., 2010. Black pine (*Pinus nigra* Arn.) growth divergence along a latitudinal gradient in Western Mediterranean mountains. Ann For Sci 401.

MARTÍN-BENITO D., CAÑELLAS I., CHERUBINI P., RÍO M., 2008a. Growth response to climate and drought in *Pinus nigra* Arn. trees of different crown classes. Trees Struct Funct 22, 363-373.

MARTIN-BENITO D., CAÑELLAS I., GEA-IZQUIERDO G., RÍO M., 2008b. Long-term trends in dominant-height growth of Black pine using dynamic models. For Ecol Manage 256, 1230-1238.

MARTÍNEZ Y., HERRANZ O. 2006. Tarifas de cubicación y curvas de perfil de *Pinus* *canariensis* y *Pinus radiata* en la isla de Tenerife. Cabildo de Tenerife. Área de Medio Ambiente y Paisaje. Servicio Técnico Forestal. 29 pp. [In Spanish].

MARTÍNEZ CHAMORRO E., 2004. Estudio del crecimiento, producción y gestión de las masas de *Pinus sylvestris* L. en Galicia. Doctoral thesis. Universidad de Santiago de Compostela, Lugo. [In Spanish].

MARTÍNEZ DE ARAGÓN J., BONET J.A., COLINAS C., FISCHER C.R., 2007. Productivity of ectomycorrhizal and selected edible saprotrophic fungi in pine forests of the pre-Pyrenees mountains, Spain: Predictive equations for forest management of mycological resources. For Ecol Manage 252, 239-256.

MARTÍNEZ MILLÁN F.J., MADRIGAL A., 1992. Alternativas selvícolas y de producción del *Pinus pinaster* Ait. en Galicia. Premio E.N.C.E. 1992. 151 pp. [Unpublished]. [In Spanish].

MARTÍNEZ-MILLAN F.J., ARA LAZARO P., GONZÁLEZ DONCEL I., 1993. Ecuaciones alometricas de tres variables: estimación del volumen, crecimiento y porcentaje de corteza de las principales especies maderables españolas. Invest Agrar: Sist Recur For, 2, 211-228. [In Spanish].

MERINO A., BRAÑAS J., REY C., RODRIGUEZ-SOALLEIRO R., 2003. Biomasa arbórea y acumulación de nutrientes en plantaciones de *Pinus radiata* D. Don en Galicia. Invest Agrar: Sist Recur For 12, 85-98. [In Spanish].

MITCHELL K.J., 1975. Dynamics and simulated yield of Douglas-fir. For Sci Monogr. 17. 39 pp.

MOLINA F., RUIZ P., 1976. Tablas de producción de *Pinus pinaster* Ait. en Galicia. I.N.I.A., CRIDA 01. Departamento Forestal de Lourizán. 93 pp. [Unpublished]. [In Spanish].

MONSERUD R.A., STERBA H., 1999. Modeling individual tree mortality for Austrian forest species. For Ecol Manage 113: 109-123.

MONTERO DE BURGOS, J.L., GONZÁLEZ-REBOLLAR, J.L., 1974. Diagramas bioclimáticos. Instituto Nacional para la Conservación de la Naturaleza (ICONA). Madrid. 380 pp. [In Spanish].

MONTERO G., 1987. Modelos para cuantificar la producción de corcho en alcornocales (*Quercus suber* L.) en función de la calidad de estación y los tratamientos selvícolas. Doctoral thesis. INIA Madrid. [In Spanish].

MONTERO G., CAÑELLAS I., 1999. Manual de reforestación, cultivo y aprovechamiento del alcornoque. INIA, Ministerio de Agricultura, Pesca y Alimentación, Madrid. 103 pp. [In Spanish].

MONTERO G., CAÑELLAS I., RUIZ-PEINADO R., 2001b. Growth and yield models for *Pinus halepensis* Mill. Invest Agrar: Sist Recur For 10(1), 179-201.

