Forest Ecology and Management 283 (2012) 56–65

Contents lists available at SciVerse ScienceDirect

Forest Ecology and Management

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

Site classification and growth models for Sitka spruce plantations in Ireland

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ARTICLE INFO

Article history:
Received 23 April 2012
Received in revised form 4 July 2012
Accepted 5 July 2012
Available online 9 August 2012

Keywords:
Site classification
Nonlinear quantile regression (NLQR)
Sitka spruce
Top height-age models
Growth model
Chapman-Richard

ABSTRACT

Site classification has been identified as an important tool in forestry for the quantification of a forest site's productivity potential. It is useful in forest management and silvicultural decision making for example when deciding on when to start thinning and or when to clearfell a forest of a particular species, and for estimating stands development patterns across sites. This paper presents top height-age site classification and growth models for Sitka spruce (*Picea sitchensis* (Bong.) Carr.) forest plantations in Ireland using nonlinear quantile regression (NLQR) methodology.

Repeated top height – age measurements were recorded from over 700 Coillte Teoranta (Irish Forestry Board) silvicultural permanent sample plots (PSPs) in seven Irish forest regions over the past six decades.

The conditional quantiles ($0 \leqslant \tau \leqslant 1$) of the top height distribution at a given age were used as a sorrugate to classify Irish Sitka spruce plantations into five polymorphic site classes of I, II, III, IV and V in order of decreasing productivity, and for fitting the site class growth models using the Chapman-Richard nonlinear growth function.

The NLQR methodology performed better than the traditional guide curve methodology for constructing top height-age site index curves when compared to the NLQR median ($\tau = 0.5$) predictive growth model. The fit statistics deviance of 10639.6 for the NLQR median ($\tau = 0.5$) predictive growth model was considerably smaller than the fit statistics deviance of 71736.3 for the comparable Nonlinear least square (NLS) mean top height-age growth model.

The model predicted top heights of 27.6 m ± 2.4%, 23.3 m ± 2.9%, 20.4 m ± 2.8%, 17.4 m ± 2.9% and 16.0 m ± 2.1% are to be expected in Sitka spruce stands at age 30 years on site classes I, II, III, IV and V respectively.

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1. Introduction

Forestry has gained prominence in Ireland with 10.82% of the total land area covered by forests (Forest Service, 2010). Sitka spruce (*Picea sitchensis* (Bong.) Carr.) is the most important commercially grown tree species in Irish forestry (Joyce and O'Carroll, 2002). It accounts for 52.3% of the total area of state and private managed forests in the Republic of Ireland (Olajuigbe et al., 2011), 61.6% of which was planted by the private sector (Forest Service, 2008). Sitka spruce is native to the Pacific Northwest, British Columbia and Alaska and was introduced into Co. Wicklow in 1835. It has been found to grow well on a wide range of soil and site conditions in Ireland (Farrelly et al., 2009).

Irish forestry still depends, at least partially, on the Forestry Commission (FC) top height-age site class growth curves for growth estimation and decision making (Phillips et al., 2009; Gallagher and O'Carroll, 2001; Picardo, 2000; Broad and Lynch, 2006a; Phillips, 1999). However, no research has addressed the need for Irish Sitka spruce site classification growth curves derived from Irish forest data.

Site classification, which is the quantification of a forest site's potential to produce timber of a particular species (Sajjaduzzaman et al., 2005; Ford et al., 2007), is usually expressed by the growth and development of a forest stand. Forest managers often rely on it for growth estimation and for important silvicultural decision making, such as when to start thinning and or when to clearfell the forest (Vanclay and Henry, 1988; Dolph, 1991). The main objective of site classification is the quantification of the height development patterns that stands are expected to follow throughout their rotations (Clutter et al., 1983; Ford et al., 2007; Kangur et al., 2007). Top height, which is the average height of a number of 'top height trees' in a stand, where a 'top height tree' is the tree of largest diameter breast height (dbh) in a randomly selected 0.01 ha sample plot (Edwards and Christie, 1981) and together with stand age have been widely used as a surrogate for determining site productivity

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http://dx.doi.org/10.1016/j.foreco.2012.07.003

especially in Ireland and the United Kingdom (Rennolls, 1995). This arises because top height is largely independent of stocking density and unaffected by thinning intensity within the normal range of thinning practices (Sajjaduzzaman et al., 2005); it is easy to derive (Ford et al., 2007) and is highly correlated with cumulative volume and basal area production (Edwards and Christie, 1981).

Site index (SI) which is height at a reference age (Dieguez-Aranda et al., 2005; Wang and Huang, 2000) has been a widely used method for quantifying forest site productivity (Sharma et al., 2002; Nunifu and Murchinson, 1999; Louw and Scholes, 2002; Onyekwelu, 2005; Sajjaduzzaman et al., 2005; Lee, 2002; Muys et al., 2011). SI method is usually very easy to implement (Dieguez-Aranda et al., 2005) by modelling mean growth or Guide Curve using nonlinear least square (NLS) or ordinary least square (OLS) to approximate average site class growth (Omule, 1987). By holding the shape parameters constant, and subjectively varying the asymptotic parameter as necessary, lower or higher sites classes are obtained (Onyekwelu, 2005; Bermejo et al., 2004). However, the Guide Curve is accurate only if the ranges of site indices are equally represented at all ages (Carmean, 1972; Graney and Burkhart, 1973; Dolph, 1991).

