Forest Ecology and Management 316 (2014) 47–53

Contents lists available at ScienceDirect

Forest Ecology and Management

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

Spatial forest structure reconstruction as a strategy for mitigating edge-bias in circular monitoring plots

A. Lilleleht [a], A. Sims [a], A. Pommerening [a,b,*]

[a] Estonian University of Life Sciences, Institute of Forestry and Rural Engineering, Department of Forest Management, Kreutzwaldi 5, Tartu 51014, Estonia
[b] Swiss Federal Institute for Forest, Snow and Landscape Research WSL, Zürcherstrasse 111, CH-8903 Birmensdorf, Switzerland

ARTICLE INFO

Article history:
Available online 19 September 2013

Keywords:
Long-term forest monitoring
Plant competition
Plus-sampling
Minus-sampling
Circular monitoring plots

ABSTRACT

Forest ecosystem monitoring is an important task of forest science worldwide and its outcomes have important consequences both for national forest policies and local decision making. Often forest monitoring is implemented using circular plots of limited size. Edge effects can seriously bias the results of spatially explicit analyses of circular plot data and little research has been carried out on how to mitigate this problem. In this study, we have compared the method of spatial forest structure reconstruction to traditional plus-sampling, to the reflection method and to a situation where no edge-bias mitigation method is used at all. Reconstruction is a non-parametric modelling method based on simulated annealing. In the context of this study, the arithmetic means of structural summary characteristics are used to extrapolate spatial patterns previously measured in the core area of the monitoring plots to the margins outside. The computer experiments were based on 706 circular monitoring plots of the Estonian long-term monitoring network maintained by the Estonian University of Life Sciences, Tartu. The results clearly indicate the superiority of the reconstruction method and suggest that this approach has great potential for future spatially-explicit data analyses and modelling involving circular monitoring plots. Further improvements can be expected from using density functions and histograms of structural summary characteristics instead of arithmetic means.

1. Introduction

Forest ecosystem monitoring is an important responsibility of the international forest research community (Motz et al., 2010). There are two main strategies in forest monitoring that involve either the use of **(1)** large scarcely replicated sample plots (Pretzsch, 2009, p. 112ff.) or of **(2)** small frequently replicated plots (van Laar and Akça, 2007, p. 229ff.). Whilst large plots usually have the potential of providing data for detailed analyses and basic research, small frequently replicated monitoring plots have a better coverage and representation of larger landscape entities.

A problem associated with the spatial analysis of all types and geometric shapes of monitoring and sample plots is the fact that off-plot trees can have an effect on trees inside the plots near the boundaries (Radtke and Burkhart, 1998). Ignoring these effects can therefore introduce a bias to spatial estimations. The problem of how to mitigate edge-bias effects is not a topic new or unique to forestry; one of the earliest descriptions of the issue is from Finney and Palca (1949). The various methods developed for edge-bias compensation can be subdivided into two main groups, *plus-sampling* and *minus-sampling* (see Table 1).

Plus-sampling usually implies the measurement of additional off-plot trees to correctly account for neighbourhood relationships of trees inside the plot near the boundaries (Illian et al., 2008).

By contrast, minus-sampling restricts the spatial analysis to a core area of the sample plot, in which the trees are unaffected by off-plot neighbours. Minus-sampling therefore usually leads to a loss of data, which is particularly crucial in small monitoring plots because of the unfavourable ratio of area to circumference. Pommerening and Stoyan (2006) could for example show that large 1-ha plots often do not even require an edge-bias compensation at all, as edge-effects are very small.

Over the years, various solutions for mitigating edge-bias effects have been proposed in the literature and Table 1 provides a systematic overview of the main methods (Pommerening, 2008).

Translation and *reflection* are traditional methods used in many spatial analyses. Both methods extrapolate the spatial structure from within the monitoring plot to an infinite plane and join parts of the spatial pattern that do not occur so close together in nature. This can lead to unrealistic spatial patterns near the plot boundaries. Particularly the reflection method has the reputation of often performing badly and therefore cannot be recommended (see Pommerening and Stoyan, 2006). Translation, *periodic boundary*

* Corresponding author at: Swiss Federal Institute for Forest, Snow and Landscape Research WSL, Zürcherstrasse 111, CH-8903 Birmensdorf, Switzerland. Tel.: +41 44 739 21 11; fax: +41 44 739 22 15.

E-mail address: arne.pommerening@gmail.com (A. Pommerening).

0378-1127/$ - see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.foreco.2013.08.039

Table 1
An overview of general plus- and minus-sampling methods. Explanations are provided in the text (adapted from Pommerening, 2008).

Plus-sampling	Minus-sampling
Translation (=periodic boundary conditions, toroidal wrapping, torus)	*Internal buffer* • Fixed buffer • Flexible buffer: NN1, NN2
Reflection • Across an axis (e.g. plot boundary) • Through a point (e.g. arbitrary point near plot boundary) *External buffer* • Additional measurements • Conditional simulation (=reconstruction)	

conditions or *toroidal wrapping* plays an important role in spatial simulations and can be applied to rectangular monitoring plots with little computational effort (Illian et al., 2008, p. 184).