MONTERO G., MUÑOZ M., RUIZ-PEINADO R., 2005. Producción de biomasa y fijación de CO_2 por los bosques españoles. Instituto Nacional de Investigación y Tecnología Agraria y Alimentaria, Ministerio de Educación y Ciencia, Madrid, 270 pp. [In Spanish].

MONTERO G., BACHILLER A., CAÑELLAS I., ORTEGA C., 1999. Productividad aérea y dinámica de nutrientes en una repoblación de *Pinus pinaster* Ait. sometida a distintos regímenes de claras. Invest Agrar: Sist Recur For Fuera de Serie nº1, 175-206. [In Spanish].

MONTERO G., BACHILLER A., MADRIGAL G., RUIZ-PEINADO R., 2004a. Red de parcelas experimentales permanentes del CIFOR-INIA. Cuadernos SECF 18, 229-236. [In Spanish].

MONTERO G., CAÑELLAS I., ORTEGA C., RÍO M., 2001a. Results from a thinning regime experiment in a Scots pine (*Pinus sylvestris* L.) natural regeneration stand in the Sistema Ibérico mountain range (Spain). For Ecol Manage 145, 151-161.

MONTERO G., CAÑELLAS I., ORTEGA C., TORRES E., 1996. Modelos para la estimación de corcho en alcornocales. Invest Agrar: Sist Recur For 5(1), 97-127. [In Spanish].

MONTERO G., MUÑOZ M., DONÉS J., ROJO A., 2004b. Fijación de CO_2 por *Pinus sylvestris* L. y *Quercus pyrenaica* Willd. en los montes "Pinar de Valsaín" y "Matas de Valsaín". Invest Agrar: Sist Recur For 13, 399-415. [In Spanish].

MONTERO G., CAÑELLAS I., GRAU J. M., ORTEGA C., RUIZ-PEINADO R., 2000. Tablas de producción para *Pinus halepensis* Mill. Cuadernos SECF 10, 183-188. [In Spanish].

MONTES F., HERNÁNDEZ M.J., CAÑELLAS I., 2005. A geostatistical approach to cork production sampling estiamtion in *Quercus suber* forests. Can J For Res 35, 2787-2796.

MUNRO D.D., 1974. Forest growth models - a prognosis. In: Growth models for tree and stand simulation. (Fries J., ed.). Royal Coll. For., Res. Notes 30, p. 7-21.

MUÑOZ P., 1985. Alternativas selvícolas en la producción del *Pinus radiata* D. Don. Doctoral thesis. Universidad Politécnica de Madrid. [In Spanish].

MUTKE S., GIL L., GORDO J., 2001. Modelo individual de producción de piñón de *Pinus pinea* L. como criterio de selección fenotípica. 3er Congreso Forestal Español. Granada, Septiembre 2001 Volumen 3, 172-178. [In Spanish].

MUTKE S., GIL L., GORDO J., 2005. Variability of Mediterranean Stone pine cone production: Yield loss as response to climate change. Agr Forest Meteorol 132(3-4), 263-272.

NANOS N., ALÍA R., GIL L., MONTERO G., TADESSE W., 2000. Modelling resin production distributions for *Pinus pinaster* Ait using two probability functions. Ann For Sci 57, 369-377.

NANOS N., ALÍA R., GIL L., MONTERO G., TADESSE W., 2001. Spatial stochastic modeling of resin yield from pine stands. Can J For Res 31, 1140-1147.

NEWTON P.F., WEETMAN G.F., 1994. Stand density management diagram for managed black spruce stands. For Chron 70, 65-74.

NÚÑEZ M.R., BRAVO F., CALVO L., 2003. Predicting the probability of seed germination *Pinus sylvestris* L. and four competitor shrub species after fire. Ann For Sci 60(1), 75-81.

ODENBAUGH J., 2006. The strategy of model building in population biology. Biology and Philosophy 21, 607-621.

ODERWALD R.G., HANS R. P., 1993. Corroborating models with model properties. For Ecol Manage 62, 271-283.

ORDOÑEZ, J.L., RETANA, J., 2004. Early reduction of post-fire recruitment of *Pinus nigra* by post-dispersal seed predation in different time-since-fire habitats Ecography 27(4), 449-458.

