Doctoral thesis

Development of a dynamic stand growth model and optimization of the management of *Pinus pinaster* Ait. in Asturias

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Dissertation submitted to the University of Santiago de Compostela for the degree of Doctor of Philosophy, carried out under the supervision of **Dr. Ulises Diéguez-Aranda**, Associate Professor of the Department of Agricultural and Forestry Engineering of the University of Santiago de Compostela, and **Dr. Marcos Barrio-Anta**, Associate Professor of the Department of Organisms and Systems Biology of the University of Oviedo.

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As well as a personal undertaking, this PhD has also been a process that I have shared with many other people who, consciously or unconsciously, have provided great help and support, which I would like to acknowledge here.

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Lugo, 2015

Manuel Arias-Rodil

Á miña familia
(To my family)

Some individuals use statistics
as a drunk man uses lamp-posts:
for support rather than for illumination.
Andrew Lang (1844-1912), writer and literary critic

List of articles

This thesis is a summary of the following articles, which are referred to in the text by Roman numerals I-III. The overall aim of these studies was to improve forest management of maritime pine stands in Asturias. The articles are reprinted in the present document with the kind permission of the publishers. The corresponding link to each of the articles is included.

I Arias-Rodil, M.; Crecente-Campo, F.; Barrio-Anta, M. and Diéguez-Aranda, U. 2015. Evaluation of age-independent methods of estimating site index and predicting height growth: a case study for maritime pine in Asturias (NW Spain). European Journal of Forest Research 134 (2), 223-233. Springer. ISSN: 1612-4669. DOI: 10.1007/s10342-014-0845-z

`http://link.springer.com/article/10.1007%2Fs10342-014-0845-z`

II Arias-Rodil, M.; Barrio-Anta, M. and Diéguez-Aranda, U. 2015. Developing a dynamic growth model for maritime pine in Asturias (NW Spain): comparison with nearby regions. Annals of Forest Science (available online). Springer. ISSN: 1286-4560. DOI: 10.1007/s13595-015-0501-x

`http://link.springer.com/article/10.1007%2Fs13595-015-0501-x`

III Arias-Rodil, M.; Pukkala, T.; González-González, J.M.; Barrio-Anta, M. and Diéguez-Aranda, U. 2015. Use of depth-first search and direct search methods to optimize even-aged stand management: a case study involving maritime pine in Asturias (northwest Spain). Canadian Journal of Forest Research 45, 1269-1279. NRC Research Press. ISSN: 0045-5067. DOI: 10.1139/cjfr-2015-0044

`http://www.nrcresearchpress.com/doi/abs/10.1139/cjfr-2015-0044#.VbsT45OvGi4`

Manuel Arias-Rodil collected some of the data used, performed the analysis and wrote the manuscripts. Ulises Diéguez-Aranda and Marcos Barrio-Anta conceived the study, supervised the work, gave advice regarding the discussion of the results and revised the manuscripts. Felipe Crecente-Campo gave advice regarding the discussion of the results in the first manuscript. Timo Pukkala helped in optimization implementation, discussion of results and revision of the third manuscript. José Mario González-González helped in the early implementation of optimization algorithms and in revision of the third manuscript.

Abstract

This dissertation comprises three studies that provide tools for improving the management of maritime pine (*Pinus pinaster* Ait.) stands in Asturias (NW Spain). The studies were based on information derived from two networks of research plots established in stands of this species in the region. In Study I, several age-independent methods were evaluated for site index estimation and height growth prediction, as information about stand age is not always collected in forest inventories. The growth intercept method proved the best for estimating site index, while an age-independent equation that uses climatic variables as predictors behaved the best for height growth prediction. In the absence of age data, these methods can be used to provide the input information required by the dynamic stand growth model developed in Study II. In this model, it was assumed that the state of a stand at any age can be described by dominant height, number of stems per hectare and stand basal area, which can be projected to any other age by using transition functions. Two alternative procedures can be used to estimate total and merchantable volumes from these state variables: a stand volume ratio function or a disaggregation system. The former proved the best method as it is more accurate and computationally more efficient. In addition, comparison of the whole model with those developed for the nearby regions of Galicia and northern Portugal showed that a single model may suffice for the entire NW the Iberian Peninsula. Using the developed model and an optimization algorithm, Study III optimized the stand-level management of the species in Asturias in economic terms, considering the number, timing and intensity of thinning operations, as well as the rotation age as decision variables. The depth-first search (DFS) method was initially used to compare the stand volume ratio function and the disaggregation system: both provided similar results, although the former was computationally more efficient and was therefore selected for further optimizations. The DFS and five direct search optimization methods (one based on one solution vector and four on a population of solution vectors) were then compared using a fixed discount rate. The differential evolution method produced the most consistent results and it was used to evaluate the effect of site quality, stem density and discount rate on optimal management schedules. In general, three heavy thinning operations were considered in the optimal schedule. As site quality and discount rate increased, the optimal timing of cutting occurred earlier, while stem density was not influent.

Keywords: site index, height growth, age-independent methods, growth intercept method, state-space approach, disaggregation system, whole-stand model, stand growth simulator, soil expectation value, depth-first search, population-based methods, differential evolution.

Contents

1 Introduction and objectives

1.1 Introduction

1.1.1 Maritime pine

Maritime pine (*Pinus pinaster* Ait.) is a tree species that is mainly distributed throughout southwestern Europe, particularly in Aquitaine (France), central and northern Portugal and northwestern Spain (Sanz et al., 2006) (see Figure 1.1). It is also naturally present in Italy, Greece, Turkey, Morocco and Tunisia, as well as in reforested areas of Australia, South Africa, New Zealand, Chile, Argentina and Uruguay (Sanz et al., 2006). Production is highest in France, where 6.4 Mm^3 volume over bark is harvested each year (Agreste, 2014). In Portugal and Spain, the volume harvested is approximately 3.7 Mm^3 a year (Eira et al., 2010; MAGRAMA, 2012a). In Spain, the species represents the largest growing stock, yielding 15% of the standing volume and 27% of the annual harvested volume (MAGRAMA, 2010). More locally, in Asturias (NW Spain), where this study was focused, maritime pine occupies 22,500 ha of land, which represents almost 5% of the total forest area in the region (MAGRAMA, 2012), with a growing stock of 2.7 Mm^3 over bark, of which 62,500 m^3 are harvested annually (SADEI, 2012).

Maritime pine is a tree species of medium size, reaching heights up to 20-30 m. The needles are large (from 15 to 27 cm), robust and thick (about 2 mm), bluish-green in colour and arranged in pairs. Cones are conical and reach up to 20 cm in length, with 7-9 mm winged seeds, which are released slowly 2 years after establishment (Alía Miranda et al., 2009). The species can grow on poor, sandy and acid soils, which constitutes a competitive advantage relative to other tree species. It also displays high resistance to wind because of its extensive root system (Rodríguez et al., 2007, p. 5).

In Spain, this species has traditionally been divided into two subspecies (Rodríguez Soalleiro and Madrigal Collazo, 2007): (i) maritime or Atlantic pine, mainly located in NW; and (ii) Mediterranean or *mesogeensis*, representing the remaining maritime pine stands. González-Martínez et al. (2004) used molecular marker data from stands within the entire natural distribution of maritime pine and found three maritime pine maternal lin-

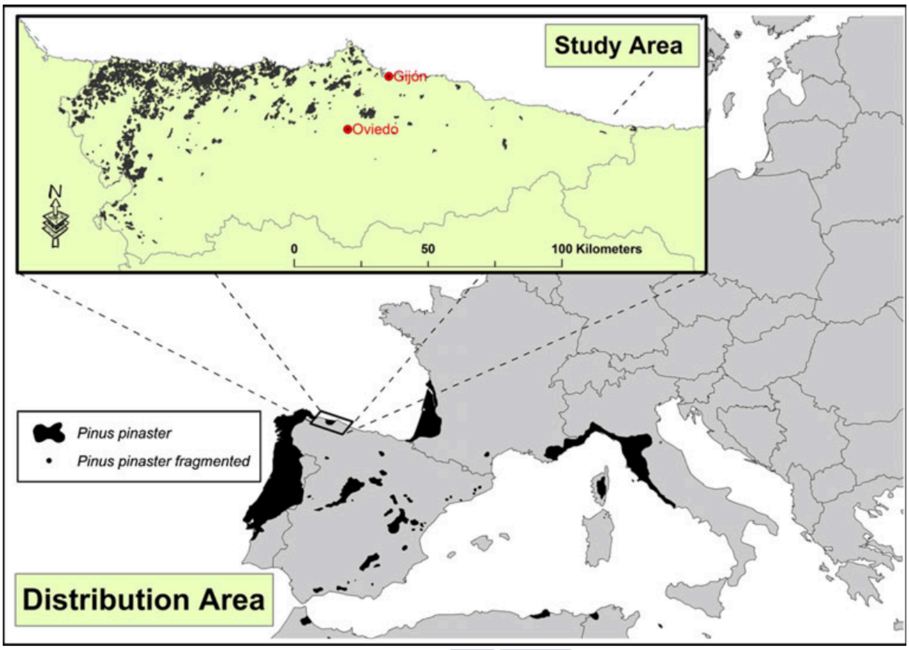

Figure 1.1 Distribution map of maritime pine in Europe (Álvarez-Álvarez et al., 2011)

eages: (i) "western", which corresponds to most of the Iberian Peninsula and western France; (ii) "eastern", which mainly comprises SE France, Italy and Tunisia; and (iii) "Moroccan", restricted to Morocco.

Alía Miranda et al. (2009) distinguished 28 provenance regions of maritime pine in the Iberian Peninsula. Two of these belong to the NW coastal and interior regions, which is consistent with the division proposed by Toval and Vega (1982) and Bara and Toval (1983). Asturias is included in the coastal region, which is characterized by annual precipitation higher than 1300 mm, a mean temperature of 13°C, and an uppermost elevation limit of 600 m.

