


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

## Journal Article

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

2

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29

30 **Running-title:** Comparison of growth release detection methods

31

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35

36 **Abstract**

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

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

48 Disturbance detection methods agreed with 60-76% of the SVM-identified growth releases  
49 under high canopy disturbance and 80-94% in a forest with canopy disturbance of low severity and  
50 frequency. The median competition index change (CIC) of trees identified as being released  
51 differed more than two-fold between methods, from -0.33 (radial-growth averaging) to -0.68 (time-  
52 series). False positives (type I error) were more common in forests with low severity disturbance,

53 whereas false negatives (type II error) occurred more often in forests with high severity disturbance.  
54 Sensitivity analysis indicated that reductions of the detection threshold and the length of the time  
55 window significantly increased detected stand-level disturbance severity across all methods.

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

64

65 **Keywords:** Absolute-increase, Boundary-line, Competition, Forest development, Forest dynamics,  
66 Radial-growth averaging, Time-series analysis, Release

67

68 **Terminology:**

69 *Tree level*

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

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

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

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

82

83 *Stand level*

84 *Disturbance severity* – the proportion of trees responding to disturbance standardised by moving  
85 kernel density estimation function. Severity is related to the number of trees with a detected event  
86 and their temporal synchrony. Our definition is adopted and modified from Pickett and White  
87 (1985a).

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

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

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

93

## 94 **Introduction**

95         Reconstruction of past forest disturbances reveals the dynamics that have led to current  
96 forest composition, structure, and function. Tree-ring reconstructions of past disturbances surpass  
97 the length of time in contemporary forest inventories and, quite often, the era of local written  
98 records. Importantly, crossdating tree rings assigns a precise calendar year to each ring so that past  
99 centuries of forest dynamics can be investigated with annual resolution (Douglass 1920). Increased  
100 precision in dating past disturbances allows ecologists a greater chance of correctly identifying  
101 agents of disturbance (Black *et al.* 2016). Relative to the lifespan of a tree, disturbance events are  
102 rapid processes that occur over the course of hours (e.g., windstorm) to months, seasons, or years

103 (e.g., drought) (Pickett & White 1985). Documenting disturbance with annual resolution, over  
104 centuries, and from the tree to continental scales is a powerful method that can shed much light on  
105 the mechanisms driving forest dynamics.

106         Almost a century after the publication of a pioneering paper on the potential identification of  
107 past forest disturbance from tree rings (Marshall 1927), a number of tree-ring-based disturbance-  
108 detection methods have been developed to differentiate disturbance-induced changes in tree growth  
109 from those caused by life-history traits, biometry, stresses, or climate variability. Briefly, an abrupt,  
110 large, and sustained increase in tree-ring width (radial growth) is inferred to be a release from tree-  
111 to-tree competition and is taken as evidence of past canopy disturbance (Lorimer 1980).  
112 Disturbance detection methods were first formalized in the mid- to late-1980s so the frequency and  
113 severity of disturbance could be objectively quantified through time and synthesized into time series  
114 of canopy disturbance (Lorimer 1985; Lorimer & Frelich 1989). A series of methods were  
115 developed soon afterward that either built directly upon these original methods (Nowacki &  
116 Abrams 1997; Fraver & White 2005) or used new approaches (Black & Abrams 2003; Druckenbrod  
117 2005; Druckenbrod *et al.* 2013; Lee *et al.* 2017). The growing interest in studying old-growth  
118 forests, ecological restoration, and forest conservation biology increased the use of these methods.

