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Original article

Uncertainty in detecting the disturbance history of forest ecosystems using dendrochronology

Pavel Šamonil[a,*], Lukáš Kotík[b], Ivana Vašíčková[a,c]

[a] Department of Forest Ecology, The Silva Tarouca Research Institute for Landscape and Ornamental Gardening, Lidická 25/27, 602 00 Brno, Czech Republic
[b] Department of Probability and Mathematical Statistics, Faculty of Mathematics and Physics, Charles University in Prague, Sokolovská 83, 186 75 Praha 8, Czech Republic
[c] Department of Forest Botany, Dendrology and Geobiocenology, Faculty of Forestry and Wood Technology, Mendel University in Brno, Zemedelska 1, 613 00 Brno, Czech Republic

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ABSTRACT

Questions: Uncertainty in detecting disturbance histories has long been ignored in dendrochronological studies in forest ecosystems. Our goal was to characterize this uncertainty in relation to the key parameters of forest ecosystems and sample size. In addition, we aimed to provide a method to define uncertainty bounds in specific forest ecosystems with known parameters, and to provide a required (conservative) minimal sample size to achieve a pre-defined level of uncertainty if no actual key forest parameters are known.
Location: Training data were collected from Žofínský Prales (48°40′N, 14°42′E, 735–830 m a.s.l., granite, Czech Republic).
Methods: We used probability theory and expressed uncertainty as the length (the difference between the upper and lower bounds) of the 95% confidence interval. We studied the uncertainty of (i) the initial growth of trees – if they originated under canopy or in a gap; and (ii) the responses to disturbance events during subsequent growth – on the basis of release detection in the radial growth of trees. These two variables provide different information, which together give a picture of the disturbance history. While initial growth date the existence of a gap in a given decade (recent as well as older gaps are included), release demonstrates the moment of a disturbance event.
Results: With the help of general mathematical deduction, we have obtained results valid across vegetation types. The length of a confidence interval depends on the sample size, proportion of released trees in a population, as well as on the variability of tree layer features (e.g., crown area of suppressed and released trees).
Conclusions: Most studies to date have evaluated the initial growth of trees with higher uncertainty than for canopy disturbed area. The length of the 95% confidence interval for detecting initial growth has been rarely shorter than 0.1 (error ± 5%) and has mostly been much longer. To reach 95% confidence interval length of 0.1 (error ± 5%) when detecting the canopy disturbed area, at least 485 tree cores should be evaluated in studied time period, while to reach a 0.05 interval length (error ± 2.5%) at least 1925 tree cores are required. Our approach can be used to find the required sample size in each specific forest ecosystem to achieve pre-defined levels of uncertainty while detecting disturbance history.
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1. Introduction

Dendrochronology is a method used globally to evaluate past forest ecosystem dynamics. In the past three decades many dendrochronological studies were published that focused on disturbance histories in subtropic, temperate and boreal forests (e.g., Frelich, 2002 Kirdyanov et al., 2013; Ferrero et al., 2014). Some studies have served as the foundations for theoretical concepts of natural forest dynamics, such as gap dynamics (e.g., Belsky and Canham, 1994; Splechtna et al., 2005), patch dynamics (e.g., Watt, 1947; Levin and Paine, 1974; Pickett and White, 1985), large scale dynamics (e.g., Oliver and Larsen, 1996; Angelstam and Kuuluvainen, 2004), cohort dynamics (Engelmark et al., 1998)

* Corresponding author. Fax: +420 541 246 001.
E-mail addresses: pavel.samonil@vukoz.cz (P. Šamonil), lukaskotik@gmail.com (L. Kotík), ivavasick@gmail.com (I. Vašíčková).

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or intermediate scale dynamics (e.g., Woods, 2004; Hanson and Lorimer, 2007; Kuuluvainen and Aakala, 2011; Stueve et al., 2011).

Forest disturbance regimes have been studied using various sample sizes regardless of the forest type. For example Diaci and Firm (2011) studied the disturbance history of a mixed conifer stand using 46 tree cores. In mountain spruce forests, Zielonka et al. (2010) dealt with the same topic using 97 core series, and Szewczyk et al. (2011) used 114 and 258 tree cores in two spruce forest stands. In beech-dominated forests, Nagel et al. (2007) and Trotsiuk et al. (2012) evaluated disturbance history using 88 and 164 tree cores, respectively. By contrast, Šamonil et al. (2013) evaluated disturbance history based on 1986 core series in a beech-dominated forest, and D'Amato et al. (2008) studied past disturbances using 2577 tree cores in hemlock forests. In two spruce forests, Svoboda et al. (2014) studied disturbance history together using circa 3500 tree cores, and Trotsiuk et al. (2014) used 2394 tree cores in the same forest type. These selected dendrochronological studies, in which the quantity of data differs by several orders of magnitude, were published during the same period in global journals. Scientific results were understandably generalized from the specific forest stand to the level of forest type or even biome. However, the question arises whether the results of these studies have the same statistical significance and thus potential for generalization. If yes, then that would mean that coring several thousand trees is unnecessary and disproportionately damages the frequently protected remnants of natural forests. The general theory of probability (e.g., Resnick, 1999) should also be valid in dendrochronological research, and therefore we should expect a close relation between sample size and the statistical significance of resulting disturbance histories, with direct impact on the potential for generalization. This relation has not been examined to date.