ORDOÑEZ J.L., FRANCO S., RETANA J., 2004. Limitation of the recruitment of *Pinus nigra* in a gradient of post-fire environmental conditiions Ecoscience 11(3), 296-304.

ORTEGA A., 1989. Modelos de evolución de masas de *Pinus sylvestris* L. Doctoral thesis. Universidad Politécnica de Madrid. [In Spanish].

PALAHI M., GRAU J.M., 2003. Preliminary site index model and individual tree and mortality models for black pine (*Pinus nigra* Arn.) in Catalonia (Spain). Invest Agrar: Sist Recur For 12, 137-148.

PALAHÍ M., MIINA, J., MONTERO, G., PUKKALA, T., 2003. Individual-tree growth and mortality models for Scots pine (*Pinus sylvestris* L.) in north-east Spain. Ann For Sci 60, 1-10.

PALAHI M., MIINA J., MONTERO G., TOMÉ M., 2002. Stand-level yield model for Scots pine (*Pinus sylvestris* L.) in north-east Spain. Invest Agrar: Sist Recur For 11, 409-424.

PALAHÍ M., MONTERO G., PUKKALA T., TRASOBARES A., 2004b. Site index models for *Pinus sylvestris* in NE Spain. For Ecol Manage 187, 35-47.

PALAHÍ M., PASCUAL L., PUKKALA T., TRASOBARES A., 2004a. Examining alternative landscape metrics in ecological forest landscape planning: a case for capercaillie in Catalonia. Invest Agrar: Sist Recur For13 (3), 1-12.

PALAHÍ M., BONET J.A., COLINAS C., FISCHER C.R., MARTÍNEZ DE ARAGÓN J., PUKKALA T., 2009. Effect of the inclusion of mushroom values on the optimal management of even-aged pine stands of Catalonia. For Sci 55(6), 503-511.

PARDO M., 1980. Tablas de producción para *Eucalyptus globulus* en el sudoeste de España. ENCE. Departamento de Inventariación Forestal. [Unpublished]. [In Spanish].

PARRESOL B.R., 1999. Assessing tree and stand biomass: A review with examples and critical comparisons. For Sci 45, 573-593.

PAUSAS J.G., RIBEIRO E., VALLEJO R., 2004. Post-fire regeneration variability of *Pinus halepensis* in the eastern Iberian Peninsula. For Ecol Manage 203(1-3), 251-259.

PEDERSEN B.S., 1998. Modeling tree mortality in response to short- and long-term environmental stresses. Ecol Model 105, 347-351.

PÉREZ-CRUZADO C., FERNÁNDEZ-RIVAS E., MERINO A., RODRÍGUEZ-DACOSTA L.M., RODRÍGUEZ-SOALLEIRO R., 2009. Diagramas de manejo de la densidad para plantaciones de *Eucalyptus nitens* Maid. en el norte de España con evaluación del carbono fijado en biomasa arbórea. 5º Congreso Forestal Español. Ávila, Septiembre 2009. Ref: 5CFE01-132. [In Spanish].

PICARDO A., 1985. Tablas de gestión a la carta. Aplicación a montes de pino silvestre.

Doctoral thesis. Universidad Politécnica de Madrid. [In Spanish].

PIQUÉ M., 2003. Modelos de producción para las masas de *Pinus pinea* L. en Catalunya: orientaciones para la gestión y el aprovechamiento sostenible de madera y piña. Doctoral thesis. Universidad de Lleida. [In Spanish].

PITA P.A., 1964. La calidad de estación en las masas de *Pinus sylvestris* L. en la Península Ibérica. Anales IFIE 9, 5-28. [In Spanish].

PITA P.A., 1966. La producción de las masas de *Eucalyptus globulus* en el norte de España. Anales del Instituto Forestal de Investigaciones y Experiencias, Tomo I: 45-60. [In Spanish].

PITA P.A., 1967a. Clasificación provisional de las calidades de la estación en las masas de "*P. pinaster*" Sol (continental) y "*P. uncinata*" Ram. de la península Ibérica. Anales del IFIE, 125-138. [In Spanish].

