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Analysing structural diversity in two temperate forests in northeastern China

Ruiqiang Ni[a], Yeerjiang Baiketuerhan[b], Chunyu Zhang[a], Xiuhai Zhao[a,*], Klaus von Gadow[c,d]

[a] Key Laboratory for Forest Resources & Ecosystem Processes of Beijing, Beijing Forestry University, Beijing 100083, China
[b] College of Forestry and Horticulture, Xinjiang Agricultural University, Urmqi 830052, China
[c] Faculty of Forestry and Forest Ecology, Georg-August-University Göttingen, Büsgenweg 5, D-37077 Göttingen, Germany
[d] Dept. of Forest and Wood Science, University of Stellenbosch, South Africa

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ABSTRACT

This contribution presents an analysis of the structural diversity in two temperate forest ecosystems in northeastern China, based on two large contiguous observational studies covering an area of 5.2 ha (260×200 m^2) each. The total number of living trees in the conifer and broad-leaved forest (CBF) study area is 2927 per ha, comprising 37 species and 21 genera. The old growth forest (OGF) study area has 2276 trees per ha, including 22 species and 13 genera. Tree species are classified according to their community status as mature and immature canopy, subcanopy and shrub. A clustering process based on two distinct communities of the bivariate dbh/height distributions is used to differentiate between mature and immature canopy species. Numerical analysis is based on these four distinct cohorts. Despite advances in remote sensing, mapped tree data in large observation windows are very rare. Thus, we are able to use methods for analysing forest structure which are suitable for both, unmapped and mapped data. The two data sets are unique in that all (approximately) 27,000 tree heights are available. Accordingly, it was possible to fit bimodal height distributions and bivariate mixed dbh/height distributions to almost all individual species that were represented by sufficiently large numbers. Methods of second order statistics (SOC), including marked point statistics as well as nearest neighbor statistics (NNS) based on nearest neighbourhood structure units are also presented, including bivariate mixtures of the NNS attributes "mingling" and "dominance". Mark correlations were investigated for several marks, including diameters, heights and nearest neighbor statistics. Finally, we discuss the most important results and motivate the need for detailed assessments in large contiguous field plots. The literature on spatial statistics is often rather technical, and there is relatively little exchange between mathematicians developing the theory and ecologists who have interesting data from observational studies, such as presented in this contribution.

1. Introduction

Structure is a fundamental notion referring to patterns and relationships within a more or less well-defined system. Important theoretical concepts relating to biological structures include *self-organisation* which involves regeneration, tree mortality and a variety of interactions between individual plants. The properties of a particular forest ecosystem, including biomass production, biodiversity and the quality of ecosystem services, are determined to a large degree by its structure. Trees propagate, grow and die, but they are sessile, bound to one specific location. Forest regeneration, growth and mortality generate very specific structures. Specific structures in turn, generate particular processes of growth and regeneration. The production and dispersal of seeds and the associated processes of germination, seedling establishment and survival are important factors of plant population dynamics and structuring (Harper, 1977). Thus, structure is not only the result of past developments, but also the starting point for future dynamics.

"Forest structure" usually refers to the way in which the attributes of trees are distributed within a forest. Associated with a specific forest structure is some degree of heterogeneity or richness which we call diversity. In a forest ecosystem, diversity does, however, not only refer to species richness, but to a range of phenomena that determine the heterogeneity within a community of trees, including the diversity of tree sizes and tree locations. New analytical tools used in *geostatistics*, *point process statistics*, and *random set statistics* allow more detailed research of the interaction between spatial patterns and biological processes. Some data are continuous, like wind, temperature and precipitation. They are measured at discrete sample points and continuous information is

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* Corresponding author. Address: Forest College in Beijing Forestry University, No. 35 Qinghua East Road, Haidian District, Beijing 100083, China.

E-mail addresses: wind0309@163.com (R. Ni), erjan0701@163.com (Y. Baiketuerhan), zcy_0520@163.com (C. Zhang), zhaoxh@bjfu.edu.cn (X. Zhao), kgadow@gwdg.de (K. von Gadow).

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obtained by spatial interpolation, for example by using Kriging techniques (Pommerening, 2008). Where objects of interest can be conveniently described as single points, e.g. tree locations, methods of point process statistics are useful. Of particular interest are the *second-order characteristics* (*SOC*) which were developed within the theoretical framework of mathematical statistics and then applied in various fields of research, including forestry (Møller and Waagepetersen, 2007; Illian et al., 2008). Examples of *SOC*'s in forestry applications are Ripley's *K*- and Besag's *L*-function, pair- and mark correlation functions and mark variograms. *SOC*'s describe the variability and correlations in marked and non-marked point processes. Functional second-order characteristics depend on a distance variable *r* and quantify correlations between all pairs of points with a distance of approximately *r* between them. This allows them to be related to various ecological scales (Pommerening, 2002).