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

125         Developers of the various release-detection methods have independently discussed the  
126 strengths and weaknesses of their specific approach (Lorimer & Frelich 1989; Black & Abrams  
127 2003; Black & Abrams 2004; Fraver & White 2005; Druckenbrod *et al.* 2013). A few studies have  
128 examined the sensitivity to varying parameters and thresholds of the growth-averaging method

129 (Rubino & McCarthy 2004; Bouriaud & Popa 2007; Stan & Daniels 2010). To date, however, no  
130 work has provided a detailed comparison of the performance of the most widely used detection  
131 methods with forest inventory datasets of controlled or observed records of disturbance. A rigorous  
132 examination of these methods is critical to correctly identify and correctly date past disturbances  
133 (Rubino & McCarthy 2004; Bouriaud & Popa 2007; Copenheaver *et al.* 2009; Altman *et al.* 2014;  
134 McEwan *et al.* 2014; Pederson *et al.* 2014; Šamonil, Kotík & Vašíčková 2015).

135         Our primary objective was to analyse the performance of four widely used disturbance-  
136 detection methods in a forest subjected to an experimentally-induced disturbance and a forest with  
137 minimal canopy disturbance. These four methods are: radial-growth averaging (Lorimer & Frelich  
138 1989; Nowacki & Abrams 1997), boundary line (Black & Abrams 2003; Black & Abrams 2004),  
139 absolute increase (Fraver & White 2005), and time series (Druckenbrod 2005; Druckenbrod *et al.*  
140 2013). Performance was assessed by a method's ability to detect a disturbance of known timing and  
141 magnitude. Our secondary objectives were to: i) investigate the efficacy of these methods in  
142 reconstructing the timing and severity of disturbance at the stand level and ii) gain insight into the  
143 sensitivity of each method to adjustments in their temporal parameters and growth thresholds. Our  
144 study will provide guidance for future tree-ring studies with respect to method selection and  
145 interpretation of results.

146

## 147 **Materials and methods**

### 148 *Study sites*

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

154 repeated forest measurements since 1969 and no significant canopy disturbance (Eisen & Plotkin  
155 2015).

156

157 *High severity disturbance forest.*

158 The hurricane manipulation experiment (“Hurricane pulldown”) was located at the Harvard  
159 Forest, Petersham, Massachusetts, USA (72.20 °N, 42.49 °W, 300-315 m a.s.l.) in a forest  
160 dominated by red maple (*Acer rubrum*) and northern red oak (*Quercus rubra*) (Cooper-Ellis *et al.*  
161 1999; Plotkin *et al.* 2013). The forest originated following a clear-cut in 1915 (Harvard Forest  
162 Archives, *unpub. data*). All trees  $\geq 5$  cm diameter at breast height (DBH) were tagged, spatially  
163 mapped and recorded as live or dead during inventory surveys (1990 before, and after the  
164 experiment, 1996, 2000, 2005 and 2010). In early October 1990, 276 trees were toppled in a  
165 northwesterly direction to effectively simulate the disturbance caused by the 1938 hurricane in New  
166 England. The Hurricane pulldown occurred over 0.8 ha of forest and was separated from a 0.6 ha  
167 control forest by a 30-m forest buffer. Similar to the impact of the 1938 hurricane, surveys  
168 immediately following the toppling of trees indicated that 80% of the canopy trees and two-thirds of  
169 all trees  $\geq 5$  cm DBH were damaged (Rowlands, 1941; D. R. Foster, 1988). In 2009, a total of 57  
170 *Acer rubrum* trees from within the hurricane experiment and the adjacent control forest were cored  
171 at approximately breast height (1.3 m) to determine how implementation of the Hurricane pulldown  
172 experiment affected the growth of surviving trees. Increment cores from the site revealed tree ages  
173 ranging from 42-95 years (median age = 79 years).

174

175 *Low severity disturbance forests*

176 Vegetation and tree-ring sampling were conducted in long-term monitoring plots at the  
177 “Lyford plot” in the Harvard Forest. Lyford plot is a second-growth mixed northern hardwood  
178 forest dominated by northern red oak and red maple with relatively little disturbance (Eisen &  
179 Plotkin, 2015) and is used here as a contrast to the high severity Hurricane pulldown. All trees  $\geq 5$



180 cm diameter at breast height (DBH) were tagged, spatially mapped and recorded as live or dead  
181 during inventory surveys (1969, 1975, 1991, 2001 and 2011) (D. Foster & Barker Plotkin, 1999). In  
182 2011, trees in three Lyford plot subplots were cored following the nested design of: i) trees >10 cm  
183 DBH out to 13 m from plot center and ii) trees >20 cm DBH from 13-20 m from center. Tree ages  
184 from cores ranged from 26-152 years (ages at breast height; median age = 93 years).