PITA P.A., 1967b. Tablas de cubicación por diámetros normales y alturas totales. Ministerio de Agricultura, Madrid. [In Spanish].

PRETZSCH H., 2009. Forest Dynamics, Growth and Yield. Springer, Berlin.

PUERTAS F., 2003. Scots pine in Navarre: Economic importance and production. In: Silviculture and sustainable management in mountain forests in the western Pyrenees, IUFRO Conference, Navarre, September 2003, 32 pp.

PUKKALA T. (ed.), 2002. Multi-objective Forest Planning. Kluwer Academic Publishers.

REINEKE L.H., 1933. Perfecting a stand density index for even-aged forests. J Agric Res 46, 627-6238.

RENNOLLS K., 1997. Data requirements for forest modelling. In: Empirical and process-based models for forest tree and stand growth simulation. (Amaro A., Tomé M., eds). Edições Salamandra. Lisboa. pp 11-22.

RICHARDS F.J., 1959. A flexible growth function for empirical use. Journal of Experimental Botany 10, 290-300.

RÍO M., 1999. Régimen de claras y modelo de producción para *Pinus sylvestris* L. en los Sistemas Central e Ibérico. Doctorales INIA. Serie: Forestal 2, 257 pp. [In Spanish].

RÍO M., MONTERO G., 2001. Modelo de simulación de claras en masas de *Pinus sylvestris* L. Monografías INIA. Serie Forestal 3, 114 pp. [In Spanish].

RÍO M., STERBA H., 2009. Comparing volume growth in pure and mixed stands of *Pinus sylvestris* and *Quercus pyrenaica*. Ann For Sci 66, DOI: 10.1051/forest/2009035.

RÍO M., BRAVO F., MONTERO G., 2001. Analysis of diameter-density relationships and self-thinning in non-thinning even-aged Scots pine stands. For Ecol Manage 142, 79-87.

RÍO M., LÓPEZ-SENESPLEDA E., MONTERO G., 2006. Manual de gestión para masas procedentes de repoblación de *Pinus pinaster* Ait., *Pinus sylvestris* L. y *Pinus nigra* Arn. en Castilla y León. Serie Técnica. Consejería de Medio Ambiente. Junta de Castilla y León. 76 pp + anexos. [In Spanish].

RÍO M, CAÑELLAS I, MONTERO G., ROIG S, 2005. Programación de claras en repoblaciones de *Pinus sylvestris* L. Seguimiento de sitios de ensayo en la

Comunidad de Madrid. Monografías del INIA: Serie forestal 12, 46 pp. [In Spanish].

RÍO M., CALAMA R., CAÑELLAS I., MONTERO G., ROIG S., 2008. Thinning intensity and growth response in SW-European Scots pine stands. Ann For Sci 65, 308.

ROBLEDO-ARNUNCIO J. J., GARCÍA C., 2007. Estimation of the seed dispersal kernel from exact identification of source plants. Mol Ecol 16, 5098-5109.

RODRÍGUEZ F., 2005. Modelos de producción de las choperas del valle del Cinca. Doctoral thesis. Universidad de Lleida. [In Spanish].

RODRIGUEZ, F., 2010. Ecuaciones de volumen comercial para las principales especies maderables de Castilla y León. Disponible en www.cesefor.com/cubifor (último acceso el 15 de abril de 2010)

RODRÍGUEZ F., MOLINA C., 2003. Modelos de perfil de fuste para tres clones de chopo (*Populus × euramerica*) en Navarra. Invest Agrar: Sist Recur For 12(3), 73-85. [In Spanish].

RODRÍGUEZ F., AUNÓS A., PEMAN J., 2010. A reduced growth model based on stand basal area. A case for hybrid poplar plantations in northeast Spain. For Ecol Manage 259, 2093-2102.

RODRÍGUEZ F., BROTO M., LIZARRALDE I., 2008. CubiFOR: Herramienta para cubicar, clasificar productos y calcular biomasa y CO_2 en masas forestales de Castilla y León. Revista Montes 95:33-39 (available at www.cesefor.com/cubifor).

