Forest Ecology and Management 409 (2018) 434–443

Contents lists available at ScienceDirect

Forest Ecology and Management

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

A stand table projection system for interior Douglas-fir in British Columbia, Canada

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ARTICLE INFO

Keywords:
Growth and yield
Diameter distribution model
Seemingly unrelated regression
Diameter growth equation
Prognosis^{BC}

ABSTRACT

This study developed a stand table projection system for interior Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco var. *glauca* (Beissn.) Franco) in British Columbia, Canada. Simulation data, obtained by running Prognosis^{BC} (with 150 year projections) using input derived from 140 permanent sample plots, were utilized for model construction. First, a whole-stand attributes (number of trees per ha, quadratic mean diameter, and arithmetic mean diameter) prediction model was constructed. Weibull parameters for the diameter distribution of the future stand were estimated from the predicted stand attributes using two parameter prediction methods (via seemingly unrelated regression and the cumulative distribution function) and one parameter recovery method. The future stand table was projected with the estimated Weibull parameters and compared with two stand diameter distribution adjustment algorithms, yielding a total of nine parameter estimation-diameter adjustment combinations. The outputs from the stand table projection model were evaluated with repeated measures data covering 20 years from 18 independent plots, as well as compared with the outcomes predicted by Prognosis^{BC} for those plots. The diameter class adjustment procedure applying tree mortality prior to growth, combined with the cumulative distribution parameter prediction method, performed best among the nine combinations we compared. The stand table projection system yielded similar results to Prognosis^{BC} on the evaluation data and is expected to be a useful tool for managing forests sustainably and effectively.

1. Introduction

A recent massive mountain pine beetle (*Dendroctonus ponderosae* Hopkins) outbreak throughout much of the interior of British Columbia (BC), Canada, has resulted in considerable lodgepole pine (*Pinus contorta* Douglas ex Loudon var. *latifolia* Engelm. ex S. Watson) mortality, leading to reconstruction of overall harvesting operation and management plans (Lamers et al., 2014; Peter and Bogdanski, 2010). These changes have emphasized increasing harvest of interior Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco var. *glauca* (Beissn.) Franco) forests (Forest Practices Board, 2014; Nicholls, 2013).

Interior Douglas-fir forests in British Columbia are managed for a variety of objectives in addition to timber products. For example, habitat management of winter range for mule deer (*Odocoileus hemionus hemionus* Rafinesque) (Armleder et al., 1994) and coarse woody debris recruitment (Clark et al., 1998) are major considerations in parts of this forest type (BC Ministry of Forests, 1995). Reducing catastrophic wildfire risk (Steele et al., 1986) and maintaining water quality and supply, while coping with an increasing human population and extreme weather events (Boon, 2007; Stednick, 1996), are also major management considerations in some areas. Furthermore, partial harvesting may be preferred to clear cutting to facilitate establishment of interior Douglas-fir regeneration (D'Anjou, 1998). Versatile forest management that is sensitive to all of these factors is necessary to manage these forests sustainably.

Prognosis^{BC} is a growth and yield simulator, derived from the North Idaho variant of the Forest Vegetation Simulator (Dixon, 2002; Stage, 1973; Wykoff et al., 1982) and calibrated to be applicable to various forest types in BC (Snowdon, 1997; Zumrawi et al., 2002). This simulator is the primary option available to evaluate silvicultural and harvesting alternatives for interior Douglas-fir forests in BC because it can handle multi-aged and multi-species stands and it can simulate a wide range of management practices and disturbance events. Prognosis^{BC} has been used widely, especially for BC's southeastern forests, for which it

Abbreviations: AD, Anderson-Darling statistic; AIC, Akaike information criterion; BC, British Columbia; CB, Cao-Baldwin (algorithm); CDF, cumulative distribution function; EI, error index; KS, Kolmogorov-Smirnov statistic; mLogL, negative log-likelihood statistic; NS, Nepal-Somers (algorithm); PPM, parameter prediction method; PRM, parameter recovery method; RMSE, root-mean-squared error; SDI, stand density index; std, standard deviation; SUR, seemingly unrelated regression; WA, without adjustment

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https://doi.org/10.1016/j.foreco.2017.11.048
Received 8 September 2017; Received in revised form 22 November 2017; Accepted 22 November 2017