185

#### 186 *Natural hurricane disturbance*

187 Vegetation and tree-ring sampling were also conducted in the Harvard Forest tract  
188 (“Harvard tract”) in Pisgah State Park, a mixed northern hardwood forest dominated by eastern  
189 hemlock (*Tsuga canadensis*) owned by the Harvard Forest. Pisgah State Park is approximately 36  
190 km to the northwest of the Harvard Forest in southwest New Hampshire. The 1938 hurricane  
191 knocked down >80% of the canopy trees in this tract of old-growth forest in Pisgah State Park  
192 (Rowlands 1941; Foster 1988), hereafter the ‘Harvard tract’. Two tree-ring sampling plots were  
193 established in 2014 following the protocol used in the Lyford plot. Because the tract is old-growth,  
194 we added an additional nest to both plots where trees >30 cm DBH and 20-30 m from plot center  
195 were surveyed and cored. Increment cores from the Harvard tract revealed 42-340 year old trees  
196 (median age = 93 years).

197

#### 198 *Tree core preparation*

199 All cores were dried, sanded, cross-dated, and measured following standard  
200 dendrochronological methods (Stokes & Smiley 1968). Each ring was measured to the nearest  
201 0.001 mm and dating was verified with the program COFECHA (Holmes 1983; Grissino-Mayer  
202 2001). A gypsy moth defoliation event (1981) was used as a marker ring. In the Hurricane pulldown  
203 experiment, dating control of all cores resulted in 15 crossdated trees from the control plot and 32  
204 crossdated trees from the Hurricane pulldown plot. A total of 144 trees were analysed from the  
205 Lyford plot and 224 from the Harvard tract.

206

207 *Disturbance detection methods*

208 Disturbance detection methods used here can be divided into two broad groups: growth  
209 averaging (radial-growth averaging, boundary-line, absolute-increase) and time-series approach  
210 (time-series). Growth averaging methods involve comparing mean growth rates prior to and after  
211 any year  $t$  within an *a priori* number of years, hereafter ‘window length’, to determine if an abrupt  
212 and sustained increase in growth occurred after year  $t$ ; further constraints are involved in the  
213 boundary-line and absolute-increase methods (Black & Abrams 2003; Fraver & White 2005). The  
214 time-series method identifies sequences of statistically extreme residual ring widths after  
215 accounting for the effects of any biological age trend and autocorrelation (Druckenbrod 2005). All  
216 methods were originally designed and developed for various forest types or species in eastern North  
217 America, and are currently applied to a much wider range of forest conditions and species.

218

219 *i) Radial-growth averaging*

220 Radial-growth averaging (GA) is one of the earliest developed and still commonly used  
221 methods and is based on running means of raw ring widths (Lorimer 1980; Lorimer 1985; Lorimer  
222 & Frelich 1989). The original method averaged radial growth over the preceding 15-year period  $M_1$   
223 (including the target year  $t$ ), and the average radial growth over the subsequent 15-year period,  $M_2$   
224 (excluding the target year  $t$ ) to calculate the percentage growth change (PGC) for each annual ring  
225 as:

226 
$$PGC = \frac{M_2 - M_1}{M_1} * 100. \quad (\text{Eq. 1})$$

227 The original percentage growth thresholds to detect growth releases in understory trees were  
228  $\geq 100\%$  growth increase for a “major, sustained” release and 50-99% for a “moderate” release  
229 (Lorimer 1985; Lorimer & Frelich 1989). Later, the original window lengths were shortened to 10  
230 years and the “moderate” release was reduced to a growth increase of 25% to derive disturbance  
231 history from old-aged canopy oak trees (Nowacki & Abrams 1997). Different  $M_1$  and  $M_2$  window

232 lengths, as well as growth thresholds, have been applied to meet species-specific or site-specific  
233 criteria (Rubino & McCarthy 2004; Stan & Daniels 2010). The default settings for the radial-growth  
234 averaging method in TRADER (Altman *et al.* 2014) are those proposed by Nowacki & Abrams  
235 (1997). Therefore, we use the TRADER default for the radial-growth averaging method.