1.1.2 Forest management

Sustainable forest management, which is a commonly accepted concept worldwide, is based on environmental responsibility, social benefits and economic profit (Diéguez-Aranda et al., 2009, p. 9). Forest science has dealt with this idea for more than 200 years by considering different forest management systems, which can be divided in two wide groups (Gadow and Hui, 2001): Rotation Forest Management (RFM), which are based on a rotation age; and Continuous Cover Forestry (CCF), the aim of which is to maintain continuous cover on forest land. In Asturias, most maritime pine stands are even-aged, which implies that they are managed by RFM systems.

Any resource management requires planning, which implies a decision-making process. Several levels of planning can be considered in forestry (Bettinger et al., 2009, p. 103): tree, stand, forest and landscape. The stand level, which considers each stand to be managed individually (Clutter et al., 1983, p. 110), is the first with true meaning in decision making, as the development of a tree is conditioned by the surrounding trees, and logistic and economic factors make the tree level approach useless, except for high-valued trees (Valsta, 1993, p. 7). The forest level comprises the joint management of all the stands of a forest, while the landscape level may deal with several forests. Decisions at different levels can be interrelated but they do not necessarily need to be complementary (Bettinger et al., 2009, p. 103).

In Asturias, the species mainly grows in even-aged stands derived from plantations or natural regeneration after clearcutting or wildfire (Álvarez-Álvarez et al., 2011). Most maritime pine stands in Asturias (about 83%) are privately owned, both by individuals or by local communities, while the remaining stands are mainly owned by local public institutions (Sendín, 1996). In addition, PROFOR (2011, p. 56) reported that the average size of private stands (of all tree species) in Asturias is 0.6 ha. Therefore, the stand level seems appropriate for managing many of the forest stands in Asturias.

Maritime pine is mainly destined for timber production and, more specifically, to produce sawn timber and also in the pulp or wood-based panel industries, depending on log dimensions (Sanz et al., 2006). In order to maximize the production of high-quality timber, Rodríguez et al. (2007, p. 44) proposed management activities that can be divided in two steps: planting and silvicultural operations. The land should first be prepared by clearing the scrub and subsoiling before planting the trees. After one year, the scrub should be cleared and dead trees replaced. Regarding silvicultural operations, these authors suggest a first set of operations at 10-14 years involving scrub clearance, first thinning and low pruning, followed by a second thinning operation and high pruning at 18-20 years, and a third thinning operation at 24-26 years. Clearcutting is recommended at 35-40 years. Rodríguez Soalleiro and Madrigal Collazo (2007) reported that similar management suggestions were observed in maritime pine stands of Spain, but without specifying any particular timing for operations.

1.1.3 Growth modelling

Some of the main objectives of forest research have included tree and forest stand growth and yield modelling and the evaluation of responses to silvicultural treatments. Correct forest management is based on extensive knowledge of the underlying growth processes of forest species. For this purpose, researchers have developed models that can be implemented in computer programs, allowing simulation of silvicultural options and assessment of their effects on forest systems (Diéguez-Aranda et al., 2009, pp. 11-12).

Several studies have considered different aspects of maritime pine stands in Asturias: Afif Khouri et al. (2009) and Álvarez-Álvarez et al. (2011) evaluated respectively the effects of edaphic factors and nutritional status, and of foliar nutrients and environmental factors on site quality; Canga Líbano et al. (2009) developed models for predicting tree biomass; Gorgoso Varela et al. (2009b) focused on estimation of tree diameter distribution, and Gorgoso Varela et al. (2009a) estimated the joint distribution of tree height and diameter. However, these tools contribute only marginally to stand-level management, whereas a growth model would be fully capable of predicting the future condition of the forest (Weiskittel et al., 2011, p. 1). No growth model was available for this species in the study region prior to carrying out this research.

Forest growth models are commonly grouped in static and dynamic models. The former are suitable for stands which are unthinned or subject to standardized silvicultural regimes, where the absence of input alternatives allows the output to be modelled through fixed functions of time (García, 1994). Examples of this type are, for example, yield tables and density management diagrams (e.g. Diéguez-Aranda et al., 2009, chapter 3 and 2012 addendum update). For dynamic models, the complex relations between inputs and outputs are not directly modelled through time, describing the state of the system in each moment and modelling its corresponding rate of change, which allows more flexibility to simulate thinning schedules (García, 1994). Other possible classification considers empirical or process-based models (Valsta, 1993, p. 11). The latter are based on the underlying growth processes of trees, while empirical models represent practical tools in forest management, as they require a few easy-to-measure (less expensive) input variables, providing accurate yield predictions. Empirical growth models can be classified into three types, depending on the level of resolution of data requirements and predictions (Davis et al., 2001, pp. 185-188): (i) whole-stand models, (ii) size-class models and (iii) individual-tree models. Whole-stand models represent a good compromise between accuracy and generality (García, 2003; Weiskittel et al., 2011, p. 53), especially for single-species, even-aged stands, such as maritime pine stands in Asturias.

Most whole-stand models developed for even-aged stands require to know stand density and to estimate site quality (e.g. Diéguez-Aranda et al., 2006; Álvarez-González et al., 2010; Gómez-García et al., 2015). Stand density can be easily obtained in the field at relatively low cost from a traditional inventory. However, site quality requires phytocentric measures (Weiskittel et al., 2011, p. 38), which are based on tree-based metrics such as site index (defined as the average height of a portion of the dominant and/or co-dominant trees –generally the 100 thickest trees per hectare– at a specific reference age for a particular species), or geocentric measures (Weiskittel et al., 2011, p. 47), which rely on environmental factors such as soil or climate characteristics. For maritime pine in Asturias, Álvarez-Álvarez et al. (2011) developed tools for estimating site index from environmental factors, i.e. they enable computation of site quality when maritime pine is not present. These authors also fitted a site index model that enables prediction of site quality in stands where maritime pine is present and dominant height and age are known. However, age is costly to measure in the field, and this information is not available in many inventories. For such stands, the presence of trees still represents valuable information for correct assessment of site quality, avoiding the error propagation through all components of the growth model (Weiskittel et al., 2011, pp. 37-38). Therefore, a tool for predicting site quality and height growth in the absence of age information would be useful. Development of such a tool was the aim of Study I.

Dynamic whole-stand models are commonly developed on the basis of the state-space concept (García, 1994), in which the state of a stand at any time can be defined by a list of state variables, which can be projected to the future by transition functions, using control functions to simulate silvicultural treatments, and output functions to compute model outputs at any time. Given the characteristics of Asturian maritime pine stands (mentioned above), which are affected by moderate thinning from below, and that the main interest is to estimate merchantable volume (up to a top diameter limit), three state variables are recommended (García, 1994) and widely used (e.g. Diéguez-Aranda et al., 2006; Castedo-Dorado et al., 2007; Álvarez-González et al., 2010; García et al., 2011; Gómez-García et al., 2014; Gómez-García et al., 2015): dominant height, number of stems per hectare and stand basal area. These driving variables, together with stand age, are the only pieces of information needed to simulate the stand growth when this kind of model is used. Nevertheless, stand basal area can be initialized by a function that relates it to other variables such as stem density, site quality, dominant height or age (e.g. Diéguez-Aranda et al., 2006; Castedo-Dorado et al., 2007; Gómez-García et al., 2014; Gómez-García et al., 2015). The aim of Study II was to develop a dynamic stand growth model for maritime pine in Asturias.

Growth and yield models have already been developed for maritime pine stands in adjacent regions in NW Iberian Peninsula: Galicia (summarized in Diéguez-Aranda et al., 2009) and northern Portugal (Tâmega valley, model termed ModisPinaster, Fonseca, 2004; Fonseca et al., 2012). These models were compared in Study II with the Asturian model, as they provide information about the behaviour of this species in each region, which represents another way of evaluating the dynamic growth model developed in this thesis.

1.1.4 Stand-level simulation and optimization

A stand growth model becomes available to use when implemented in a growth simulator, i.e. a computer program that includes a set of functions and algorithms that mimics the development of a stand under different management schedules. In RFM systems, these schedules are defined by number, type, timing and intensity of thinning operations, as well as by the rotation age (or clearcut age). Management alternatives can be sorted by different criteria, depending on the owner's interests, e.g. economic benefit or mean growth. Growth simulators are useful tools that help forest managers evaluate the suitability of each management alternative. This suitability is represented for Asturian maritime pine stands by economic benefit.

For appropriate selection of the best management schedule, we can use an automatic search procedure that iteratively generates and evaluates different alternatives according to an objective function, e.g. economic benefit, until a specific criterion is reached. This is called stand-level optimization, and involves combining a stand growth simulator with an optimization algorithm. However, when a broader forest- or landscape-level perspective is considered, a trade-off may be required for stand-level decisions (Bettinger et al., 2009, p. 125).

A large variety of procedures are used in stand-level optimization, and these have been grouped in two broad categories by Pukkala (2009) and Pasalodos-Tato (2010, p. 13): (i) dynamic programming (Bellman, 1957) and (ii) direct search methods. The former limits the search to a set of nodes defined by discrete state descriptors, where the algorithm guarantees reaching the global optimum, although its computational cost increases with the number of optimized variables (Valsta, 1993, p. 14). Some examples of the application of dynamic programming in this field are those reported by Arimizu (1958), Amidon and Akin (1968), and Díaz-Balteiro and Rodríguez (2006). Direct search methods do not require discretized variables, but have the disadvantage that they do not guarantee that a global optimum will be reached (Valsta, 1993, p. 40). These are the methods most commonly used in recent studies (e.g. Cao et al., 2010; Pukkala and Kellomäki, 2012; Tahvonen et al., 2013). A subdivision was considered in this group (Pukkala, 2009), differentiating between methods that use only one solution vector and those operating with several solution vectors (so-called population-based methods).