Site classification and growth modelling largely relies on permanent sample plot (PSP) data which are longitudinally correlated in nature (Kangur et al., 2007), and a common feature of tree growth data is that they are usually skewed. Therefore, site classification and growth estimation using data of this nature requires a more robust methodology (Coad and Rao, 2008). Various approaches have been adopted in order to take account of the longitudinal nature of the PSP data in quantifying tree growth (Fonweban et al., 2012) with varying success. Examples of such methodologies includes mixed effect modelling (Calegario et al., 2005) and differential equations (Garcia and Ruiz, 2003; Broad and Lynch, 2006a). A common feature of these methods is that they usually use the mean as a measure of centrality (Karlsson, 2005), but the mean is said to have low efficiency and difficult to interpret for skewed data (Koenker and Bassett, 1978).

Consequently, this study introduces nonlinear quantile regression (NLQR) as a tool for objective forest site classification and growth modelling. NLQR is known to be robust to outliers, nonlinearity of observed response, longitudinal correlated data (Kangur et al., 2007; Lee et al., 2003) and less strict on the distributional assumption of error terms (ε_i) (Koenker and Bassett, 1978).

The aims of this study were: (1) to develop reliable top height-age site classification models for Sitka spruce sites in Ireland; (2) to develop site growth models for the site classes; (3) to compare the NLQR median growth model and the NLS mean or Guide Curve growth model and (4) to populate a site classification parameter database for Sitka spruce plantations in Ireland to facilite forecasting timber supply.

2. Materials and methods

2.1. Study area and PSP database

The study was conducted using repeatedly measured data from the silvicultural PSP database provided by Coillte Teoranta (Irish Forestry Board). From the 1960s, silvicultural thinning/spacing and spacing/nothining experiments were conducted by Coillte in over 700 PSPs scattered over seven Irish forest regions; Wicklow; Kilkenny; Sligo; Mullingar; Limerick; Cork and Galway (Fig. 1). The spatial distribution of the PSPs was considered sufficient to capture the various Irish forest site edaphic and climatic conditions. The PSPs varied in size typically from 0.01 to 0.05 ha.

Most of the PSP experiments were laid out using randomised block designs. Within each PSP, a number of top height trees were selected and repeatedly measured at a regular interval for height (m) and age (years) (Table 1a). Where the height of a selected tree was less than 1.3 m (breast height), which is common in young stands, the individual tree height was assumed to be top height. The silvicultural experiments were established on more productive public-owned forest sites across the seven regions. In order to include a wider range of Irish forest site growing conditions, additional sample plots were laid out in non-research state-owned forest sites across the same regions (Broad and Lynch, 2006a). Within each non-research plot a number of top height trees were selected and measured for height and age (Table 1a). Coillte Teoranta has maintained an extensive computerized database of remeasured PSP and non-research plot data (Broad and Lynch, 2006b).

As the Coillte experimental and non-research plots did not cover private-owned forests, the current project laid out a number of randomly selected plots in privately owned Sitka spruce stands in Wicklow and Cork regions. Within each plot, a number of top height trees were selected and the distance between consecutive whorls were measured to obtain annual top-height-age remeasured private forest data.

2.2. Modelling data

In this study, Sitka spruce top height-age data for the public forest for each region were selected from the database and were subsequently pooled with the private forest data to give a total of 578 plots (355 thin/spacing and 223 nothin/spacing) which resulted in 4190 remeasured top height trees and a total of 11421 paired top height-age Sitka spruce national dataset which were used for modelling (Fig. 2) and the summary statistics computed (Table 1b). To create the model validation dataset, the nothin/spacing PSPs in the Sitka spruce database whose names started with letters E–Z across the seven regions were set aside from the modelling dataset for model validation, which resulted in a total of 77 nothin/spacing PSPs, 499 top height trees and 1120 individual independent paired top height-age observations.

2.3. Growth modelling for site evaluation

2.3.1. Mean growth or Guide Curve model for evaluating average site productivity

The mean growth or Guide Curve functional form may be expressed as:

$$\mathbf{y}_i = f(\mathbf{t}_i, \mathbf{b}) + \mathbf{e}_i \tag{1}$$

where $\mathbf{b} = (b_0, b_1, \ldots, b_k)^t$ is the k-dimensional vector of unknown asymptotic biological parameters to be approximated, $\mathbf{y} = (y_1, y_2, \ldots, y_n)^t$ is $n \times 1$ dimensional vector of the observed response variable; $\mathbf{t} = (t_1, t_2, \ldots, t_n)^t$ is the $n \times 1$ dimensional vector of the observed independent variable; $\mathbf{e} = (e_1, e_2, \cdots, e_n)^t$ is the random error term and n the number of measurements with $i = 1, 2, \ldots, n$.

The Chapman-Richards four parameter growth function (Khamis et al., 2005; Fekedulegn et al., 1999; Zhao-gang and Feng-ri, 2003; Colbert et al., 2003; Rennolls, 1995) Eq. (2) and three parameter growth function (Díaz-Maroto et al., 2010; Rupšys and Petrauskas, 2010; Onyekwelu, 2005; Bermejo et al., 2004) Eq. (3) were used to fit a mean growth model to the 11421 top height-age paired dataset.

$$y_i = b_0(1 - b_1 e^{-b_2 t})^{(1-b_3)^{-1}} + e_i \tag{2}$$

$$y_i = b_0(1 - e^{-b_2 t})^{b_3} + e_i \tag{3}$$

where y_i is the observed top height (m), t is the age at measurement (year), b_0 is the maximum attainable top height and also the site

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