Forest Ecology and Management 378 (2016) 111–121

Contents lists available at ScienceDirect

Forest Ecology and Management

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

A decompositional stand structure analysis for exploring stand dynamics of multiple attributes of a mixed-species forest

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ARTICLE INFO

Article history:
Received 30 March 2016
Received in revised form 14 July 2016
Accepted 18 July 2016

Keywords:
Stand dynamics
Mortality rate
DSSA technique
Radial growth model
Height growth model
Structure analysis

ABSTRACT

Forest dynamics is a particularly important issue as it describes changes in forest structure over time. Forest structure can be presented from using the attributes of age, diameter, height, abundance, density, etc. During the last few decades, most research has focused on these attributes separately while rarely investigating the dynamics of multiple attributes. This was due to the lack of an appropriate algorithm for this particular purpose. Recently, more attention has been given to investigation of the inter-species dynamics within a mixed forest. The traditional method of probability density function (PDF) fitting is unable either to reveal the compositional changes or investigate competition between species within a given period of time. This paper proposes a novel approach, "Decompositional Stand Structure Analysis (DSSA)" that integrates species-based PDF fitting (SBPDFF) and growth modelling (GM) of tree-size parameters to construct a chronology of individual trees within a forest stand. This enables investigation of the features of diameter, height, and age structures and the changes in the abundance, survival, and mortality rate of the predominant species in a forest canopy. A mixed pristine forest stand primarily composed of Siberian spruce (*Picea obovata*) and Siberian larch (*Larix sibirica*) located in a riparian ecotone of boreal forest in Mongolia was used for validating the appropriateness of the DSSA prototype. Results showed that the diameter and height structure of the mixed forest stand can be described using bimodal Weibull distribution composed of a combination of two unimodal distributions contributed by the spruce and the larch respectively. Spruce was found to demonstrate reverse-J distribution while larch had approximately normal distribution. The spruce's mortality rate followed an exponential decay model while the larch exhibited changes resembling an exponential growth model. Individuals of the spruce and the larch took 51–60 and 42–48 years respectively to grow into the overstorey canopy. The results indicate that the DSSA technique is able to achieve an appropriate performance in the derivation of the dynamics of mixed species forest, thus providing information that may facilitate better conservation management.

1. Introduction

Probability density functions (PDFs) or probability distributions, based on plot-based inventory data, have been used extensively to produce descriptions of stand structures that are useful in a number of contexts. Weibull (Bailey and Dell, 1973), Gamma (Nelson, 1964), Burr (Lindsay et al., 1996), and Johnson S_B (Hafley and Schreuder, 1977) are some of the typical prototypes originating from single-mode distribution, hereafter abbreviated as unimodal PDFs. Those models can adjust flexible parameters to fit variant shapes of the binned data for a particular application. For example, the shape and scale parameters of the three-parameter Weibull distribution can be adjusted to describe the Gaussian distribution (the typical even-aged forest diameter distribution) and the reverse J-shape distribution (the typical uneven aged forest diameter distribution).

Unimodal PDFs have demonstrated their appropriateness in describing changes of diameter structure overtime (Qin et al., 2007) as well as the conservation status of endangered species from the viewpoint of age structure (Lin et al., 2007). However, unimodal PDFs are not always suitable for practical use in model performance because stand structures may lack uniformity due to disturbances caused by anthropogenic factors and/or natural events. According to Shorohova et al. (2009), the stand development in Eurasian boreal forest revealed multiple successional pathways in all types of pristine forest. All-aged stands driven by small-scale disturbances are formed over successional development

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http://dx.doi.org/10.1016/j.foreco.2016.07.022
0378-1127/

of several hundreds of years. Major disturbances such as forest fires, storms, insect damage and diseases may change stand structure and stand dynamics by physically destroying the tree canopy and even uprooting trees. This leads to increased deforestation (Pantis and Mardiris, 1992), mortality (Thies et al., 2006) and potential degradation (Camarero and Gutiérrez, 2007). With repeated disturbances, growth in the diameter and height of trees and the stock of forest seedbank decrease significantly and thus are gradually induced to form multimodal shaped or irregular shaped distributions. Multi-cohort stands, for example, are more frequent in old-growth forests with multimodal distributions (Rossi et al., 2009).

A mixture distribution model (MDM) is an integration of multiple unimodal PDFs. Recently, many studies have shown that the MDM approach is appropriate for the modelling of irregular shaped distribution of stand structures, especially for the diameter structures of mixed stands (Stage, 1973; Zhang et al., 2001; Liu et al., 2002; Zasada and Cieszewski, 2003; Zhang and Liu, 2006; Wang et al., 2006; Podlaski, 2010; Jaworski and Podlaski, 2012; Podlaski and Roesch, 2014). The usefulness of the mixture distribution model has been expanded by Tsogt and Lin (2014) to include the estimation of forest volume. That study demonstrated a satisfactory performance of the MDM approach in forests that had been frequently disturbed by natural events. While previous studies have been primarily concerned with tree diameter structure, other attributes of a forest stand, such as tree height, and age have not been combined in accounts of stand dynamics.