Stand-level optimization of maritime pine stands in Asturias was carried out in Study III. Several direct search methods, including population-based methods, were tested. The depth-first search, which has not previously been used in this field and is not included in any of the categories proposed by Pukkala (2009) and Pasalodos-Tato (2010, p. 13), was also evaluated.

1.2 Objectives

This thesis reports three studies with the overall aim of improving the management of maritime pine stands in Asturias. Study I presents several methods of estimating site index and predicting height growth in the absence of age data, even enabling estimation of age. The predictions of these tools can be used as inputs in the dynamic stand growth model developed in Study II, which will provide model predictions less accurate than those obtained with measured age and dominant height. Finally, the dynamic model was used in Study III for optimizing the stand-level management of the species in this region.

Therefore, the objectives of the present study were:

1. Development of a tool for estimating site index and predicting height growth in absence of age information (Study I).
2. Development of a dynamic stand growth model (Study II).
3. Optimization of stand-level management from an economic perspective (Study III).

2 Materials and methods

2.1 Data

Two networks of plots installed in pure, even-aged maritime pine stands were used in the study: (i) 74 permanent plots and (ii) 18 plots included in a thinning trial. The permanent plots were installed in 2007 throughout the distribution area of the species in Asturias (mainly in the NW of the region), covering the existing range of ages, stand densities and site qualities. The plots were measured at the time of establishment, and a second measurement was made in 2011 and 2012 only on a subset of 58 plots because 16 of the initially established plots had disappeared as a result of forest fires or clear-cutting. Growth intercept measurements and destructive sampling of trees were also made within this network of plots. The former were measured in the dominant trees (the proportion of the 100 thickest trees per hectare, depending on plot size) of each plot. The intercepts were considered as the distance (m) between the 1st and the 5th–8th whorls above breast height (BH), averaged by plot. Destructive sampling included stem analysis of two dominant trees and taper data of two intermediate and two suppressed trees located around each plot (only in 73 plots). All these trees were felled and divided into logs of length 0.3–2.5 m; then, height and two diameter measurements were taken at each cross-sectional point; additionally, the number of rings was counted at each section in the dominant trees, which were then converted to age. Diameter measurements along the stem were used to develop a stem taper function (Arias-Rodil et al., 2015), which was then included in the dynamic growth model.

The second data source comprised 18 plots located in 6 sites (3 plots of 1000 m^2 per site), in which each plot was treated in a different way: no thinning (control), light thinning from below (or low thinning), and heavy thinning from below. Three inventories were carried out in 2009, 2011, and 2013, thus providing two available growth intervals per plot.

The measurement protocol was the same for both data sources: diameter at breast height (d, cm, at 1.3 m from the ground) and total height (h, m) were measured respectively to the nearest 0.1 cm and 0.1 m in all trees. Descriptive variables were also recorded for each tree, e.g. if they were alive or dead. The following stand variables were calculated by plot-inventory combination: age (t, years, from plantation date or average age of randomly selected trees); dominant height (H, m, defined as the mean height of the 100 thickest trees per hectare); site index (S, defined as the dominant height of the stand at a reference age of 20 years), estimated using the site index model developed by Álvarez-Álvarez et al. (2011)[1]; number of stems per hectare (N); basal area (G, m^2 ha^{-1}, defined as the total cross-sectional area of all stems in a stand measured at breast height, and expressed as per unit of land area); and total (V, m^3 ha^{-1}) and merchantable (V_i) volumes to different top diameter limits. Stand volumes were computed by aggregation of the corresponding tree volumes estimated with the stem taper function fitted in Arias-Rodil et al. (2015). Summary statistics of stand variables measured in both data sources are presented in Table 2.1. A more detailed summary table can be found in Studies I and II.

Growth intercept and stem analysis measurements of the first data source, together with soil, climatic, and topographic variables (see Álvarez-Álvarez et al., 2011) were used in Study I, while plot measurements from both data sources were used in Study II.

2.2 Methods

2.2.1 Age-independent methods for estimating site index and predicting height growth (Study I)

To estimate site index and predict height growth when stand age and dominant height of the stand are known, the site index curves developed by Álvarez-Álvarez et al. (2011, Table 3.2) can be used. In the absence of data on age, alternative methods must be considered. A growth intercept method (which is only valid for site index estimation), the method proposed by Tomé et al. (2006) and a new iterative method were considered in this study.

[1]Site index values were averaged by plot, assuming that site quality is constant over time

Table 2.1 Data summary

Variable	Mean	Min	Max	SD
1st data source (permanent plots)				
t	30.8	8.0	63.0	14.0
H	16.1	5.5	29.3	5.3
N	1012	111	2480	451
G	39.1	7.8	76.2	15.7
V	269.7	23.5	785.4	169.5
S	11.9	7.1	19.4	2.2
2nd data source (thinning trial)				
t	19.5	12.0	33.0	6.6
H	12.0	7.8	18.3	3.1
N	961	460	1490	326
G	24.3	13.7	44.1	7.3
V	127.1	53.7	278.2	55.2
S	12.7	11.0	15.1	1.2

t stand age (years), H dominant height (m), N number of stems per hectare, G stand basal area (m^2 ha^{-1}), V total stand volume (m^3 ha^{-1}), S site index (m, at reference age of 20 years)

Growth intercept method (GIM)

The growth intercept method (GIM), which was widely used some decades ago (e.g. Warrack and Fraser, 1955; Wakeley and Marrero, 1958; Alban, 1972), is currently recommended for site index estimation at early stages of stand development in some areas (e.g. British Columbia, Mah and Nigh, 2003). It is based on the existing relationship between the growth intercepts between the 1st and 5th–8th whorls of each tree and site quality. Preliminary analysis indicated that a linear model may suffice in our case:

$$S = b_0 + b_1 \mathrm{GI}_{ij} \tag{2.1}$$

where S is the site index (m), GI_{ij} the growth intercept between the ith and jth whorls above breast height, and b_0 and b_1 the intercept and slope of the linear model, respectively.

Tomé et al. (2006) method (TM)

Tomé et al. (2006) proposed a method that formulates growth functions as age-independent equations. This is achieved by solving an equation for age t, then replacing it in the original expression with age $t+\Delta t$, where Δt is the interval age difference. This procedure is implemented with Equations 2.2, 2.3, and 2.4 for Hossfeld (1822) model:

$$H_t = \frac{a_1}{1 + a_2 t^{-a_3}} \tag{2.2}$$

$$t = \left(\frac{a_2}{\frac{a_1}{H_t} - 1} \right)^{1/a_3} \tag{2.3}$$

$$H_{t+\Delta t} = \frac{a_1}{1 + a_2 \left[\left(\frac{a_2}{\frac{a_1}{H_t} - 1} \right)^{1/a_3} + \Delta t \right]^{-a_3}} \tag{2.4}$$

where H_t and $H_{t+\Delta t}$ are dominant heights at ages t and $t + \Delta t$, and a_1, a_2 and a_3 are model parameters.

A family of curves can be obtained if at least one parameter is expressed as a function of site variables, such as climatic, topographic and soil factors, which must be invariant over time. We therefore tested several site variables (by multiple linear regression) already used by Álvarez-Álvarez et al. (2011) to explain site index.

Iterative method (IM)

This method requires an existing height growth model in algebraic difference form (e.g. site index curves developed by Álvarez-Álvarez et al., 2011, see Table 3.2). If two successive height measurements and the time interval between them are known, the age can then be computed numerically by using the above-mentioned model. Finally, age estimate can be used by the height growth model to make predictions.

2.2.2 Development of a dynamic stand growth model (Study II)

The dynamic growth model developed in this study is based on the state-space approach (García, 1994). According to this, stand state at any age is defined by a list of stand variables, which are in this case dominant height (H), stem density (N) and stand basal area (G). These variables are projected by transition functions, and volume can then be predicted at a given time by two volume estimation alternatives: a stand volume ratio function or a disaggregation system. The volume growth can then be estimated by subtraction of the corresponding volumes at different ages. Figure 2.1 shows a scheme of the dynamic stand growth model developed. To evaluate the performance of the dynamic model, we projected the information obtained from the first inventory of the plots used to the ages of second and third inventories. We also compared the developed dynamic model with those already developed for the same species in the nearby regions of Galicia and northern Portugal.

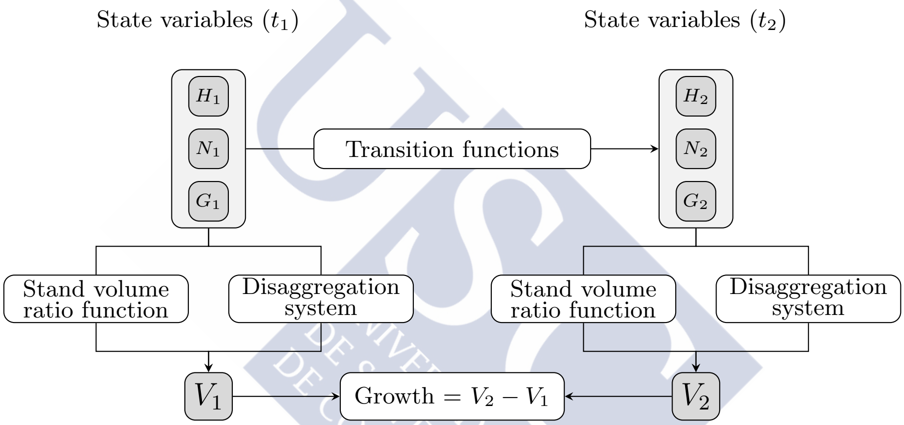

Figure 2.1 Structure of the dynamic model developed. Dominant height (H_1 and H_2), number of stems per hectare (N_1 and N_2), stand basal area (G_1 and G_2), and stand volume (total or merchantable, V_1 and V_2) at ages t_1 and t_2

Transition functions

As a dominant height growth function has already been developed by Álvarez-Álvarez et al. (2011), it was included in the dynamic model as the transition function for dominant height. It was fitted on the basis of stem analysis data from the network of plots of the first data source used in the present study.

