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Testing the efficacy of tree-ring methods for detecting past disturbances

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A B S T R A C T

The retrospective study of abrupt and sustained increases in the radial growth of trees (hereinafter 'releases') by tree-ring analysis is an approach widely used for reconstructing past forest disturbances. Despite the range of dendrochronological methods used for release-detection, a lack of in-depth comparison between them can lead researchers to question which method to use and, potentially, increases the uncertainties of disturbance histories derived with different methods.

Here, we investigate the efficacy and sensitivity of four widely used release detection methods using tree-ring width series and complete long-term inventories of forest stands with known disturbances. We used support vector machine (SVM) analysis trained on long-term forest census data to estimate the likelihood that *Acer rubrum* trees experiencing reductions in competition show releases in their tree-ring widths. We compare methods performance at the tree and stand level, followed by evaluation of method sensitivity to changes in their parameters and settings.

Disturbance detection methods agreed with 60–76% of the SVM-identified growth releases under high canopy disturbance and 80–94% in a forest with canopy disturbance of low severity and frequency. The median competition index change (CIC) of trees identified as being released differed more than two-fold between methods, from −0.33 (radial-growth averaging) to −0.68 (time-series). False positives (type I error) were more common in forests with low severity disturbance, whereas false negatives (type II error) occurred more often in forests with high severity disturbance. Sensitivity analysis indicated that reductions of the detection threshold and the length of the time window significantly increased detected stand-level disturbance severity across all methods.

Radial-growth averaging and absolute-increase methods had lower levels of type I and II error in detecting disturbance events with our datasets. Parameter settings play a key role in the accuracy of reconstructing disturbance history regardless of the method. Time-series and radial-growth averaging methods require the least amount of *a priori* information, but only the time-series method quantified the subsequent growth increment related to a reduction in competition. Finally, we recommend yearly binning of releases using a kernel density estimation function to identify local maxima indicating disturbance. Kernel density estimation improves reconstructions of forest history and, thus, will further our understanding of past forest dynamics.

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1. Terminology

1.1. Tree level

Window length parameter – number of consecutive years used to calculate average growth for radial-growth averaging disturbance detection methods prior to and following a potential disturbance event. For the time-series approach, window length is the number of years used to calculate residuals.

Threshold parameter – minimum change in radial growth (absolute or relative depending on method) that must be exceeded for an increase in radial growth to be defined as a growth release (i.e., an abrupt increase in radial growth).

False positive – an event is detected by the dendrochronological method, but not by support vector machine analysis based on changes in the competition index before and after the event (type I error).

False negative – an event is detected by support vector machine analysis based on changes in competition index before and after the event, but not by the method (type II error).

1.2. Stand level

Disturbance severity – the proportion of trees responding to disturbance standardised by moving kernel density estimation function. Severity is related to the number of trees with a detected event and their temporal synchrony. Our definition is adopted and modified from Pickett and White (1985a).

Peak disturbance year – year with the greatest estimated disturbance severity for a specific event.

Accuracy – agreement between the severity of the disturbance identified by SVM analysis and that of the peak disturbance estimated from tree rings for the same event.

Precision – temporal agreement between the disturbance identified by SVM analysis and peak disturbance year estimated from tree rings.

2. Introduction

Reconstruction of past forest disturbances reveals the dynamics that have led to current forest composition, structure, and function. Tree-ring reconstructions of past disturbances surpass the length of time in contemporary forest inventories and, quite often, the era of local written records. Importantly, crossdating tree rings assigns a precise calendar year to each ring so that past centuries of forest dynamics can be investigated with annual resolution (Douglass, 1920). Increased precision in dating past disturbances allows ecologists a greater chance of correctly identifying agents of disturbance (Black et al., 2016). Relative to the lifespan of a tree, disturbance events are rapid processes that occur over the course of hours (e.g., windstorm) to months, seasons, or years (e.g., drought) (Pickett and White, 1985). Documenting disturbance with annual resolution, over centuries, and from the tree to continental scales is a powerful method that can shed much light on the mechanisms driving forest dynamics.