Many recent studies have been concerned with the structure and/or recruitment dynamics of mixed forest at northern latitudes (Harvey et al., 2002; Lopatin, 2007; Lopatin et al., 2007, 2008; Zielonka et al., 2009; Liang, 2010; Lines et al., 2010; James, 2011; Fernandes et al., 2014), southern latitudes (Echeverría et al., 2007; Arévalo et al., 2012), and tropical areas (Sharma and Raghubanshi, 2006; Pappoe et al., 2010). In addition, forest ecologists have been attempting to explore the changes in stand dynamics due to climate changes (Briffa et al., 1998; Lindner et al., 2014; Smyth et al., 2014; Chen and Luo, 2015) and land cover changes (Gilani et al., 2014). Due to a general trend of heart decay in many large individual trees, tree age, obtained by tree ring analysis, cannot be considered as a reliable variable as it is not possible to obtain an accurate age for decayed trees; James (2011) therefore suggested that parameters of tree stature are possible substitutes for tree age and competitiveness. This makes it important to obtain information regarding the diameter of trees within a forest stand in addition to the stand dynamics in order to analyse the long-term growth response to environmental changes.

As the necessity to derive the diameter and the canopy strata (Wilkes et al., 2015) of trees within mixed forest increases, the traditional method of using all individuals of every species as one unit for deriving unimodal PDFs and/or multimodal PDFs (abbreviated WBPDFF which shorts for Whole-Based PDF Fitting) is found to be problematic with regards to the acquisition of detailed species dynamics in a forest stand. Apparently, as the attributes of individual trees' diameter, height, and age of the dominant species were retrieved simultaneously with appropriate methods based on inventory data of large-plot-based samples, multiple structures of a forest stand can then be derived using appropriate probability density functions. In addition, canopy-space competition of dominant species over the lifespan of trees in a mixed-species forest can be further explored. As a result, moderate management plan can be made in advance to satisfy the sustainability, which is particularly important for conservation management of endangered species in mixed-species forest and probably sustainable yield planning of specific species over mixed-species woodland.

So, the main objective of this study was to overcome the inability of traditional methods to produce appropriate distribution models through the proposal of a "Decompositional Stand Structure Analysis protocol (DSSA)". DSSA was designed to explore the stand diameter, height, and age structures as well as the dynamics of species population and competition between the dominant species of a mixed forest. A pristine larch-spruce mixed forest in Mongolia was used to examine the appropriateness of the DSSA prototype. Further discussion was made based on the experimental results to address the development of the species within the mixed-species forest.

2. The prototype of the DSSA technique

DSSA technique consists of two major parts: Species-Based Probability Density Function Fitting (abbreviated SBPDFF) and Growth Modelling (GM). SBPDFF is designed to explore the stand structure of stem statue parameters (such as diameter, height, and age) of trees for the species in mixed forest, and GM is applied to develop age-diameter models to construct tree chronology of the species for investigating the mortality dynamics of the forest stand. Fig. 1 demonstrated the flowchart with input/output data flows and analysis methods of the DSSA technique. Detail of the methods was given in the following sections.

2.1. Species-based decomposition of a mixed-forest stand structure

In forest ecology and management, the Weibull distribution has been extensively applied to examine diameter structure (Bailey and Dell, 1973; Tanouchi and Yamamoto, 1995) and age structure (Lin et al., 2007). Theoretically, the three-parameter Weibull probability density function (PDF) is given by Eq. (1),

$$f(x) = \frac{\alpha}{\beta}\left(\frac{x-\gamma}{\beta}\right)^{\alpha-1} \exp\left(-\left(\frac{x-\gamma}{\beta}\right)^{\alpha}\right) \tag{1}$$

where x is a continuously or discretely random variable, and α, β, γ is the shape, scale, and location parameter respectively. The PDF is expressed as Weibull (x; α, β, γ) and its cumulative distribution function (CDF) is given by Eq. (2).

$$F(x) = 1 - \exp\left(-\left(\frac{x-\gamma}{\beta}\right)^{\alpha}\right) \tag{2}$$

Suppose that a mixed forest is composed of species A and B. Stem frequency of one of the tree stature parameters (X) of species A and B in the forest stand has Weibull distribution whose scale values are same while shape values are different. Say that for example A is Weibull (x; 1.5, 10, 0) and B is Weibull (x; 4.5, 10, 0), then the combined stem frequency (C) of the tree stature parameter of the species A and B would have a PDF of Weibull (x; 3.0, 10.2, 0.3). As shown in Fig. 2, the two single-mode PDFs reveal that the regeneration status of species A is good while that of B is poor if x is age or diameter. The two statuses might be an ecological indicator of species competition. This information cannot be explored by a single-mode PDF of the mixed stand when both X's of A and B are combined as a whole for distribution modelling. Due to the stand structure of the combined variable X being approximately normal distribution, we conclude that the regeneration status of the forest is moderately poor. The decomposition of a stand structure (C) into its species components (A and B) for distribution modelling is ascribed the title, "species-based decompositional stand structure analysis".

In this study, the species-based decompositional stand structure analysis is a three-step procedure. First, individual trees of the spruce and the larch were separately used to create species-based diameter/height histogram in a 1-cm/1-m class. Then, the maximum likelihood estimation (MLE) was applied to derive the parameters of the cumulated distribution function, i.e., Weibull