The remaining transition functions (for stem density and stand basal area) were fitted by the base-age invariant dummy variables method proposed by Cieszewski et al. (2000) to account for measurement and environmental errors. In addition, as observations of both variables used for fitting were measured in the same plots, the correlation between the errors of these two equations was taken into account by fitting them using seemingly unrelated regression (SUR, Zellner, 1962). Preliminary analyses showed that the best equation for stem density reduction was the Algebraic Difference Approach (ADA, Bailey and Clutter, 1974) model originally proposed by Tomé et al. (1997, Equation 2.5), while the GADA (generalization of ADA, Cieszewski and Bailey, 2000) form of Hossfeld (1822) model (Equation 2.6) was the best for stand basal area projection.

$$N_2 = N_1 \exp\left(a_0(t_2 - t_1)\right) \tag{2.5}$$

$$G_2 = \frac{X_0}{1 + \dfrac{b_2}{X_0} t_2^{-b_3}} \tag{2.6}$$

where N_2 and G_2 are respectively the projected number of stems per hectare and stand basal area ($\mathrm{m}^2\ \mathrm{ha}^{-1}$) at age t_2 (years); N_1, G_1 and t_1 are respectively the initial values of number of stems, stand basal area, and age; $X_0 = \frac{1}{2}\left(G_1 + \sqrt{G_1^2 + 4b_2G_1t_1^{-b_3}}\right)$; and a_0, and b_2 and b_3 are the model parameters.

In addition, an initialization function was developed for stand basal area, which yields an initial estimate of G if site index or dominant height, stem density and age are known for a stand.

Volume estimation

Two alternative methods of estimating merchantable and total stand volume were considered for the developed model: a stand volume ratio function and a disaggregation system. The former equation predicts merchantable volume (to a top diameter limit) as a ratio of total stand volume, directly from stand variables (e.g. stand basal area, dominant height and quadratic mean diameter):

$$V_i = VR_i \tag{2.7}$$

where V_i is the stand volume (m^3 ha^{-1}) to a top diameter limit d_i (cm), $V = f(H, G)$ the total stand volume (m^3 ha^{-1}), depending on G (stand basal area, m^2 ha^{-1}) and H (dominant height, m), and $R_i = f(D_g, d_i)$ the ratio of stand volume to d_i, depending on D_g (quadratic mean diameter, cm) and d_i.

The disaggregation system is the preferred approach for predicting volume within dynamic stand growth models for single-species, even-aged stands in NW Spain (e.g. Diéguez-Aranda et al., 2006; Castedo-Dorado et al., 2007; Gómez-García et al., 2014; Gómez-García et al., 2015). It makes use of a diameter distribution model, which estimates the number of stems in diameter classes, a height–diameter (h–d) model, which predicts the height for the average tree of each class, and a stem taper function, which computes and classifies the volume according to top diameter limits and log lengths (specified by market requirements). For estimation of the diameter distribution, we used the method of moments (Cao et al., 1982) with the Weibull distribution, the parameters of which are recovered from arithmetic and quadratic mean diameter (D_m and D_g, respectively). The latter is easily obtained from stem density and stand basal area $\left(D_g = 100\sqrt{\dfrac{4G}{\pi N}}\right)$, while D_m was modelled with an expression of the form:

$$D_m = D_g - \exp(\beta \mathbf{x}) \tag{2.8}$$

where D_m is the arithmetic mean diameter (cm), D_g the quadratic mean diameter (cm), $\mathbf{x}$ the vector of explanatory variables (e.g. dominant height, stem density), and β is a vector of model parameters. Diameter distribution estimation was evaluated by the Kolmogorov-Smirnov test.

According to previous analyses, the height–diameter model was the generalized form of the model of Burkhart and Strub (1974, Equation 2.9), while the selected stem taper function was the Kozak (2004) model, fitted by OLS in Arias-Rodil et al. (2015) with the information from stem measurements of the first data source.

$$h = 1.3 + (H - 1.3) \exp\left((a_0 + a_1 H + a_2 D_g)\left(\frac{1}{d} - \frac{1}{D_d}\right)\right) \tag{2.9}$$

where h is the tree height (m), d the tree diameter at breast height (cm), H the dominant height (m), D_d the dominant diameter (cm), D_g the quadratic mean diameter (cm), and a_i $(i = 0, 1, 2)$ are the model parameters.

Comparison with other dynamic models

After developing the dynamic growth model, we compared the results with those provided by models for the same species and nearby regions in terms of projection of state variables (projecting information from first inventory of Asturian stands to second and third inventories), prediction of diameter distribution and total stand volume computed from projected state variables, and optimal biological rotation age (the age at which the mean annual increment –MAI– of total stand volume is maximal). The models considered to compare with were those developed for Galicia (included in Diéguez-Aranda et al., 2009) and northern Portugal (ModisPinaster, Fonseca, 2004; Fonseca et al., 2012), which both have a similar structure to the model developed for Asturias (and are based on the same state variables). The dynamic growth model for Galicia was composed by two sub-models corresponding to the two maritime pine provenance regions in Galicia (coast and interior) as considered by Alía Miranda et al. (2009). Nevertheless, Mata and Zas (2010) did not find sufficient evidence for this subdivision.

2.2.3 Optimization of stand-level management from an economic perspective (Study III)

Implementation of the developed dynamic growth model in a stand growth simulator (which also allows simulation of thinning treatments) enables evaluation of different management schedules. Moreover, timber prices and management costs were considered in simulations in order to evaluate the economic profitability. In this study, the objective function (to be maximized) was the soil expectation value (SEV, € ha^{-1}; Equation 2.10; e.g. Valsta, 1993; Pasalodos-Tato et al., 2009), which allows comparison of management schedules involving different rotation lengths, as it assumes that the revenues are reinvested (Bettinger et al., 2009, p. 41).

$$\max_{\{\mathbf{dv}\}} \mathrm{SEV} = \frac{\mathrm{NPV}(\mathbf{dv})}{1 - \dfrac{1}{(1+r)^R}} \qquad (2.10)$$

where r is the discount rate, R the rotation length (years), NPV($\mathbf{dv}$) the net present value computed for the first rotation, and $\mathbf{dv}$ the vector of decision variables, which is composed in this case by the timing and intensity (maximum removal of 45% of the trees) of a maximum of three thinning operations (the first comprises uniform thinning –maximum removal of 20% of the trees– and low thinning, while the remaining consider only low thinning) and the rotation length (or clearcut age).

Stand-level optimization was applied over 16 example stands resulting from the combination of four site indices (S of 7, 10, 13, and 19 m at 20 years) and four stem densities (N of 500, 900, 1300, and 1700 stems ha^{-1} at 20 years). The stand basal area was estimated from these variables by using the initialization function. As several optimization methods were compared, the discount rate was fixed at 4% for this purpose, but was then varied from 1% to 6% for the best method, in order to evaluate the effect of this variable on optimization results.

First, for stand-level optimization, comparison was made of the two volume estimation alternatives considered within the dynamic growth model. A depth-first search was used for this purpose, as it guarantees that a global optimum will be reached, although it requires discretization of the space of solutions. Second, several direct search methods were compared, as they have provided good results in previous studies (e.g. Miina, 1996; Pukkala, 2009; Pukkala et al., 2014a), do not require model differentiability and work with a continuous space of solutions, although they do not guarantee that the global optimum will be reached. Within these, the first considered was the Hooke and Jeeves (1961) method, which uses one solution vector and has been commonly used in stand-level optimization (e.g. Roise, 1986; Haight and Monserud, 1990; Hyytiäinen et al., 2004; Pukkala et al., 2014b). In addition, four population-based methods, which use several solution vectors, were considered. These have been tested recently and showed good results (Pukkala, 2009; Pukkala et al., 2010; Pukkala and Kellomäki, 2012). The following methods were considered: differential evolution (DE, Storn and Price, 1997), particle swarm optimization (PS, Kennedy and Eberhart, 1995), evolution strategy (ES, Beyer and Schwefel, 2002), and Nelder and Mead (1965) (NM). Optimizations with direct search methods were repeated 100 times as the algorithms include a stochastic component.

3 Results and discussion

3.1 Age-independent methods for estimating site index and predicting height growth (Study I)

Regarding site index estimation, GIM proved the best method (root mean square error, RMSE, of 1.194 m), by using the following linear model, which explains the site index from a 7-year growth intercept (from 1st to 8th whorl above breast height):

$$S = -0.162 + 2.430\mathrm{GI}_{18} \tag{3.1}$$

The iterative method outperformed GIM in cases where the observations used were close to or older than the reference age (20 years). The GIM is therefore recommended for site index estimation in young stands, and the iterative method is recommended for old stands.

Regarding height growth prediction, the TM was the best method (RMSE of 1.174 m), yielding even better results than the age-dependent model. The best results were obtained with Equation 3.2, in which a_3 was expanded with the minimum mean temperature of the coldest month (MMTCM, °C) and annual total precipitation (TP, mm):

$$H_{t+\Delta t} = \frac{38.65}{1 + 135.4\left[\left(\dfrac{135.4}{\dfrac{38.65}{H_t} - 1}\right)^{1/a_3} + \Delta t\right]^{-a_3}} \tag{3.2}$$

where $a_3 = 2.83 - 0.0503$ MMTCM $- 0.00125$ TP.

Parameter a_3 was directly related to site index. According to this, the effect of TP on site quality is consistent with that reported by Álvarez-Álvarez et al. (2011), who found that site quality was lower for stands with higher winter precipitation (directly related to TP). However, these authors also observed that a higher mean summer temperature (directly related to MMTCM) corresponded to stands of higher site quality, which contrasts with the results observed in Study I. This was explained by the fact that the true effect of MMTCM on site quality (a more in depth analysis showed that it was directly related with site index) is masked by the effect of the intercept and the TP-related parameter of the a_3 expression (Equation 3.2), i.e. the dimension of intercept and TP parameters masked the positive relation between MMTCM and a_3 (and consequently with S).