RODRIGUEZ F., CONDÉS S., FERNANDEZ A., LIZARRALDE I., 2009. CriterionTM RD1000: Una oportunidad para calcular el volumen de árboles en pie. 5º Congreso Forestal Español, Ávila, septiembre 2009. Ref 5CFE01-175. [In Spanish].

RODRÍGUEZ-SOALLEIRO R., 1995. Crecimiento y Producción de masas forestales regulares de *Pinus pinaster* Ait. en Galicia. Alternativas selvícolas posibles. Doctoral thesis. Universidad Politécnica de Madrid [In Spanish].

RODRÍGUEZ SOALLEIRO R., ÁLVAREZ GONZÁLEZ J.G., VEGA G., 1994. Piñeiro do país: modelo dinámico de crecemento de masas regulares de *Pinus pinaster* Aiton en Galicia (Guía para o usuario do programa PINASTER). Capacitación e Extensión. Serie Manuais Prácticos 8. Consellería de Agricultura, Gandería e Montes, Xunta de Galicia. Santiago de Compostela. 40 pp. [In Spanish].

RODRIGUEZ-SUAREZ J.A., DIAZ-FIERROS F., IGLESIAS M.L., SOTO B., 2010. Application of the 3PG forest growth model to a *Eucalyptus globulus* plantation in Northwest Spain Eur J Forest Res DOI 10.1007/s10342-010-0355-6.

ROJO A., 1994. Crecimiento y producción de *Pinus sylvestris* L. en la Sierra de Guadarrama. Doctoral thesis. Universidad Politécnica de Madrid. [In Spanish].

ROJO A., MONTERO G., 1994. Tablas de producción españolas. Montes 38, 35-42. [In Spanish].

ROJO A., MONTERO G., 1996. El pino silvestre en la Sierra de Guadarrama. Historia y selvicultura de los pinares de Cercedilla, Navacerrada y Valsaín. Ministerio de Agricultura, Pesca y Alimentación. Secretaría General Técnica. Madrid. 293 pp. [In Spanish].

ROJO A., ÁLVAREZ-GONZÁLEZ J.G., DIÉGUEZ-ARANDA U., GRANDAS J.A., 2005a. Tablas de producción de selvicultura media para el abedul (*Betula alba* L.) en Galicia. 4º Congreso Forestal Español, Zaragoza, Septiembre 2005. [In Spanish].

ROJO A., ÁLVAREZ-GONZÁLEZ J. G., GADOW K.v, PERALES X., SÁNCHEZ-RODRÍGUEZ F., 2005b. Stem taper functions for maritime pine (*Pinus pinaster* Ait.) in Galicia (Northwestern Spain). Eur J Forest Res 124, 177–186.

ROMANYÀ J., VALLEJO V. R., 2004. Productivity of *Pinus radiata* plantations in Spain in response to climate and soil. For Ecol Manage 195, 177-189.

RUIZ-PEINADO R., BRAVO-OVIEDO A., CAÑELLAS I., RÍO M., 2010. Modelling dominant height growth in Aleppo pine (*Pinus halepensis* Mill.) forests. IUFRO meeting Global change and Mediterranean Pines: Alternatives for management. Abstract Book p. 78.

RUIZ-PEINADO R., MONTERO G., RÍO M., 2011. New models for estimating the carbon sink capacity of Spanish softwood species. Forest Systems 20, 176-188.

SAN MIGUEL A., FERNÁNDEZ CANCIO A., SAN MIGUEL J., 1992. Tablas de peso para pies individuales de rebollo (*Quercus pyrenaica* Willd.) en montes bajos del Sistema Central español. Invest Agrar: Sist Recur For 1, 173-179. [In Spanish].

SÁNCHEZ GONZÁLEZ M., 2006. Modelo de crecimiento y producción para monte alcornocal. Doctoral thesis. Universidad Politécnica de Madrid. [In Spanish].