Almost a century after the publication of a pioneering paper on the potential identification of past forest disturbance from tree rings (Marshall, 1927), a number of tree-ring-based disturbance-detection methods have been developed to differentiate disturbance-induced changes in tree growth from those caused by life-history traits, biometry, stresses, or climate variability. Briefly, an abrupt, large, and sustained increase in tree-ring width (radial growth) is inferred to be a release from tree-to-tree competition and is taken as evidence of past canopy disturbance (Lorimer, 1980). Disturbance detection methods were first formalized in the mid- to late-1980s so the frequency and severity of disturbance could be objectively quantified through time and synthesized into time series of canopy disturbance (Lorimer, 1985; Lorimer and Frelich, 1989). A series of methods were developed soon afterward that either built directly upon these original methods (Nowacki and Abrams, 1997; Fraver and White, 2005) or used new approaches (Black and Abrams, 2003; Druckenbrod, 2005; Druckenbrod et al., 2013; Lee et al., 2017). The growing interest in studying old-growth forests, ecological restoration, and forest conservation biology increased the use of these methods.

Several methods of disturbance detection have been compiled into the R package TRADER (Altman et al., 2014). The creation of TRADER allows for the opportunity to simultaneously compare several methods and modify the parameters and thresholds for each method. Yet, faced with the diversity of approaches and parameters, researchers are likely to ponder, "*How should one choose which method, parameters, and thresholds to use given particular research goals and specific forest conditions*?"

Developers of the various release-detection methods have independently discussed the strengths and weaknesses of their specific approach (Lorimer and Frelich, 1989; Black and Abrams, 2003, 2004; Fraver and White 2005; Druckenbrod et al., 2013). A few studies have examined the sensitivity to varying parameters and thresholds of the growth-averaging method (Rubino and McCarthy, 2004; Bouriaud and Popa, 2007; Stan and Daniels, 2010). To date, however, no work has provided a detailed comparison of the performance of the most widely used detection methods with forest inventory datasets of controlled or observed records of disturbance. A rigorous examination of these methods is critical to correctly identify and correctly date past disturbances (Rubino and McCarthy, 2004; Bouriaud and Popa, 2007; Copenheaver et al., 2009; Altman et al., 2014; McEwan et al., 2014; Pederson et al., 2014; Šamonil et al., 2015).

Our primary objective was to analyse the performance of four widely used disturbance-detection methods in a forest subjected to an experimentally-induced disturbance and a forest with minimal canopy disturbance. These four methods are: radial-growth averaging (Lorimer and Frelich, 1989; Nowacki and Abrams, 1997), boundary line (Black and Abrams, 2003, 2004), absolute increase (Fraver and White, 2005), and time series (Druckenbrod, 2005; Druckenbrod et al., 2013). Performance was assessed by a method's ability to detect a disturbance of known timing and magnitude. Our secondary objectives were to: (i) investigate the efficacy of these methods in reconstructing the timing and severity of disturbance at the stand level and (ii) gain insight into the sensitivity of each method to adjustments in their temporal parameters and growth thresholds. Our study will provide guidance for future tree-ring studies with respect to method selection and interpretation of results.

3. Materials and methods

3.1. Study sites

To examine how each method performed in forests with differing canopy disturbance, we used repeated forest census data and tree rings from two nearby forest stands. First, for a forest with severe disturbance we examined trees from an experiment designed to mimic the damage in upland forests caused by a hurricane (Cooper-Ellis et al., 1999). To examine how methods performed in forests with little to no canopy disturbance, we used each method on trees in a 3-ha study plot with repeated forest measurements since 1969 and no significant canopy disturbance (Eisen and Plotkin, 2015).

3.1.1. High severity disturbance forest

The hurricane manipulation experiment ("Hurricane pulldown") was located at the Harvard Forest, Petersham, Massachusetts, USA (72.20 °N, 42.49 °W, 300–315 m a.s.l.) in a forest dominated by red maple (*Acer rubrum*) and northern red oak (*Quercus rubra*) (Cooper-Ellis et al., 1999; Plotkin et al. 2013). The forest originated following a clear-cut in 1915 (Harvard Forest Archives, *unpub. data*). All trees ≥ 5 cm diameter at breast height (DBH) were tagged, spatially mapped and recorded as live or dead during inventory surveys (1990 before, and after