According to the length of the prediction age interval, the IM performed best for long intervals, while the TM performed best for short intervals. Therefore, TM is recommended for height growth prediction in the absence of age information, except for long intervals, for which IM is preferred. For known age, the age-dependent method is recommended as it does not require climatic variables (like the TM).

3.2 Development of a dynamic stand growth model (Study II)

Numerical and graphical analyses showed that transition functions appropriately described the changes in stand variables observed in maritime pine stands in Asturias (RMSE in projection: 0.6681 m for H, 24.67 stems ha^{-1} for N, and 2.252 m^2 ha^{-1} for G). For volume estimation, the stand volume ratio function was more accurate than the disaggregation system (22.39 m^3 ha^{-1} against 23.11 m^3 ha^{-1} using projected state variables), with a clear advantage in terms of computational efficiency as it does not involve iterative procedures (the disaggregation system requires this kind of procedures for diameter distribution estimation and volume estimation by the stem taper function). Within the disaggregation system, the Kolmogorov-Smirnov test showed that the diameter distribution was accurately predicted in 94% of the plot-inventory combinations. Table 3.2 shows the equations included in the dynamic stand growth model developed in Study II.

Table 3.1 Equations of the dynamic stand growth model for *Pinus pinaster* Ait. in Asturias. Root mean square error (RMSE) from the fitting process is also shown

	Expression
Transition functions	H transition function (RMSE = 0.594 m)[1]
	$H_2 = \dfrac{41.40}{1 - \left(1 - \dfrac{41.40}{H_1}\right)\left(\dfrac{t_1}{t_2}\right)^{1.325}}$
	N transition function (RMSE = 23.4 stems ha^{-1})
	$N_2 = N_1 \exp\left(-4.296\ 10^{-3}(t_2 - t_1)\right)$
	G transition function (RMSE = 1.88 m^2 ha^{-1})
	$G_2 = \dfrac{X_0}{1 + \dfrac{220117}{X_0} t_2^{-2.255}}$, where $X_0 = \dfrac{1}{2}\left(G_1 + \sqrt{G_1^2 + 880468 \cdot G_1 t_1^{-2.255}}\right)$
	G initialization function (RMSE = 4.78 m^2 ha^{-1})
	$G_1 = 0.005790 S^{1.030} N_1^{0.3971} t_1^{1.057}$
	Stand volume ratio function (RMSE = 11.94 m^3 ha^{-1})
	$V_i = 0.6677 G^{0.9789} H^{0.8440} \exp\left(-0.3427 D_g^{-2.949} d_i^{3.313}\right)$

Continued on next page

Table 3.1 – continued from previous page

	Expression
Disaggregation system	D_m prediction (RMSE = 0.26 cm)
	$D_m = D_g - \exp\left(-1.967 + 0.07495H + 2.430\ 10^{-4}N\right)$
	h–d relationship (RMSE = 1.25 m)
	$h = 1.3 + (H - 1.3)\exp\left(\left(-1.114 - 0.1111H - 0.2562D_g\right)\left(\frac{1}{d} - \frac{1}{D_d}\right)\right)$
	Stem taper function (RMSE = 1.24 cm)[2]
	$d_i = 0.9891 d^{0.9633} h^{0.04585} x^{(0.3672q^4 - 0.3350(1/\exp(d/h)) + 0.5192x^{0.1} + 0.8471(1/d) + 0.01777h^w - 0.02647x)}$, where $x = \frac{w}{1-(1.3/h)^{1/3}}, w = 1 - q^{1/3}, q = h_i/h$

H dominant height (m); N number of stems per hectare; G stand basal area (m^2 ha^{-1}); H_1 and H_2 (m), N_1 and N_2 (stems ha^{-1}), and G_1 and G_2 (m^2 ha^{-1}), state variables at ages t_1 and t_2 (years); S site index (m, at reference age of 20 years); D_g (cm) quadratic mean diameter; D_m (cm) arithmetic mean diameter; D_d (cm) dominant diameter; h (m) tree height; d (cm) over bark tree diameter at breast height (1.3 m above ground level); h_i (m) stem height at which top diameter limit d_i (cm) is reached; V_i ($m^3 ha^{-1}$) stand volume over bark to a top diameter limit d_i.

[1] Computed for the present study using all observed growth intervals of height in both data sources, as done for stem density and basal area.

[2] Extracted from Arias-Rodil et al. (2015)

All the errors obtained from stand variable projection and volume estimation (critical error of 18.4% for stand volume ratio function using projected state variables) were within the limits generally accepted in forest modelling (10-20%, Huang et al., 2003). However, the main limitation of the dynamic growth model developed is that it does not consider subsequent effects of thinning and pruning, unlike in other models (e.g. Amateis, 2000; Álvarez-González et al., 2010; García, 2013).

The comparison between models developed for nearby regions revealed slight differences between transition functions. The Galician model lacks a mortality model, which seems unrealistic given the observed tree mortality in Asturias and northern Portugal. For volume, the Portuguese model provided the poorest predictions over Asturian stands, which is explained by overestimation of the volume equation. Finally, because of differences in the range of the variables used to develop the region-specific models, the results obtained with the whole models (e.g. optimal biological rotations) were affected and therefore not further discussed.

Despite the observed differences between the models developed for these regions, the findings suggest that a single model may suffice for maritime pine throughout NW Iberian Peninsula, which is consistent with the findings of Mata and Zas (2010) regarding the division of Galicia in two provenance regions for maritime pine.

In practice, when using the dynamic growth model, we can take advantage of the tools developed in Study I if information about age is not available (it is assumed that at least dominant height and stem density are known): site index should be estimated by the growth intercept method, and age could then be estimated by the iterative method from the current height and estimate of site index and its corresponding reference age (it represents a height–age pair); height growth could be predicted by the Tomé et al. (2006) method if climatic variables are available, otherwise the age-dependent method should be used with the age estimate (obtained from the iterative method). If age is known, site index and height growth can directly be obtained by the age-dependent model, as it avoids measurement of growth intercepts (required by GIM for site index estimation) and estimation of climatic variables (required by TM for height growth prediction).

If stand basal area cannot be obtained from an inventory, it can be estimated with the initialization equation, which uses stem density, site index and age as predictors. Stand basal area estimates will obviously be more accurate when age is known and does not need to be estimated.

3.3 Optimization of stand-level management from an economic perspective (Study III)

The dynamic growth model developed in Study II was the basic tool used in Study III. For the calculations, we assumed that age is known, i.e. tools from Study I were not considered in this work.

The two alternative methods of volume estimation with the dynamic growth model were compared in stand-level optimization by using the depth-first search algorithm. The soil expectation values were slightly higher when the stand volume ratio function was used, although the differences between optimal schedules were minimal. Therefore, and given that the stand volume ratio function was computationally more efficient, this method was selected for further optimizations.

Concerning the comparison between optimization methods, direct search methods yielded generally higher optimal SEV than DFS, especially Hooke and Jeeves (1961) and differential evolution, as DFS involves discretization of decision variables, which restricts the solution space to a limited set of solutions. In addition, DFS was the slowest method. Within HJ and DE, which yielded the highest optimal SEV, the variability was lower for DE across 100 repetitions. Therefore, DE was subsequently used to evaluate the effect of site quality, stem density and discount rate in optimal schedules.

The optimal SEV increased with site quality because of the higher growth rates associated with higher site quality. It decreased with stem density, as management costs increased further with stem density than the associated income, and it obviously also decreased with discount rate. For the initially assumed discount rate of 4%, it was not profitable to plant maritime pine in stands with site index lower than 13 m (at 20 years). Within this context (even taking into account that 4% may not be truly realistic), costs could be reduced by restricting management operations such as scrub clearance or low pruning, although it may lead to side effects not considered in this study.

For optimal schedules, the timing of cutting corresponds to the moment at which the stand reaches financial maturity, i.e. when its relative value increment (percentage) becomes lower than the discount rate (Duerr et al., 1956). Low thinning (considered in Study III) removes the smallest trees (i.e. less vigorous, with a low relative value increment) and yields an increase in the relative value increment, delaying the moment when financial maturity is reached. Optimal timing of thinning occurred earlier as the discount rate increased because financial maturity was reached earlier, i.e. it is more profitable to extract more of the growing stock when the return from alternative investments increases (Palahí and Pukkala, 2003). Regarding site quality, thinning operations were applied earlier for higher values, because financial maturity is achieved earlier. Stem density did not influence the timing of thinning operations.

Three thinning operations were optimal for most of the example stands, although the number decreased as discount rate decreased and site quality increased. The intensity of thinning was high in all cases (removal of 45% of the stems).

Recommendations for Asturias (Rodríguez et al., 2007) were based on earlier thinning than recommended in the present study, although the thinning intensity was also high. In addition, these recommendations were based on a fixed stem density (1333 stems ha^{-1}), while stand-level optimization can be applied over variable initial stand conditions.

The dynamic growth model (Study II) was developed on the basis of data from stands up to 65 years old. Therefore, although projections beyond this age seem reasonable (Study II), optimal management schedules with rotation beyond this age should be considered with caution. In addition, this model does not consider the later effect of thinning and pruning, advanced regeneration or thinning from above (or high thinning), which would imply removal of dominant trees and, therefore, modification of dominant height.

4 Conclusions

Study I dealt with the development of tools for estimating site index and predicting height growth when information about stand age is not available. In these cases, the growth intercept method is recommended for site index estimation for young stands, but not for old stands, for which the iterative method is suggested. For height growth prediction, the method proposed by Tomé et al. (2006) is recommended, except for long interval predictions, for which the iterative method was more accurate.