236

237 *ii) Boundary-line*

238 In the boundary-line (BL) method, the percentage growth change of each year for each tree  
239 (Eq. 1) is scaled by its maximum potential observed growth, as defined by prior growth rates for  
240 that species growing at one or several locations (Black & Abrams 2003). Growth pulses exceeding  
241 20% of the prior growth boundary-line were classified as releases. The rationale of this method is  
242 that standardizing growth should account for the influence of site condition, species, size and tree  
243 age on the radial growth rates (Black & Abrams 2003; Black & Abrams 2004; Ziaco *et al.* 2012).  
244 Defining the boundary-line requires a large amount of data from a single species within similar site  
245 conditions, in some cases up to 50,000 radial increments, which may make the boundary line  
246 difficult to fit for certain stands and species.

247

248 *iii) Absolute-increase*

249 While the two previous methods are based on the relative changes of ring-width averages,  
250 the absolute-increase (AI) method (Fraver & White 2005) relies on the subtraction of the average  
251 pre-event growth rate ( $M_1$ ) from the average post-event rate ( $M_2$ ), using 10-year window lengths.

$$252 \quad AI = M_2 - M_1. \quad (\text{Eq. 2})$$

253 The growth increase is determined as a release if the difference in growth rate exceeds a  
254 predetermined threshold for a given species. The method is meant to detect overhead canopy  
255 disturbances, making it similar to the ‘major’ releases referred to in radial-growth averaging and  
256 boundary-line methods. Fraver & White (2005) demonstrated the appropriate species-specific  
257 release threshold by testing it against empirical absolute increases found in different trees

258 responding to dated canopy gaps. In cases where knowledge of species' growth potential is not  
259 available, they suggest selecting a threshold value equal to 1.25 times the standard deviation, or  
260 somewhat less than the 90<sup>th</sup> percentile, of all absolute increases. In the current study, we used the  
261 latter procedure (1.25 SD) to determine species-specific thresholds for the absolute increase  
262 method.

263

#### 264 *iv) Time-series*

265 Time-series (TS) analysis is central to the reconstruction of past climate using tree rings  
266 (Cook & Kairiukstis 1990) but also for reconstructing past ecological changes (Druckenbrod 2005).  
267 This release detection approach removes the long-term growth trend from a series, accounts for the  
268 autocorrelation present in width measurements of sequential tree-rings and uses intervention  
269 detection, enabling its release criteria to scale with a tree's growth rate similar to the boundary-line  
270 and absolute-increase methods. Release events are identified as sequences of unusually large,  
271 positive departures from autoregressive residuals over intervals of 9 to 30 years. Using Tukey's  
272 biweight mean as a robust estimate of location and scale, the detection criteria identifies any  
273 sequence with a scale greater than 3.29 (or 99.95% of the observations for a one-tailed analysis) as  
274 an outlier (Druckenbrod *et al.* 2013). A Hugerhoff curve (Warren 1980; Cook & Kairiukstis 1990;  
275 Druckenbrod *et al.* 2018) is then fit at the start of the growth release. The flexibility of this curve  
276 captures both transient and sustained release events. Unlike growth averaging methods, this curve  
277 intervention detection approach allows time-series analysis to reconstruct not only the year of  
278 release but also the magnitude and duration of the subsequent growth change caused by the  
279 disturbance event (Rydval *et al.* 2015).