Only a few works have discussed the uncertainty in dendrochronological data acquisition and processing in detail (Rubino and McCarthy, 2004; Thompson et al., 2007). Some arbitrary decisions and hidden preconditions fundamentally limit the use of dendrochronology in forest dynamic research. This study discusses the limitations created by the quantity of data. Our goal is to characterize the uncertainty in the detection of disturbance histories of forest ecosystems in relation to their key parameters and sample size. In addition, we aim to provide a method to define uncertainty bounds in each specific forest ecosystem where forest parameters are known, and to provide a required (conservative) minimal sample size to achieve a pre-defined level of uncertainty if no actual key forest parameters are known. We hope to arrive at results that are valid for various forest types. To illustrate our findings, we used data from a case study by Šamonil et al. (2013). In this previous study we evaluated disturbance history in one beech-dominated old-growth forest in the Czech Republic. We expect our results to foster a more correct interpretation of existing and future dendrochronological studies as well as a deeper understanding of forest ecosystem dynamics.

2. Materials and methods

2.1. Site characteristics

Our aim is to define a relationship between uncertainty and sample size in each specific forest ecosystem while studying disturbance history. For this purpose we used training data collected in the Žofínský Prales forest reserve in the Czech Republic (hereafter Žofín, 48°40′N, 14°42′E, Šamonil et al., 2013). This forest reserve is situated along an altitudinal gradient of 735–830 m a.s.l. The bedrock is almost homogenous and consists of granite. Annual average rainfall is 917 mm; annual average temperature is 4.3 °C. Most plant communities can be classified in the association *Galio odorati-Fagetum*. *Fagus sylvatica* dominates in the forest (62% of living tree volume), followed by *Picea abies* (34%). Other tree species (*Abies alba*, *Acer pseudoplatanus*, *Acer platanoides*, *Sorbus aucuparia*, *Ulmus glabra*) represent approximately 4% of the living tree volume (Král et al., 2010).

2.2. Data collection

In 2008, we geodetically set up a regular network of 354 points with 44.25 m spacing, which covered 74 ha of the reserve. The centers of square plots were used as the basis for the subsequent tree censuses and dendrochronological, geomorphological as well as natural regeneration surveys. We measured the locations of all trees with diameter at breast height (DBH) ≥10 cm in 2008.

Six tree cores (nine in cases where there were gaps) were taken from non-suppressed trees closest to the center of all square plots, one from each tree. From the total of 18,899 standing and 2862 lying trunks recorded in 2008, we tried to core 3020 individuals in 2008–2011. Cores were taken at the height of 1.3 m because recruitment age and former growth were not studied in detail (see Šamonil et al., 2013).

2.3. Data analysis

2.3.1. Basic laboratory analysis

The cores were dried and smoothed with fine sandpaper. The widths of the growth rings were measured using the PAST 4 program (SCIEM, 2007). Cores without sub-bark growth rings, damaged cores and cores that were missing more than 30 mm of the pith were rejected. A total number of 1986 cores were accepted for evaluation of the disturbance history. We used a pith locator (Applequist, 1958) to count the number of missed tree rings to the pith and we cross-dated individual core series using the PAST 4 program (SCIEM, 2007) and COFECHA (Holmes, 1983).

2.3.2. Evaluation of disturbance history

The disturbance history was studied on an irregular network of precisely located trees by Šamonil et al. (2013). That study evaluated **(i) the initial growth of trees** – if it occurred under canopy or in a gap; and **(ii) the responses to disturbance events during subsequent growth** – on the basis of the detection of release in the radial growth of trees (tree age did not have direct impact in calculation). These two variables provide different information. While initial growth indicates the existence of a gap (recent as well as older gaps are included), release reflects the moment of a disturbance event. We therefore strictly separated the two statistics in statistical calculations. Calculations of both statistics were described in detail by Šamonil et al. (2013). That study provided training data for our current evaluation of uncertainty in dendrochronological research.

2.3.2.1. Uncertainty of initial growth calculations. Initial growth was evaluated according to Lorimer and Frelich (1989). We assessed the mean width of five tree rings when a cored tree reached a DBH of 6 cm. In each decade, we identified: (i) the number of such trees (sample size, n) and at the same time, (ii) the proportion of these trees in the entire population of trees (more exactly in the community of woody species) whose ring-widths showed gap origin (unknown parameter $p \in [0, 1]$). According to Šamonil et al. (2013), the threshold of gap origin was 1.45 mm for broadleaves and 1.58 mm for conifers.

We express uncertainty as the length of the 95% confidence interval for the proportion of trees with gap origin (p) given a certain sample size (n). Variable n represents the number of trees from which initial growth is calculated in concrete time periods rather

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