SÁNCHEZ-GONZÁLEZ M., CAÑELLAS I., MONTERO G., 2007c. Generalized height-diameter and crown diameter models for cork oak forests in Spain. Invest Agrar: Sist Recur For 16(1), 76-88.

SÁNCHEZ-GONZÁLEZ M., CAÑELLAS I., MONTERO G., 2008. Base-age invariant cork growth model for Spanish cork oak (*Quercus suber* L.) forests. Eur J Forest Res 127, 173-182.

SÁNCHEZ-GONZÁLEZ M., CAÑELLAS I., SÁNCHEZ M.M., 2007d. Modelo de predicción del calibre de bornizo mediante funciones de perfil del tronco. Cuadernos SECF 23, 239-243. [In Spanish].

SÁNCHEZ-GONZÁLEZ M., MONTERO G., TOMÉ M., 2005. Modelling height and diameter growth of dominant cork oak trees in Spain. Ann For Sci 62, 633-643.

SÁNCHEZ-GONZÁLEZ M., CALAMA R., CAÑELLAS I., MONTERO G., 2007a. Variables influencing cork thickness in Spanish cork oak forests: A Modelling Approach. Ann For Sci 64, 1-12.

SÁNCHEZ-GONZÁLEZ M., CALAMA R., CAÑELLAS I., MONTERO G., 2007b. Management oriented growth models for multifunctional Mediterranean Forests: the case of Cork Oak (*Quercus suber* L.). EFI Proceedings 56, 71-84.

SÁNCHEZ-GONZÁLEZ M., CAÑELLAS I., MONTERO G., RÍO M., 2006. Distance independent tree diameter growth model for cork oak stands. For Ecol Manage 225, 262-270.

SÁNCHEZ OROIS S., RODRÍGUEZ SOALLEIRO R., 2002. Modelling the growth and management of mixed uneven-aged maritime pine-broadleaves species forests in Galicia (Northwestern Spain). Scan J For Res 17 (6), 538-547.

SÁNCHEZ-PALOMARES O., SÁNCHEZ-SERRANO F., 2000. Mapa de la Productividad Potencial Forestal de España. Cartografía Digital. Ed. Ministerio de Medio Ambiente. Dirección General de Conservación de la Naturaleza. Madrid. [In Spanish].

SÁNCHEZ-RODRÍGUEZ F., 2001. Estudio de la calidad de estación, crecimiento, producción y selvicultura de *Pinus radiata* D. Don en Galicia. Doctoral thesis. Universidad de Santiago de Compostela, Lugo. [In Spanish].

SÁNCHEZ-RODRIGUEZ F., ESPAÑOL E., LÓPEZ C.A., MERINO A., RODRÍGUEZ-SOALLEIRO R., 2002. Influence of edaphic factors and tree nutritive status on the productivity of *Pinus radiata* D. Don plantations in northwestern Spain. For Ecol Manage 171, 181-189.

SÁNCHEZ-RODRÍGUEZ F., ÁLVAREZ-GONZÁLEZ J. G., CASTEDO F., GORGOSO J., LÓPEZ-SÁNCHEZ C., RODRÍGUEZ-SOALLEIRO R., ROJO A., 2003. Crecimiento y tablas de producción de *Pinus radiata* D. Don en Galicia. Invest Agrar: Sist Recur For 12(2), 65-83. [In Spanish].

SANTA REGINA I., 2000. Organic matter distribution and nutrient fluxes within a sweet chestnut (*Castanea sativa* Mill.) stand of the Sierra de Gata, Spain. Ann For Sci 57, 691-700.

SANTA REGINA I., CALVO R., TARAZONA T., 1997. Aboveground biomass in a beech forest and a scots pine plantation in the Sierra de la Demanda area of northern Spain. Ann Sci For 54, 261-269.

SANTALLA M., 2010. Empleo de cenizas de las industrias de tableros como restituyente de nutrientes en plantaciones aclaradas de *Pinus radiata* D. Don. Doctoral thesis. Universidad de Santiago de Compostela, Lugo. [In Spanish].