Study II showed that the dynamic stand growth model developed for maritime pine in Asturias was adequate for describing the growth and yield of this species in the region. In addition, the stand volume ratio function is recommended for volume estimation, because it was more accurate and computationally more efficient than the disaggregation system. The comparison with models from nearby regions suggested that a single model for maritime pine would suffice for the whole NW Iberian Peninsula.

When using the dynamic growth model in stand-level optimization (Study III), the stand volume ratio function was also preferred as it provided similar results (both in soil expectation values and optimal schedules) to the disaggregation system in terms of SEV, and it is computationally more efficient. When comparing algorithms, differential evolution was deemed the best method because of stability and ranking of soil expectation values provided across repetitions. Thinning operations were applied earlier as discount rate and site quality increased, while stem density did not influence the results. In general, three heavy thinning operations were optimal. Finally, the results from Study III were consistent with the recommendations of Rodríguez et al. (2007) for maritime pine stands in Asturias, in terms of thinning intensity, although they suggested earlier thinning than recommended in the present study.

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6 Study I

Evaluation of age-independent methods of estimating site index and predicting height growth: a case study for maritime pine in Asturias (NW Spain)

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7 Study II

Developing a dynamic growth model for maritime pine in Asturias (NW Spain): comparison with nearby regions

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8 Study III

Use of depth-first search and direct search methods to optimize even-aged stand management: a case study involving maritime pine in Asturias (northwest Spain)

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Appendix: Resumen en español

1 Introducción

El pino marítimo (*Pinus pinaster* Ait.) se encuentra distribuido principalmente en el suroeste de Europa, en la región de Aquitania (Francia), el centro y norte de Portugal, y el noroeste de España. En Asturias (noroeste de España) ocupa 22,500 ha, con un volumen en pie de 2.7 Mm^3 (MAGRAMA, 2012). Las masas situadas en esta región corresponden a la subespecie Atlántica (Rodríguez Soalleiro y Madrigal Collazo, 2007), al linaje maternal "occidental"de acuerdo con González-Martínez et al. (2004), y a la región de procedencia denominada como noroeste-costa por Alía Miranda et al. (2009).

La mayoría de los rodales de pino marítimo de Asturias son regulares (i.e. de la misma clase de edad), por lo que se gestionan en base a un turno de corta (o edad de corta final) (sistemas RFM, por sus siglas en inglés, Gadow y Hui, 2001). La gestión de cualquier recurso requiere una planificación, que en el caso forestal se divide en cuatro niveles: árbol, rodal, monte y paisaje. Puesto que el desarrollo de un árbol se ve afectado por el de los de su alrededor, el primer nivel con significado real en el proceso de toma de decisiones es el de rodal. El nivel monte implica la gestión conjunta de los rodales que lo constituyen, mientras que el nivel de paisaje puede incluir varios montes. Dado que los rodales asturianos de pino marítimo son mayoritariamente de propiedad privada (83 % Sendín, 1996) y la extensión media de las parcelas (considerando todas las especies) es pequeña (0.6 ha, PROFOR, 2011, p. 56), el nivel de rodal parece apropiado para la gestión de muchos rodales de esta especie en la región.

Varios trabajos han considerado diferentes aspectos relacionados con el pino marítimo en Asturias (e.g. Afif Khouri et al., 2009; Álvarez-Álvarez et al., 2011; Gorgoso Varela et al., 2009). Sin embargo, las herramientas desarrolladas hasta el momento ayudan sólo parcialmente a la gestión de esta especie, siendo necesario desarrollar un modelo que permita predecir la evolución general de un rodal. Los modelos forestales de crecimiento se pueden agrupar en modelos estáticos y dinámicos. En los primeros, apropiados para rodales sin claras o sometidos a regímenes estandarizados, la ausencia de alternativas de entrada permite modelar las salidas como funciones fijas del tiempo (García, 1994). Modelos de este tipo son, por ejemplo, las tablas de producción y los diagramas de manejo de la densidad (e.g. Diéguez-Aranda et al., 2009, capítulo 3 y adenda de actualización de 2012). Por su parte, en los modelos dinámicos se evita modelar directamente las complejas relaciones entre entradas y salidas a través del tiempo, describiéndose en su lugar el estado del sistema en cada instante y modelándose la tasa de cambio de estado, lo que permite una mayor flexibilidad en la simulación de alternativas selvícolas (García, 1994). Otra posible clasificación considera modelos empíricos y modelos basados en procesos (Valsta, 1993, p. 11). Los últimos son útiles principalmente en investigación como ayuda para entender, sintetizar y relacionar conocimientos previamente aislados, así como para identificar vacíos donde se necesitan más estudios (García, 1994). Los modelos empíricos se emplean para predecir y están destinados a la planificación de la gestión forestal, al requerir menos variables de entrada y más fáciles de medir (menos costosas), siendo a su vez capaces de proporcionar predicciones precisas. En función del nivel de resolución, los modelos empíricos se pueden clasificar en (Davis et al., 2001, pp. 185-188): (i) modelos de rodal, (ii) modelos de clases de tamaño y (iii) modelos de árbol individual. Los primeros representan un buen compromiso entre precisión y generalidad (García, 2003; Weiskittel et al., 2011, p. 53), especialmente para rodales monoespecíficos y regulares como los de *Pinus pinaster* en Asturias.

La mayoría de los modelos de rodal requieren para su uso una estimación previa de la calidad de estación y la densidad de masa (e.g. Diéguez-Aranda et al., 2006; Castedo-Dorado et al., 2007; Álvarez-González et al., 2010; Gómez-García et al., 2014; Gómez-García et al., 2015). La densidad se puede obtener fácilmente en campo mediante un inventario tradicional. Por su parte, la calidad de estación se puede evaluar basándose en mediciones realizadas sobre los propios árboles (e.g. el índice de sitio, definido como la altura media de los 100 árboles más gruesos por hectárea a una edad de referencia Weiskittel et al., 2011, p. 38), o en medidas ambientales, que se basan en propiedades físicas de la estación como las fisiográficas, climáticas o edáficas (Weiskittel et al., 2011, p. 47). Álvarez-Álvarez et al. (2011) desarrollaron herramientas para predecir el índice de sitio a partir de factores ambientales, i.e. se puede estimar la calidad de estación en lugares en los que la especie no está presente. Por otra parte, estos autores también desarrollaron unas curvas de calidad de estación, que permiten predecir el índice de sitio en rodales en los que el pino marítimo está presente y la altura y la edad son conocidas. Sin embargo, la edad es costosa de medir en campo y, por lo tanto, no está disponible en muchos inventarios. Para dichos rodales, la presencia de la especie aún representa información valiosa para una correcta estimación de la calidad de estación. Por ello, en el Trabajo I se ha desarrollado una herramienta para la predicción de la calidad de estación y del crecimiento en altura en ausencia de información sobre la edad.

Una alternativa común para el desarrollo de modelos dinámicos de rodal es el enfoque del espacio de estados (García, 1994), que se basa en que un rodal puede ser definido en cualquier instante por un conjunto de variables, que pueden ser proyectadas al futuro a través de funciones de transición, empleando a su vez funciones de control para simular tratamientos selvícolas y funciones de salida para calcular las salidas del modelo en cualquier momento. Esta alternativa ha sido la empleada en numerosos trabajos (e.g. Diéguez-Aranda et al., 2006; Álvarez-González et al., 2010; Gómez-García et al., 2015). El objetivo del Trabajo II ha sido el desarrollo de un modelo dinámico de rodal para *Pinus pinaster* en Asturias. Dado que también existen modelos para pino marítimo en regiones próximas del noroeste de la Península Ibérica (Galicia, resumido en Diéguez-Aranda et al. –2009; norte de Portugal, valle del Tâmega, modelo denominado ModisPinaster –Fonseca, 2004; Fonseca et al., 2012), se comparó el modelo desarrollado para Asturias con estos para obtener información sobre el comportamiento de la especie en las diferentes regiones y como otra forma de evaluación del modelo desarrollado.

Un modelo dinámico de rodal se puede incluir en un simulador de crecimiento para evaluar diferentes programas de gestión, que para los sistemas RFM se definen por el número, tipo, momento e intensidad de las claras, así como la edad de corta final. Así, se puede emplear un procedimiento automático de búsqueda que de forma iterativa genere y evalúe diferentes alternativas de acuerdo a una función objetivo, hasta que se alcanza un criterio de parada. Esto es lo que se conoce como optimización a nivel rodal, en la que se pueden utilizar una gran variedad de algoritmos, que han sido agrupados en dos amplias categorías por Pukkala (2009) y Pasalodos-Tato (2010, p. 13): (i) programación dinámica (Bellman, 1957) y (ii) métodos de búsqueda directa. La primera limita la búsqueda a un conjunto de nodos definidos por descriptores discretos de estado, en el que el algoritmo garantiza alcanzar el óptimo global, aunque su coste computacional se incrementa con el número de variables optimizadas (Valsta, 1993, p. 14). Algunos ejemplos de la aplicación de programación dinámica en el campo forestal son Arimizu (1958), Amidon y Akin (1968) y Díaz-Balteiro y Rodríguez (2006). Los métodos de búsqueda directa no requieren variables discretizadas, pero presentan la desventaja de que no garantizan alcanzar el óptimo global. Sin embargo, son los métodos más comúnmente empleados en estudios recientes (e.g. Cao et al., 2010; Pukkala y Kellomäki, 2012; Tahvonen et al., 2013). Dentro de este grupo se puede considerar una subdivisión (Pukkala, 2009), diferenciando entre los que emplean un único vector solución y aquellos que utilizan varios vectores solución (también llamados métodos basados en poblaciones).

En el Trabajo III se ha realizado la optimización económica a nivel rodal de *Pinus pinaster* en Asturias. Para ello se evaluaron varios métodos de búsqueda directa, incluyendo métodos basados en poblaciones, y se probó además el método de búsqueda en profundidad (DFS, por sus siglas en inglés), que no había sido empleado previamente en este campo.