280

#### 281 *Analysis of disturbance methods*

#### 282 *Tree level methods evaluation*

283 To independently determine the likelihood of a growth release for each individual tree, we  
284 first used the census data to calculate the distance-weighted size competition index (CI) proposed  
285 by Hegyi (1974) as:

$$286 \quad CI = \sum_{j=1}^n \left[ \frac{\left(\frac{D_j}{D_i}\right)}{R_{ij}} \right] \quad (\text{Eq. 3})$$

287 where  $D_j$  is the DBH of competitor tree,  $D_i$  the DBH of focal tree,  $R_{ij}$  the distance between  
288 the neighbouring and focal trees, and  $n$  the number of trees included in the sample. The maximum  
289 radius for the competitor tree to be included was 10 m and the  $DBH \geq 5$  cm. CI was calculated in R  
290 library ‘siplab’ (García 2014).

291 Competition index change for each tree (CIC) was estimated from inventory data as the  
292 difference of CI from two subsequent inventories as:

$$293 \quad \Delta CIC_t = \frac{(CI_t - CI_{t-1})}{N} \quad (\text{Eq. 4})$$

294 where  $CI_t$  is the competition index at measurement  $t$ ,  $CI_{t-1}$  the competition index at  
295 measurement preceding to  $t$ ,  $N$  the number of years between two subsequent inventories ( $t$  and  $t-1$ ).  
296 CIC was calculated for each tree and measurement year within the Hurricane pulldown (1990,  
297 1996) and the Lyford plot (1991, 2001), excluding the trees in the buffer zone (7 m). Thus, negative  
298 values of CIC indicate that competition around the focus tree has decreased. Later, we applied  
299 support vector machine (SVM) analysis to CIC and diameter change of the trees at Hurricane  
300 pulldown and control plots at the individual tree level to empirically determine the likelihood that  
301 individual trees had responded to the reduction in competition after the experimental hurricane  
302 disturbance. We identified the optimal separating hyperplane (line) between the two classes by  
303 maximizing the margin (distance between nearest points and hyperplane) between the classes using  
304 the linear kernel fit and C-classification (binary classification). To do so, SVM maps the input  
305 vectors into a  $n$ -dimensional feature space (where  $n$  is number of features) to construct the linear  
306 decision surface (Cortes & Vapnik 1995). In our case SVM operates with a linear kernel to separate

307 the repeated measure data into two classes, simply trees that likely experienced a growth releases  
308 versus those that did not. SVM analysis was performed with R library ‘e1071’ (Meyer *et al.* 2015).

309 Trees identified as released or not released through SVM analysis were used as the standard  
310 for comparing the efficacy of the four disturbance detection methods. Efficacy at the tree level was  
311 evaluated by the (i) correct classification of trees identified as having been released through SVM  
312 analysis and (ii) timing of the detected event compared to the year of the known event. We  
313 considered two types of false detections: i) a false positive (type I error): where SVM analysis did  
314 not show the tree having a significant change in competition, but a release detection method  
315 identified a release, and ii) a false negative (type II error): where SVM analysis classified a tree as  
316 released, but a disturbance was not detected by the release detection method.

317

#### 318 *Stand-level methods evaluation*

319 We recorded the timing and severity of each disturbance event identified by each method at  
320 the stand level. To overcome limitations of temporal resolution incurred by the decadal binning of  
321 annual disturbances, we fit a kernel density estimation (KDE) function to reconstructed disturbance  
322 histories to better characterize the timing and severity of disturbance events at the stand level. The  
323 moving KDE function was fit to 15-year windows, and the value of the fitted function for a  
324 particular year was extracted from the distribution at the mid-point. Values were standardized by  
325 the maximum value calculated by fitting the KDE to the normal distribution with 1 standard error  
326 and a 15-year window (0.28184). Using outcomes from the KDE analysis, we derived a disturbance  
327 severity, which incorporates both the proportion of trees showing response and synchrony in the  
328 timing of response. Thus, peaks in detected disturbances represent the standardized proportion of  
329 trees responding to a disturbance. These calculations were performed using the ‘density’ function in  
330 the ‘pracma’ R package (Borchers 2017) and ‘findpeaks’ function in the ‘quantmod’ R package  
331 (Ryan 2008).