The *external buffer* method can include the measurement of additional trees outside the monitoring plot, which might interact with those inside. Determining the optimal width of the buffer is difficult; if it is too small residual edge effects will remain; if it is too large unnecessary sampling effort is applied. However, with nearest-neighbour summary statistics (NNSS, Pommerening, 2002) in practical implementations of forest inventory, it is often sufficient to sample the nearest off-plot neighbours of trees near the plot boundaries, although this precludes retrospective analyses including changes to the number of neighbours of a structural measure.

An alternative to measuring additional trees as part of the external buffer method is *conditional simulation* outside the monitoring plot. This method involves a structural analysis of the spatial pattern inside the plot and a simulation of this pattern outside the plot based on the results of the structural analysis. "Conditional" in this context means that the simulation does not modify the spatial pattern within the monitoring plot but only generates new patterns outside, which are statistically similar to those inside and have statistically correct ties to inner trees (see Biber, 1999; Illian et al., 2008).

The *internal buffer* or *guard* method is a minus-sampling method. Like all minus-sampling methods the *fixed-buffer* method only uses a subset of the trees in the monitoring plot. Again the choice of the buffer width is difficult (see Diggle, 2003, p. 5) and refined versions have been developed which create a *flexible buffer* by addressing each tree's potential relation to off-plot neighbours individually. These methods are known as nearest-neighbour edge mitigation methods and have been proposed and investigated as NN1 and NN2 methods in Pommerening and Stoyan (2006), where a detailed description can be found. The NN1 method was identified as a very reliable and robust option.

In forest monitoring, the second strategy of using small, frequently replicated sample units is mostly implemented with *circular plot designs*. Whilst circular plot shapes can markedly ease mensuration effort (van Laar and Akça, 2007), edge-bias compensation for the data involved is less straightforward. Most edge-bias mitigation methods have been developed for rectangular plots (see Radtke and Burkhart, 1998; Pommerening and Stoyan, 2006) because the necessary mathematics are less complex for this plot shape. One of the few methods that are applicable to circular plots is the transformation of circular plots to square ones followed by the torus edge-correction as suggested by Williams et al. (2001). Windhager (1997) reflects neighbouring trees through points of the circular plot boundaries defined by lines parallel to the line connecting the subject tree and the plot centre. In general, reflection and translation methods are difficult to apply to circular sample plots because of a lack of common reflection axes in the first case and because of disjoint boundaries in the latter. Inspired by edge-correction methods in forest inventory (Schmid, 1969), Sims et al. (2009) developed a reflection method replacing missing off-plot neighbours by trees from inside the plot (see Fig. 1).

Edge-correction methods for circular monitoring plots have been proposed only on rare occasions and yet this plot design finds considerable application in forest monitoring and inventory. There is clearly a need for developing suitable compensation methods for data gathered in circular plots and we address the question in this paper.

The original idea of plus-sampling is based on the measurement of additional off-plot trees. In this paper, however, we follow suggestions by Illian et al. (2008, p. 185) to simulate plus-sampling instead by using the reconstruction method. This is a useful approach because often additional measurements are not feasible or the data used in current analysis have been collected in the past. Reconstruction in this context can be considered as a spatial extrapolation of forest structure from inside the research plot to an area outside the plot. To our knowledge this is the first time that a study of simulated plus-sampling has been published.

The objective of this paper is therefore to present and to test this new method of edge-bias mitigation for circular monitoring plots based on the reconstruction technique (Yeong and Torquato, 1998; Torquato, 2002, p. 294ff.; Tscheschel and Stoyan, 2006; Pommerening and Stoyan, 2008; Nothdurft et al., 2010).

2. Materials and methods

2.1. The reconstruction method

The reconstruction of forest structure from a knowledge of limited structural information (e.g. NNSS and second-order characteristics) is an intriguing inverse problem (Yeong and Torquato, 1998). It is based on the idea that meaningful summary characteristics should allow the analysis of forest structure to be reversed and thus enable the simulation of spatial patterns from estimated summary statistics (Pommerening, 2006). Therefore reconstruction is a non-parametric modelling method that is independent of model assumptions and empirical model parameters. An effective reconstruction based on summary characteristics enables one to synthesise accurate structures at will (Yeong and Torquato, 1998) which can be used for multiple analyses. Such reconstructions are of great value in a wide variety of fields including materials science, geology and biology.

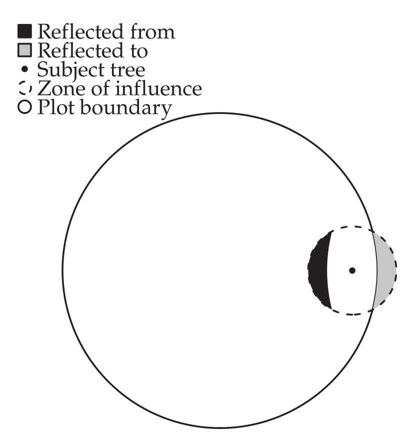

Fig. 1. The principle of the reflection method for edge-bias mitigation. The area highlighted in black is reflected across the plot boundary to provide off-plot tree neighbours in the grey area to compensate for the loss of original tree neighbours.