2 Objetivos

Dada la importancia del pino marítimo en Asturias, el presente trabajo tiene como objetivo global la mejora de la gestión de los rodales de esta especie en dicha región. Esta tesis engloba tres trabajos en los que se consideran respectivamente los siguientes objetivos:

1. Desarrollo de herramientas para la estimación del índice de sitio y la predicción de crecimiento en altura en ausencia de información de la edad (Trabajo I).

2. Desarrollo de un modelo dinámico de rodal (Trabajo II).
3. Optimización de la gestión a nivel rodal desde el punto de vista económico (Trabajo III).

3 Datos

En este trabajo se emplearon dos redes de parcelas instaladas en rodales puros y regulares de pino marítimo: (i) 74 parcelas permanentes y (ii) 18 parcelas de un ensayo de claras. Las parcelas permanentes fueron instaladas en el 2007 en el área de distribución de la especie en Asturias (principalmente en el noroeste de la región), cubriendo el rango existente de edades, densidades y calidades de estación. Se realizó la primera medición en el momento de la instalación y una segunda en 2011 y 2012 solamente en un subconjunto de 58 parcelas, ya que 16 de las inicialmente instaladas desaparecieron debido a un incendio o a que fueron cortadas. En esta red de parcelas también se realizaron mediciones de interceptos de crecimiento y de análisis de tronco. Las primeras se realizaron en árboles dominantes (la proporción de los 100 árboles más gruesos por hectárea, dependiendo del tamaño de la parcela), considerados como la distancia (m) entre el 1er y el 5^{o}–8^{o} verticilos por encima de la altura normal (1.3 m), promediados por parcela. Un muestreo destructivo incluyó análisis de tronco de dos árboles dominantes e información de perfil de tronco de dos árboles intermedios y dos sumergidos situados en las proximidades de cada parcela (sólo en 73 parcelas). Se apearon y dividieron en trozas de longitud 0.3–2.5 m, midiendo la altura y dos diámetros perpendiculares en cada sección, y también el número de anillos en el caso de los árboles dominantes, que se convirtió posteriormente en edad. La mediciones de altura y diámetro a lo largo del tronco se emplearon para el desarrollo de una función de perfil (Arias-Rodil et al., 2015), que se incluyó en el modelo dinámico de rodal.

La segunda fuente de datos comprende 18 parcelas localizadas en 6 sitios (3 parcelas de 1000 m^2 por sitio), en los que cada parcela fue tratada de una forma distinta: sin clara (testigo), clara débil por lo bajo y clara fuerte por lo bajo. Se realizaron tres inventarios en 2009, 2011 y 2013, por lo que se dispone de dos intervalos de crecimiento por parcela.

El protocolo de medición fue el mismo en ambas fuentes de datos: se midieron el diámetro a la altura normal (d, cm, a 1.3 m desde el suelo) y la altura total (h, m) en todos los árboles, además de registrarse si estaban vivos o muertos. Posteriormente se obtuvieron variables de rodal para cada combinación de parcela e inventario: edad (t, años); altura dominante (H, m, definida como la media de la altura de los 100 árboles más gruesos por hectárea); índice de sitio (S, definido como la altura dominante a una edad de referencia de 20 años), estimado empleando las curvas de calidad de estación desarrolladas por Álvarez-Álvarez et al. (2011); número de árboles por hectárea (N); área basimétrica (G, m^2 ha^{-1}); y volúmenes total (V, m^3 ha^{-1}) y comercial (V_i) hasta ciertos diámetros límite. El volumen de rodal se obtuvo a partir de la agregación de los correspondientes volúmenes de árbol obtenidos con la función de perfil ajustada por Arias-Rodil et al. (2015).

En el Trabajo I se emplearon las mediciones de los interceptos de crecimiento y el análisis de tronco de la primera fuente de datos, junto con variables de suelo, climáticas y topográficas (ver Álvarez-Álvarez et al., 2011), mientras que en el Trabajo II se emplearon las mediciones de todos los árboles de las parcelas de ambas fuentes de datos.

4 Métodos

4.1 Métodos independientes de la edad para la estimación del índice de sitio y la predicción del crecimiento en altura (Trabajo I)

Para estimar el índice de sitio y predecir el crecimiento en altura cuando la edad y la altura dominante del rodal están disponibles, se pueden emplear las curvas de calidad de estación desarrolladas por Álvarez-Álvarez et al. (2011). Sin embargo, en ausencia de información sobre la edad, se deben considerar métodos alternativos. En este trabajo se consideraron el método basado en los interceptos de crecimiento (sólo válido para la estimación del índice de sitio), el método propuesto por Tomé et al. (2006) y un nuevo método iterativo.

El método de los interceptos del crecimiento (GIM, por sus siglas en inglés) fue ampliamente utilizado hace unas décadas (e.g. Warrack y Fraser, 1955; Wakeley y Marrero, 1958; Alban, 1972) y se recomienda actualmente para la estimación del índice de sitio en algunas áreas para edades tempranas del desarrollo de un rodal (e.g. British Columbia, Mah y Nigh, 2003). Está basado en un modelo linear que relaciona los interceptos de crecimiento entre el 1^{er} y el 5^{o}–8^{o} verticilos de cada árbol con el índice de sitio.

Tomé et al. (2006) propusieron un método (TM, por sus siglas en inglés) que consiste en la reformulación de funciones de crecimiento como ecuaciones independientes de la edad, lo que se consigue resolviendo la ecuación para la edad t, substituyéndola después en la expresión original por $t + \Delta t$, siendo Δt la diferencia de edad. Se puede obtener una familia de curvas si se expresa al menos un parámetro en función de variables de sitio como factores climáticos, topográficos o de suelo, que se suponen invariantes en el tiempo. Se evaluaron diferentes variables de sitio (mediante regresión lineal múltiple), que ya fueron empleadas por Álvarez-Álvarez et al. (2011) para explicar el índice de sitio.

El método iterativo (IM, por sus siglas en inglés) requiere la existencia de un modelo de crecimiento en altura en forma de diferencias algebraicas (e.g. curvas de calidad de estación desarrolladas por Álvarez-Álvarez et al., 2011). Si se dispone de dos mediciones de altura sucesivas y el intervalo de tiempo entre ellas, se puede obtener numéricamente la edad a partir del modelo mencionado. Finalmente, se puede utilizar la edad estimada en dicho modelo de crecimiento en altura para hacer predicciones.

4.2 Desarrollo de un modelo dinámico de rodal (Trabajo II)

El modelo dinámico de rodal desarrollado en este trabajo está basado en el enfoque del espacio de estados (García, 1994). Así, el estado de un rodal está representado por la edad y una lista de variables de estado, que son en este caso la altura dominante (H, media de la altura de los 100 árboles más gruesos por hectárea), el número de árboles por hectárea (N) y el área basimétrica (G, suma de las secciones a la altura normal –1.3 m– de todos los árboles que hay en una hectárea), lo que permite estimar satisfactoriamente, entre otras variables, volúmenes de productos comerciales y parámetros de distribuciones diamétricas para un amplio rango de regímenes selvícolas. Estas variables se proyectan hacia el futuro mediante funciones de transición y se puede estimar el volumen en un instante determinado mediante dos alternativas: una función de razón de volumen de rodal o un sistema de desagregación.

El modelo de crecimiento en altura desarrollado por Álvarez-Álvarez et al. (2011) constituye la función de transición de altura dominante, puesto que se ajustó con los datos de análisis de tronco correspondientes a la primera fuente de datos. Por otra parte, las funciones de transición de número de árboles y área basimétrica se ajustaron por el método de variables *dummy* propuesto por Cieszewski et al. (2000), para tener en cuenta errores ambientales y de medición. Además, se ajustaron de forma simultánea (mediante *seemingly unrelated regression*, SUR, Zellner, 1962) para tener en cuenta la correlación existente entre los errores de ambas funciones al emplearse observaciones procedentes de las mismas parcelas. También se construyó una función de inicialización para el área basimétrica que depende del índice de sitio, el número de árboles y la edad.

La función de razón de volumen de rodal está basada en una ecuación que predice el volumen hasta un cierto diámetro límite a partir de variables de rodal como el área basimétrica, la altura dominante o el diámetro medio cuadrático. El sistema de desagregación está compuesto por un componente de estimación de la distribución diamétrica, un modelo altura–diámetro (h–d) y una función de perfil de tronco. El primero estima el número de árboles por clase diamétrica, en este caso basándose en el método de los momentos (Cao et al., 1982) y la función de distribución de Weibull. El modelo altura–diámetro (h–d) predice la altura para el árbol medio de cada clase diamétrica, empleando una forma generalizada del modelo de Burkhart y Strub (1974). Finalmente, la función de perfil de tronco, que se basa en el modelo de Kozak (2004) ajustado por OLS por Arias-Rodil et al. (2015, con la información de las mediciones de tronco procedentes de la primera fuente de datos), permite calcular y clasificar el volumen de árbol de acuerdo a diámetros límite y longitudes de troza.

Una vez desarrollado el modelo dinámico de rodal para el pino marítimo en Asturias se realizó una comparación con los existentes para la misma especie en: Galicia (incluido en Diéguez-Aranda et al., 2009) y el norte de Portugal (ModisPinaster, Fonseca, 2004; Fonseca et al., 2012).

4.3 Optimización de la gestión a nivel rodal desde un punto de vista económico (Trabajo III)

Para la optimización de la gestión a nivel rodal desde un punto de vista económico de *Pinus pinaster* en Asturias, el modelo dinámico desarrollado se implementó en un simulador de crecimiento de rodal (que también permite la simulación de claras). Además, se consideraron precios de madera y costes de gestión en las simulaciones para evaluar la viabilidad económica de los programas selvícolas generados durante la optimización. En este estudio se consideraron un máximo de tres claras (en las que se corta hasta un máximo del 45 % de los árboles existentes): la primera se compone de una parte sistemática de hasta un 20 % y una parte por lo bajo mientras que el resto son claras por lo bajo. La función objetivo a maximizar fue el valor esperado del suelo (SEV, por sus siglas en inglés, € ha^{-1}, e.g. Valsta, 1993; Pasalodos-Tato et al., 2009), que permite la comparación de programas de gestión con diferentes edades de corta final o turnos, al asumir que los beneficios son reinvertidos (Bettinger et al., 2009, p. 41).