SANTAMARÍA J.E., CASTEDO-DORADO, F., FERNÁNDEZ MANSO A., 2009. Tablas de producción de selvicultura media observada para el pino pinaster de la Sierra del Teleno (León). 5º Congreso Forestal Español, Ávila, Septiembre 2009. [In Spanish].

SCHRÖDER J., ÁLVAREZ GONZÁLEZ J.G., 2001. Comparing the performance of generalized diameter-height equations for maritime pine in Northwestern Spain. Forstw Cbl 120, 18-23.

SCHRÖDER J., GADOW K. v., 1999. Testing a new competition index for maritime pine in northwestern Spain. Can J For Res 148, 7-17.

SCHRÖDER J., RODRIGUEZ SOALLEIRO R., VEGA ALONSO G., 2002. An age-independent basal area increment model for maritime pine trees in northwestern Spain. For Ecol Manage 157 (1-3), 55-64.

SEVILLANO-MARCO E., CASTEDO-DORADO F., FERNÁNDEZ-MANSO A., 2009. Development and applications of a growth model for *Pinus radiata* D. Don plantations in El Bierzo (Spain). Invest Agrar: Sist Recur For 18(1), 64-80. [In Spanish].

SNOWDON P., 2002. Modeling Type 1 and Type 2 growth responses in plantations after application of fertilizer or other silvicultural treatments. For Ecol Manage 163, 229–244.

SOARES P., TOMÉ M., 2001. A tree crown ratio prediction equation for eucalypt plantations. Ann For Sci 58, 193-202.

SOARES P., TOMÉ M., 2007. Model evaluation: from model components to sustainable forest management indicators. Cuadernos SECF 23, 27-34.

SOARES P., SKOVSGAARD J.P., TOMÉ M., VANCLAY J.K., 1995. Evaluating a growth model for forest management using continuous forest inventory data. For Ecol Manage 71, 251-265.

SOLLA F., 2004. Aplicación de cenizas de biomasa arbórea como fertilizante y encalante de plantaciones forestales en Galicia. Doctoral thesis. Universidad de Santiago de Compostela, Lugo. [In Spanish].

SOLLA F., MERINO A., RODRÍGUEZ SOALLEIRO R., SANTALLA M., 2006. Nutritional status and growth of a young *Pseudotsuga menziesii* plantation in a temperate region after application of wood-bark ash. For Ecol Manage 237, 312-321.

TORRE M., 1994. Degradación inducida por algunas prácticas agrarias tradicionales. El caso de los rebollares (*Quercus pyrenaica* Willd.) de la provincia de León. Doctoral thesis. Universidad Politécnica de Madrid. [In Spanish].

TORRES ÁLVAREZ E., CALZADO CARRETERO J.A., SUÁREZ M.A., VÁZQUEZ PIQUÉ J., 2004. Dispositivo experimental para el estudio de la influencia de los factores ambientales y silvícolas sobre el crecimiento de alcornoque. Cuadernos SECF 18, 261-268. [In Spanish].

TRASOBARES A., PUKKALA T., 2004a. Optimising the management of uneven-aged *Pinus sylvestris* L. and *Pinus nigra* Arn. mixed stands in Catalonia, north-east Spain. Ann For Sci 61 (8), 747-758.

TRASOBARES A., PUKKALA T., 2004b. Using past growth to improve individual-tree diameter growth models for uneven-aged mixtures of *Pinus sylvestris* L. and *Pinus nigra* Arn. in Catalonia, north-east Spain. Ann For Sci 61, 409-417.

TRASOBARES A., MIINA J., PUKKALA T., 2004a. Growth and yield model for uneven-aged mixtures of *Pinus sylvestris* L. and *Pinus nigra* Arn. in Catalonia, north-east Spain. Ann For Sci 61 (1), 9-24.

TRASOBARES A., MIINA J., TOMÉ M., 2004b. Growth and yield model for *Pinus halepensis* Mill. in Catalonia, north-east Spain. For Ecol Manage 203 (1-3), 49-62.