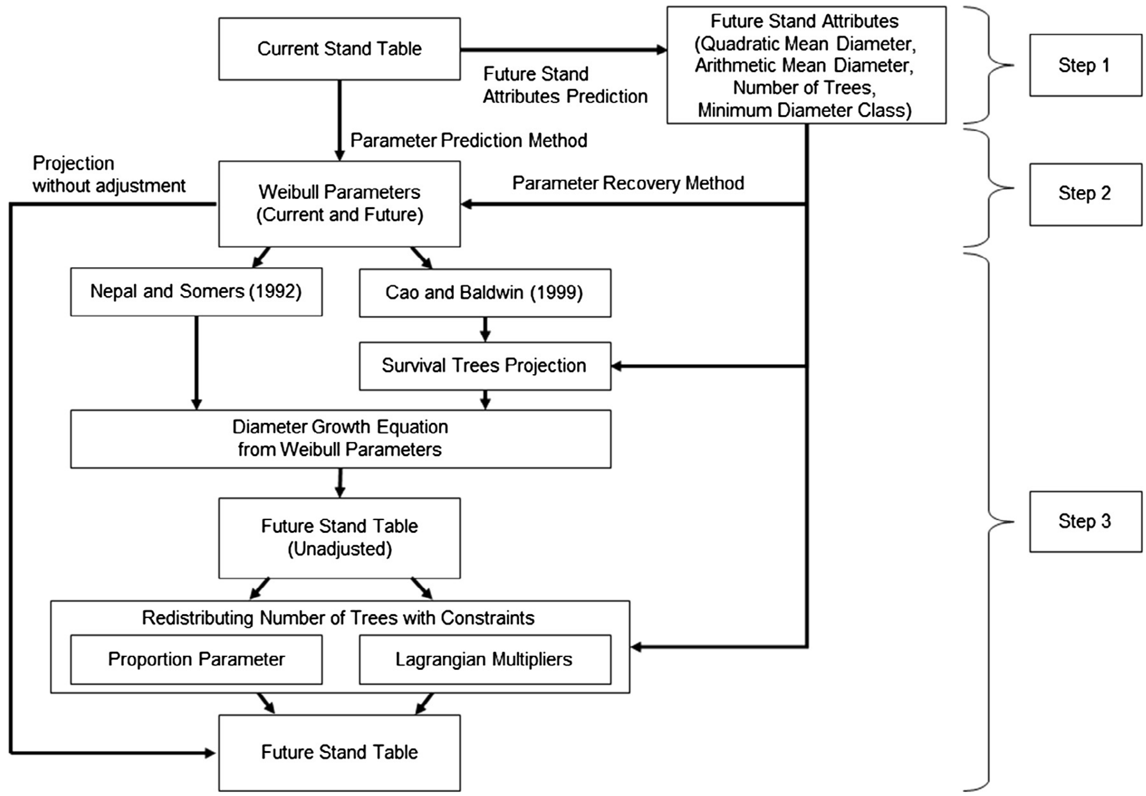

Fig. 1. Schematic diagram of the stand table projection model development.

has been demonstrated to provide quite accurate and robust outcomes (Marshall et al., 2008).

Despite its practical utility and relative high accuracy, Prognosis^{BC} has several limitations generally found in individual-tree models. First, because it is an individual-tree (i.e., high-resolution) model, it requires relatively large amounts of individual tree data for model calibration. This results in relatively higher costs than low-resolution models (e.g., whole-stand and stand table projection models) (Vanclay, 1995). In addition, insufficient information regarding initial stand conditions likely results in unreliable model outcomes (e.g., Mowrer and Frayer, 1986). Forest managers commonly depend on lower-resolution information for decision making (e.g., diameter distribution, whole-stand level, or landscape models) (Weiskittel et al., 2011). However, if individual tree predictions involve large errors, aggregation to stand-level attributes can lead to the propagation of errors, producing less reliable outcomes (Cao, 2014; Gadow and Hui, 1999; Hevia et al., 2015; Ritchie and Hann, 1997). Moreover, problems of redundancy and over-parameterization can affect the precision of estimates (García, 2001).

Prognosis^{BC} simulation results are sometimes incorporated into other modelling frameworks, such as forest estate models, for decision making purposes on larger-scale areas (FORUM Consulting Group, 1997). One of the benefits of using this fine-resolution model is evaluating the potentials of management practices and their interactions among different scales from individual tree to entire forests. Forest managers can then choose the preferred prescriptions to produce the most desired future outcomes (Ritchie, 1999). However, it is cumbersome and complex to incorporate Prognosis^{BC} simulation results directly into such models (Bettinger, 2001), especially when harvest delays are included. Harvest delays can result in a change of state that, in turn, can cause a change in the treatment prescription, and/or a change in the response to a treatment. Under the current paradigm, all of these delays must be anticipated in advance in order to produce an appropriate set of candidate untreated growth forecasts, schedule of treatments associated with the untreated conditions, growth response curves associated with each pre- and post-treatment stand condition, as well as a set of transition rules to facilitate forest estate model applications (McCann et al., 2011).

Stand table projection models (also known as diameter distribution models) can be feasible alternatives to individual-tree models. Stand table projection is one of the classic techniques to predict future size class distributions, and is a compromise between whole-stand and individual-tree models (Cao, 2014; Gadow and Hui, 1999; Weiskittel et al., 2011). Such models provide more useful details for decision making (e.g., future diameter distribution, volume prediction by size class) than whole-stand models, and require less input data than individual-tree models (Gadow and Hui, 1999). Moreover, stand table projection approaches are easily implemented.

Diameter distributions related to stand table projection models can be fit using various probability distributions. Utilizing the mathematical characteristics of fit distributions allows higher-resolution (e.g., diameter class) information to be generated from lower-resolution (e.g., stand level) information (Gadow and Hui, 1999). Diverse theoretical distributions, such as the Weibull, beta, gamma, lognormal, Johnson's SB, and logit-logistic functions, have been implemented to describe diameter distributions (e.g., Cao and Burkhart, 1984; Liu et al., 2009; Maltamo et al., 2000; Wang and Rennolls 2005; Zhang et al., 2003; Zhou and McTague, 1996). Various approaches have been used to relate the probability density function parameters to stand attributes as well, including parameter prediction (PPM), moment-based or percentile-based parameter recovery methods (PRM) (Burkhart and Tomé, 2012; Hyink and Moser, 1983; Siipilehto and Mehtätalo, 2013; Vanclay, 1994), and segmented distribution approaches (Cao and Burkhart, 1984).

The objective of this study was to develop a stand table projection model for interior Douglas-fir forests in southeastern BC that resulted in predictions similar to those provided by Prognosis^{BC}. This would allow stand table projections to be readily provided without running Prognosis^{BC} within forest estate models. We focused on comparing the generalized stand table projection algorithms of Nepal and Somers (1992) (NS) and Cao and Baldwin (1999) (CB), in combination with