La optimización a nivel rodal se aplicó sobre 16 rodales de ejemplo, resultado de la combinación de cuatro índices de sitio (S de 7, 10, 13, y 19 m a los 20 años) y cuatro densidades de árboles (N de 500, 900, 1300 y 1700 stems ha^{-1} a los 20 años). El área basimétrica se estimó a partir de estas variables empleando la función de inicialización. Dado que se evaluaron varios métodos de optimización, en un primer paso la tasa de descuento se fijó en el 4 %, variándose posteriormente del 1 % al 6 % para el mejor método, con el fin de evaluar el efecto de esta variable en los resultados de la optimización.

El método de la búsqueda en profundidad (DFS, por sus siglas en inglés) se empleó para la comparación en la optimización a nivel rodal de las dos alternativas de estimación de volumen incluidas en el modelo dinámico. La elección de este método se debió a que garantiza que se alcanza el óptimo global, aunque requiere la discretización del espacio de soluciones. Posteriormente, se compararon varios métodos de búsqueda directa que han mostrado buenos resultados en estudios previos (e.g. Miina, 1996; Pukkala, 2009; Pukkala et al., 2014a) y no requieren diferenciabilidad de los modelos. De entre ellos, el primero considerado fue el método de Hooke y Jeeves (HJ, 1961), que emplea un único vector solución y ha sido ampliamente utilizado en optimización a nivel rodal (e.g. Roise, 1986; Haight y Monserud, 1990; Hyytiäinen et al., 2004; Pukkala et al., 2014b). Se evaluaron además cuatro métodos basados en poblaciones, que emplean varios vectores solución y han mostrado buenos resultados recientemente (Pukkala, 2009; Pukkala et al., 2010; Pukkala y Kellomäki, 2012). Los métodos considerados fueron: evolución diferencial (DE, por sus siglas en inglés –Storn y Price, 1997), optimización por enjambre de partículas (PS, por sus siglas en inglés –Kennedy y Eberhart, 1995), estrategia evolutiva (ES, por sus siglas en inglés –Beyer y Schwefel, 2002), y Nelder y Mead (1965) (NM). Las optimizaciones con los métodos de búsqueda directa se repitieron 100 veces ya que los algoritmos incluyen un componente estocástico.

5 Resultados y discusión

5.1 Métodos independientes de la edad para la estimación del índice de sitio y la predicción del crecimiento en altura (Trabajo I)

Para la estimación del índice de sitio, el método que proporcionó mejores resultados fue GIM (empleando un modelo lineal que explica el índice de sitio a partir del intercepto de crecimiento de 7 años –desde el 1er al 8^{o} verticilo por encima de la altura normal). En rodales con una edad próxima o superior a la de referencia (20 años), IM se comportó mejor.

En cuanto a la predicción del crecimiento en altura, TM fue el mejor, mostrando incluso mejores resultados que el método dependiente de la edad.

Dicho método emplea la temperatura media de las mínimas del mes más frío y la precipitación anual total para explicar las diferencias entre estaciones. Teniendo en cuenta la longitud del intervalo de predicción, TM se mostró mejor para intervalos cortos mientras e IM para intervalos largos.

5.2 Desarrollo de un modelo dinámico de rodal (Trabajo II)

Tras un análisis numérico y gráfico se consideró que las funciones de transición explicaron correctamente los cambios observados en las variables de rodal de pino marítimo en Asturias (raíz del error cuadrático medio de 0.6681 m, 24.67 árboles ha^{-1} y 2.252 m^2 ha^{-1} para proyección de H, N y G respectivamente). Para la estimación del volumen, la función de razón de volumen de rodal fue más precisa que el sistema de desagregación, y presenta además una ventaja clara en términos de eficiencia computacional, puesto que no incluye procedimientos iterativos (el sistema de desagregación requiere este tipo de procedimientos para la estimación de la distribución diamétrica y la estimación del volumen por la función de perfil del tronco).

Los errores obtenidos para la proyección de variables de rodal y la estimación del volumen a partir de dichas variables proyectadas (error crítico de 18.4 % en volumen, empleando la función de razón de volumen de rodal) se encuentran dentro de los límites generalmente aceptados en modelización forestal (10-20 %, Huang et al., 2003).

Las comparaciones con los modelos existentes para regiones cercanas (Galicia y norte de Portugal) revelaron ligeras diferencias entre las funciones de transición, atribuibles a las diferencias en los rangos de datos empleados para su desarrollo. Por otra parte, el modelo gallego no dispone de ecuación de reducción del número de árboles debido a competencia intra-específica, lo que parece poco realista dada la mortalidad observada en Asturias y el norte de Portugal. En cuanto al volumen, se observó que la correspondiente ecuación del modelo de Portugal sobreestima el volumen de los rodales de Asturias. Pese a las diferencias observadas entre modelos, los resultados muestran que un único modelo podría ser suficiente para pino marítimo para todo el noroeste de la Península Ibérica, lo que concuerda con las conclusiones de Mata y Zas (2010), quienes cuestionan la división de Galicia en dos regiones de procedencia para el pino marítimo.

Para el uso del modelo dinámico en la práctica, se pueden aprovechar las herramientas desarrolladas en el Trabajo I cuando no se dispone de información de edad (se asume que se conocen al menos la altura dominante y densidad de árboles).

5.3 Optimización de la gestión a nivel rodal desde un punto de vista económico (Trabajo III)

En la comparación entre alternativas de estimación de volumen en la optimización a nivel rodal, la función de razón de volumen de rodal proporcionó valores ligeramente mayores del valor esperado del suelo, aunque las diferencias entre programas óptimos fueron mínimas, por lo que se recomienda ésta para posteriores optimizaciones puesto que es más eficiente computacionalmente.

La comparación entre métodos de optimización mostró que los de búsqueda directa proporcionaron generalmente valores de SEV más altos que DFS, especialmente el método de Hooke y Jeeves (1961) y el de evolución diferencial, ya que DFS implica la discretización de variables de decisión, restringiendo el espacio de soluciones a un conjunto limitado. Además, DFS fue el método más lento. Entre HJ y DE, la variabilidad del SEV para las 100 repeticiones fue menor para DE, por lo que éste fue el método seleccionado para evaluar el efecto de la calidad de estación, la densidad de árboles y la tasa de descuento en los programas de gestión óptimos.

El SEV óptimo aumentó con la calidad de estación por las mayores tasas de crecimiento asociadas a una mayor productividad. En cambio, estos valores se reducieron con la densidad de árboles, debido a que el incremento de los costes de gestión es mayor que el de los ingresos asociados. Según el modelo y para los costes e ingresos considerados, los resultados indican que para una tasa de descuento del 4 %, no es rentable plantar pino marítimo en rodales con índice de sitio menor de 13 m (a los 20 años). Sin embargo, se debe tener en cuenta que 4 % puede no ser realista y que los costes se pueden reducir restringiendo operaciones de gestión como el desbroce de matorral o la poda baja, aunque puede tener efectos colaterales no considerados en este estudio.

El momento óptimo para la realización de las claras se adelantó a medida que aumentó la tasa de descuento, ya que es más rentable extraer la mayor parte de la producción si el retorno de las inversiones alternativas aumenta (Palahí y Pukkala, 2003). En cuanto a la calidad de estación, las claras se aplicaron en los rodales más productivos mientras que la densidad de árboles no fue influyente. En el programa óptimo se consideran tres claras, aunque este número se reduce a medida que disminuye la tasa de descuento y aumenta la calidad de estación. La intensidad óptima de clara fue alta en todos los casos (extracción del 45 % de los árboles).

Las recomendaciones selvícolas existentes para Asturias (Rodríguez et al., 2007) están basadas en claras más tempranas que las propuestas en este estudio, aunque las intensidades propuestas concuerdan.

6 Conclusiones

En el Trabajo I se recomienda el método del intercepto para la estimación de índice de sitio en ausencia de información de edad, excepto para rodales de avanzada edad, para los que se recomienda el método iterativo. Para la predicción del crecimiento en altura cuando no se dispone de la edad se recomienda el método de Tomé et al. (2006), excepto para intervalos largos de predicción, para los que el método iterativo fue más preciso. En el caso que se conozca la edad del rodal, se recomienda utilizar el modelo dependiente de la edad desarrollado por (Álvarez-Álvarez et al., 2011) para estimar el índice de sitio y el crecimiento en altura, ya que no requiere la medición de interceptos de crecimiento (como el GIM) ni disponer de los valores de variables climáticas (como el TM).

El modelo dinámico de rodal desarrollado en el Trabajo II describe adecuadamente el crecimiento y producción del pino marítimo en Asturias. Para la estimación del volumen se recomienda el empleo de la función de razón de volumen de rodal frente al sistema de desagregación, ya que proporcionó resultados más precisos y es más eficiente desde un punto de vista computacional. En cuanto a la comparación entre modelos de diferentes regiones, los resultados obtenidos sugieren que un único modelo podría ser suficiente para todo el noroeste de la Península Ibérica.

En la optimización económica a nivel rodal (Trabajo III) se recomienda también la función de razón de volumen de rodal dado que proporcionó resultados similares al sistema de desagregación y es más eficiente computacionalmente. En la comparación entre algoritmos, el método de evolución diferencial se mostró como el más adecuado debido a la estabilidad y orden de los valores esperados del suelo proporcionados en todas las repeticiones. El momento óptimo de realización de claras se adelantó a medida que la tasa de descuento y la calidad de estación se aumentaron. En general, el programa selvícola óptimo se compone de tres claras intensas.

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