VALBUENA P., BRAVO F., 2005. Diagramas para el manejo de la densidad de rodales de pino carrasco (*Pinus halepensis* Miller) en la zona catalana interior y aragonesa. IV Congreso Forestal Español. 26-30 de septiembre. Zaragoza. [In Spanish].

VALBUENA P., BRAVO F., DEL PESO C., 2008. Stand Density Management Diagrams for two Mediterranean pine species in Eastern Spain. Invest Agrar: Sist Recur For 17(2), 97-104.

VALERO MORENO J., 1998. Experiencias de producción de resina mediante el método de "pica de corteza descendente con estimulación continua con pasta zeta" en Cataluña. Proc. 1er Simposio de aprovechamiento de resinas naturales. Segovia, Spain, Feb. 5-7. [In Spanish].

VANCLAY J.K., 1994. Modelling forest growth and yield. Applications to mixed tropical forests. CAB International, Wallingford, 312 p.

VANCLAY J.K., 1995. Growth models for tropical forests: a synthesis of models and methods. For Sci 41, 7-42.

VANCLAY J.K., SKOVSGAARD J.P., 1997. Evaluating forest growth models. Ecol Model 98, 1-12.

VANNIÈRE B., 1984. Tables de production pour les forêts françaises. E.N.G.R.E.F., I.N.R.A., O.N.F. 2ª Ed. Ecole Nationale du Génie Rural, des Eaux et des Forêts. Nancy. 158 pp. [In French].

VÁZQUEZ PIQUÉ J., 2002. Modelos predictivos de producción de corcho y detección precoz de la calidad. Doctoral thesis. Universidade Técnica de Lisboa. Lisboa.

VÁZQUEZ-PIQUÉ J., SUAREZ M.A., TAPIAS R., TORRES E., 2008. Influence of silviculture and environment on cork+wood growth based on band dendrometer data. In: Suberwood. New challenges for the integration of cork oak forests and products. (Vázquez-Piqué J., Pereira H. González-Pérez A., eds). University of Huelva. pp. 183-194

VEGA J.A., FERNÁNDEZ C., FONTURBEL T., PÉREZ-GOROSTIAGA P., 2010. Response of maritime pine (*Pinus pinaster* Ait.) recruitment to fire severity and post-fire management in a coastal burned area in Galicia (NW Spain). Plant Ecol 206(2), 297-308.

WESTFALL J.A., ALLEN H.L., BURKHART H.E., 2004. Young stand growth modelling of intensively-managed loblolly pine plantations in Southeastern US. For Sci 50(6), 823-835.

WILSON J.S., OLIVER C.D., 2000. Stability and density management in Douglas-fir plantations. Can J For Res 30, 910–920.

WOOLLONS R.C., 1998. Even-aged stand mortality estimation through a two-step regression process. For Ecol Manage 105,189-195.

WYKOFF W.R., 1990. A basal area increment model for individual conifers in the Northern Rocky Mountains. For Sci 36(4), 1077-1104.

AÑO INTERNACIONAL
DE LOS BOSQUES · 2011

Edition funded by:

Instituto Universitario de Investigación en
GESTIÓN FORESTAL SOSTENIBLE
Universidad de Valladolid-INIA

Universidad de Valladolid

INIA
Instituto Nacional de Investigación
y Tecnología Agraria y Alimentaria

www.research4forestry.eu

UNIDAD DE GESTIÓN FORESTAL SOSTENIBLE
Universidad de Santiago de Compostela

USC
UNIVERSIDADE
DE SANTIAGO
DE COMPOSTELA

FEDER
Fondo Europeo de
Desarrollo Regional
UNIÓN EUROPEA
"Una manera de hacer Europa"

XUNTA DE GALICIA
CONSELLERÍA DE EDUCACIÓN
E ORDENACIÓN UNIVERSITARIA

www.usc.es/uxfs

Red temática sobre Selvicultura y Gestión Sostenible
de los Sistemas Forestales (SELVIRED)

INIA
Instituto Nacional de Investigación
y Tecnología Agraria y Alimentaria

www.inia.es/selvired