Forest Ecology and Management 262 (2011) 1491–1499

Contents lists available at ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco

Prediction of annual tree growth and survival for thinned and unthinned even-aged maritime pine stands in Portugal from data with different time measurement intervals

Luís Nunes [a,*], José Tomé [b], Margarida Tomé [b]

[a] Centro de Investigação de Montanha (CIMO), Escola Superior Agrária, Instituto Politécnico de Bragança, Campus de Santa Apolónia, Apartado 1172, 5301-854 Bragança, Portugal
[b] Centro de Estudos Florestais (CEF), Instituto Superior de Agronomia, Universidade Técnica de Lisboa, Tapada da Ajuda, 1349-017 Lisboa, Portugal

ARTICLE INFO

Article history:
Received 22 April 2011
Received in revised form 27 June 2011
Accepted 28 June 2011
Available online 2 August 2011

Keywords:
Individual tree model
Diameter growth
Height growth
Survival
Thinning response
Pinus pinaster Ait.

ABSTRACT

An annual individual tree survival and growth model was developed for pure even-aged stands of maritime pine in Portugal, using a large data set containing irregularly time-spaced measurements and considering thinning effects. The model is distance-independent and is based on a function for diameter growth, a function for height growth and a survival function. Two approaches are compared for modeling annual tree growth. The first approach directly estimates a future diameter or height using well-known growth functions formulated in difference form. The second approach estimates diameter or height using a function in differential form estimating the increment over a year period. In both approaches, the function parameters were related to tree and stand variables reflecting the competition *status* of the tree as well as of a thinning response factor. Variable growth and survival rates were assumed in the modeling approaches. An iterative method was used to continuously update tree and stand attributes using a cut-off to convert the survival probability for a living or a dead tree. The individual tree diameter growth model and the survival probability model were fitted simultaneously using seemingly unrelated regression (SUR). Parameters of the height function were obtained separately as the number of observations for height was much lower than the number of observations for diameter, which may affect the statistical inference and the estimation of contemporaneous cross-equation error correlation inherent to the system of equations. PRESS residuals were used to evaluate the predictive performance of the diameter and the height growth functions. Additional statistics based in the log likelihood function and also in the survival probability were computed to evaluate the survival function. The second modeling approach, which integrates components of growth expansion and decline, performed slightly better than the first approach. A variable accounting for the thinning response that was tested proved to be significant for predicting diameter growth, even if the model already included competition-related explanatory variables, namely the basal area of trees larger than the subject tree. However, this thinning response factor was not significant for predicting height growth.

1. Introduction

Maritime pine (*Pinus pinaster* Ait.) is the most important Portuguese conifer species occupying an area of 885,000 ha (Autoridade Florestal Nacional, 2010). In the last century, the area of maritime pine in Portugal reached 1.3 million ha in the decade of 60, maintaining this level until the beginning of the decade of 80. During this period, many industries related to the exploitation of the maritime pine succeeded and grew rapidly. Mainly as a result of forest fires, the area of maritime pine decreased to less than 1 million ha in the last two decades but it still remains relevant to the national economy.

The Portuguese national forest strategy (Direcção Geral dos Recursos Florestais, 2006) proposed a specialization of the Portuguese forest territory according to three main functions: wood production, multifunctional systems and protected areas. Wood production is mostly related to pure even-aged stands of two species, the maritime pine and the blue gum (*Eucalyptus globulus* Labill.). Sustainable forest management of these productive areas requires adequate prediction of wood stocks and growth.

Individual tree growth and yield models are especially useful for management planning because they are capable of simulating a wide variety of management activities, particularly thinning (Clutter et al., 1983). They often describe annual changes in growth and survival of individual trees providing detailed information about stand structure, thus being very useful when linked to other models such as systems of equations predicting total and

* Corresponding author. Tel.: +351 273 303 381; fax: +351 273 325 405.
E-mail address: lfnunes@ipb.pt (L. Nunes).

0378-1127/$ - see front matter © 2011 Elsevier B.V. All rights reserved.
doi:10.1016/j.foreco.2011.06.050

merchantable volume or systems of biomass equations for carbon stocks estimation as well. In Portugal, these last models have already been developed for maritime pine (Nunes et al., 2010; Faias, 2009). However, no individual tree growth model is available for this important tree species.