The scientific literature abounds with studies of diameter distributions of even-aged monocultures. Other structural characteristics of a forest which are important for analysing disturbances are a group which Pommerening (2008) calls *nearest neighbor summary statistics* (NNSS). In this contribution we are using the term *nearest neighbor statistics* (abbreviated to *NNS*). *NNS* methods assume that the ecosystem is a mosaic of neighborhood groups and that the spatial structure of a forest is largely determined by the distribution of neighborhood characteristics. NNS methods have important advantages over classical spatial statistics, including low cost field assessment and cohort-specific structural analysis. Trees need not be mapped (which is usually expensive) and neighborhood statistics may be assessed in routine forest inventories without additional cost, which is one of the important practical advantages of using NNS (Gadow et al., 2012). Despite advances in remote sensing and other assessment technologies, mapped tree data are often not available, except in specially designed research plots. Forest inventories tend to provide tree data samples in small spatial observational windows. Thus, in the overwhelming number of cases, the amount of data and their spatial range is too limited to use *SOC* methods.

The objective of this contribution is to compare the results of a structural analysis in a multi-species temperate forest based on two large observational study areas with mapped tree locations. In contrast to traditional approaches which are usually limited to numerical analysis, this study attempts to refer to a biological basis where tree species are identified according to their specific social status within the community. The quantitative analysis is then based on distinct social cohorts.

2. Data and methods

This section describes the data sets and methods. The methods are grouped into two categories. One group applies to unmapped, the other to mapped tree data. Often, tree locations are not mapped, but the tree attributes, e.g. species, *dbh*'s and *heights*, are available. Mapped data in two large observation windows are available. Thus it is possible to use second order characteristics (*SOC*'s) which may depart from the hypothesis of complete spatial randomness (*CSR*). Thus, our null hypothesis is that marks are spatially independent. Cumulative characteristics such as the *L* function or the mark-weighted *L* functions (Montes et al., 2008) can be used to test such hypotheses. If they are rejected, it makes sense to proceed with an analysis involving *SOC's*, such as pair correlation functions or mark variograms. If the hypothesis of mark independence is accepted, it suffices to use nearest neighbor statistics (*NNS*) (see Illian et al., 2008 for details).

2.1. The data sets

This investigation is based on observations collected in a broadleaved Korean pine mixed forest, in the Changbai Nature Reserve in north-eastern China. The climate in this region has been classified as a continental mountain affected by monsoon climate. The annual average temperature is 3.6 °C, the highest monthly average temperature is 19.6 °C measured in August, and the lowest monthly average temperature is −15.4 °C, measured in January. The average temperature extremes are 32.3 °C and −37.6 °C. The annual mean precipitation is 707 mm, the mean relative humidity 66%. The distribution of the precipitation during the year is relatively uneven. A relatively wet season occurs from June to August, a relatively dry season begins in September and ends in May of the following year. The soil is a brown forest soil and the topography is flat and slightly undulating (Zhang et al., 2010a,b).

Both study sites cover an area of 5.2-ha (260×200 m^2). The CBF site was established in the summer of 2005, the OGF site in October 2007. Fig. 1 shows the spatial distribution of trees by species, in both plots. The total number of living trees in the CBF plot was 15,221 (i.e. 2927 trees per ha) in 2005, comprising 37 species and 21 genera. The main canopy species are *Pinus koraiensis*, *Tilia amurensis, Quercus mongolica, Fraxinus mandshurica, Acer barbinerve, Acer tegmentosum*, *Acer mono* and *Ulmus japonica*. The OGF plot had 11,833 trees in 2007 (i.e. 2281 trees per ha), comprising 22 species and 13 genera.

The main canopy species in OGF are *P. koraiensis, T. amurensis, Abies nephrolepis, A. barbinerve, A. tegmentosum*, *A. mono* and *Picea jezoensis*. The CBF plot represents a secondary conifer and broadleaved mixed forest (128°07.99′E, 42°20.91′N), the OGF an old growth forest (128°4.573′E, 42°13.684′N). The mean elevations of the CBF and OGF plots are 748 and 1042 m, respectively. The topography is almost flat in both study areas, and for this reason topographical effects on the community structure can be neglected (Zhang et al., 2010a,b).

2.2. Species grouping

Unmapped tree data are often available or can be obtained at low cost. Therefore, because of their practical relevance, analytical tools that do not depend on mapped tree data are particularly important. Some non-spatial methods are relatively easy to apply, others require advanced methods. An important first step in analysing a forest ecosystem involves classification of tree species on the basis some physical or functional property.

Typically, temperate forests display three reasonably well-defined layers of woody vegetation. The tallest trees are the canopy trees which intercept most of the radiation. Directly beneath the canopy there is another layer of woody vegetation, known as the subcanopy layer. Trees forming this cohort typically never reach canopy height. The shrub layer is formed by low woody plants, sometimes with multiple shoots or stems from the base that attain a height at maturity which is usually less than one third of the canopy height. In this study, each of the 51 tree species belongs to one of these cohorts: canopy trees, subcanopy trees and shrubs. This classification, which is straight forward for most species, has been adopted following standard ecological handbooks that describe each species as belonging to one of the three layers (Fu, 1995).

The canopy species typically occur in two distinct cohorts which can be identified by a suitable clustering approach. We used a bivariate mixed normal distributions of tree diameter and height to identify the two clusters (see Section 2.3.2 for technical details). Fig. 2 shows the typical two clusters for canopy species using *T. amurensis* and *P. koraiensis* as examples, in the CBF and OGF plots. The examples show that the relationship between dbh's and heights is quite different between the mature and immature canopy trees. The trees in the immature canopy-tree cluster of the two canopy species are suppressed, they have small crowns and a bigger height/dbh ratio. The mature canopy-tree cluster has large crowns and a smaller height/dbh ratio. Before reaching