Available data sets for fitting individual tree models frequently have measurement intervals greater than 1 year and many times these intervals are irregularly spaced. Also, thinning can occur between measurements. This causes difficulty when modeling annual tree growth and survival. Individual tree growth depends on stand variables which are usually taken into account by expressing some of the model parameters as a function of stand variables. This implies the need to fit individual tree growth models on an annual basis (the model time step), so that the development of stand variables can be taken into account. The linear growth assumption for interpolating tree growth during time step intervals greater than 1 year is almost always inconsistent with the mathematical function used to estimate growth and can introduce bias in the projections (McDill and Amateis, 1993). These authors introduced two interpolation methods as an improvement to the constant rate method in diameter growth modeling. The concept was further extended by Cao et al. (2002) to more than one tree variable. However, these interpolation methods still considered a constant survival rate for the growth period. Cao (2000) proposed a method to account for variable rates of both tree survival and diameter growth, using an iterative technique to update interim values of stand-related explanatory variables in the model. This methodology was successfully used by Crecente-Campo et al. (2010) to model Scots pine growth in Galicia (Spain). An alternative requiring less computational efforts and performing equally well consists in predicting stand attributes using a stand-level model (Cao, 2004; Cao and Strub, 2008). This last method has the disadvantage of depending on the quality of the stand level models used.

In this study, an annual individual tree survival and growth model is developed for pure even-aged stands of maritime pine in Portugal, using data with irregularly spaced measurement intervals and considering thinning effects. The central components of the model are the equations for diameter growth, height growth and survival. Variable growth and survival rates are assumed in the modeling approach. The model is distance-independent and will be useful for intensively managed areas of pure even-aged stands of maritime pine.

2. Materials and methods

2.1. Data

The data set used to develop the individual tree survival and growth model were from thinning experiments in a total of 145 permanent sample plots. The experiments, established between 1981 and 1998 in pure even-aged stands dating back from the decades of 1960 and 1970, cover a broad range of the maritime pine distribution area in Portugal (Fig. 1). Plot sizes ranged between 500 and 1000 m^2 (mostly 1000 m^2) and the number of measurements per plot varied between a minimum of two and a maximum of 10. All trees in the plots were measured for diameter at breast height (d) and a record whether the tree was alive or dead was made. Total height (h) was measured on the dominant trees (100 largest in *dbh* trees per hectare) and also on some sample trees by diameter class. There are different treatments concerning thinning intensity that goes from low to heavy thinning, including no thinning, and also situations of increasing and decreasing thinning intensity. All thinnings were from below but taking into account the quality of the trees for industry, namely stem shape, branchiness, broken tops, forking. This implies that, even if the thinning is from below, some large trees are also thinned, especially in the thinnings at young ages.

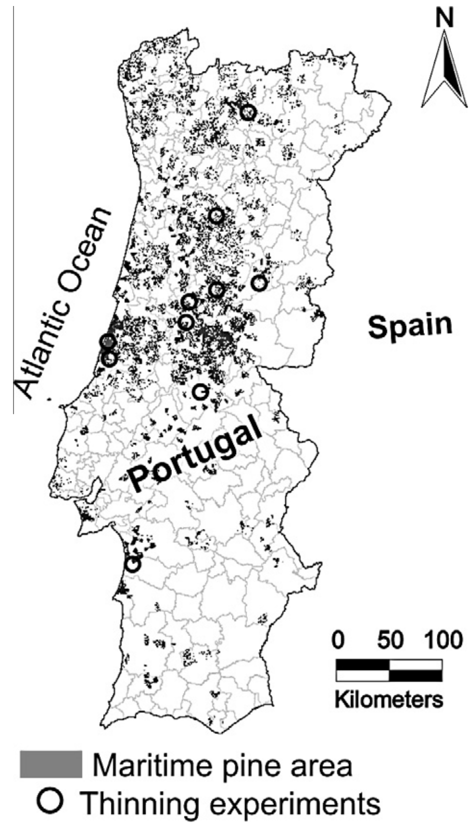

Fig. 1. Location of the thinning experiments.

There were 40367 observations for fitting the individual tree diameter growth model and 20520 observations for the individual tree height growth model. The time intervals between two consecutive measurements ranged from 1 to 5 years. Summary statistics of the data are presented both at the tree and stand level (Table 1).

2.2. Models

The individual tree growth model here developed includes components for the increase of stem diameter and total tree height. Two modeling approaches were compared. In the first approach, both diameter and height were expressed as a function directly estimating a future diameter or height. In this approach, several well-known growth functions were tested in the difference form, relating the parameters to site, stand variables and distance-independent competition indices.

Table 1
Summary statistics for the fitting data set.

Variable	Unit	Obs.	Mean	SE	Minimum	Maximum
Tree level						
d	cm	40367	12.7	6.6	0.5	45.5
h	m	20520	8.1	4.7	1.3	27.5
Stand level						
N	trees ha^{-1}	145	1540	828	300	6330
G	m^2 ha^{-1}	145	23.5	16.8	0.21	59.06
dg	cm	145	13.2	5.4	1.2	31.6
hdom	m	145	11.4	4.6	2.5	25.3
t	years	145	23	8	5	43

d – tree diameter, *h* – tree height, *N* – number of trees per hectare, *G* – stand basal area, *dg* – quadratic mean diameter, *hdom* – dominant height, *t* – stand age.