332 We then conducted a sensitivity analysis to quantify how different window lengths and  
 333 thresholds for each method influenced the stand-level reconstruction of disturbance history (Table  
 334 1). Thresholds varied depending on the method used. For the growth averaging methods, moving  
 335 averages were calculated for window lengths between 5 and 15 years with a 1-year time step. For  
 336 the time-series method, window lengths from 1 to 22 years were used to calculate residuals (Table  
 337 1). We used the R package TRADER (Altman *et al.* 2014) for growth averaging methods, and an  
 338 executable program for the time-series approach (Druckenbrod *et al.* 2013) in Matlab (Mathworks  
 339 2014). All subsequent analyses were done using R statistical software ver. 3.0.3 (Team 2017).

340 **Table 1** Ranges of window lengths and thresholds used for the sensitivity analysis of  
 341 disturbance detection methods.

Method	Window length ( $M_1 = M_2$ , in years)	Threshold
Radial-growth averaging		From 25% to 175% by 25% increments
Boundary line	From 5 to 15 by 1 step	From 20% to 80% by 10% increments
Absolute increase		From 70% to 130% of default absolute increase threshold
Time series	Time step of 1,2,3,4,5,7,12,17,22	From 70% to 130% of default time series threshold

342

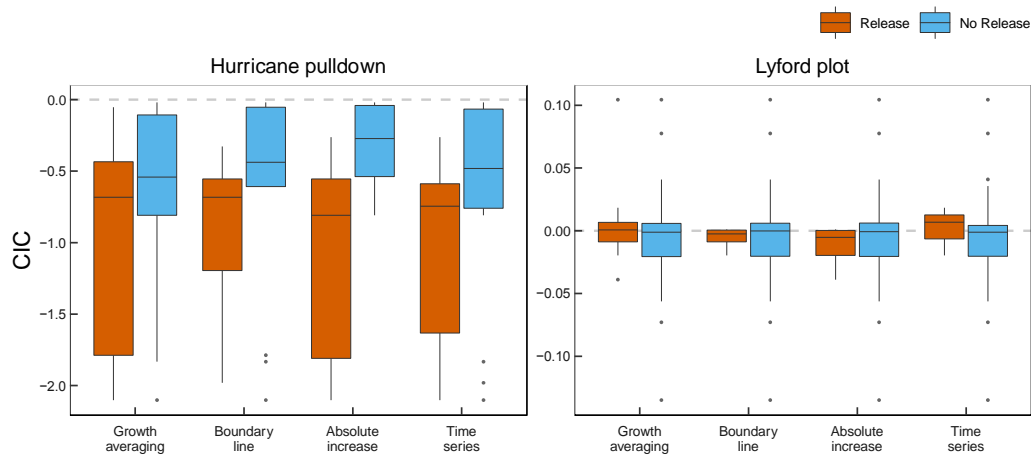
## 343 Results

### 344 *Event Detection at the Tree Level*

345 Based upon changes in estimated tree competition in the Hurricane pulldown experiment,  
 346 SVM analysis classified 87% of surviving trees as having been released from competition. A  
 347 decrease of 0.325 of the CI, translating to approximately 33% loss of basal area around trees within  
 348 five years, was determined to result in a significant chance of a growth release for trees in the  
 349 pulldown plot versus those in the control plot (accuracy 0.94, sensitivity = 0.95,  $p < 0.001$ ).

350 The median competition index change (CIC) of trees identified as being released by the four  
 351 disturbance detection methods ranged from -0.68 (boundary-line and radial-growth averaging) to -  
 352 0.81 (absolute-increase) for Hurricane pulldown and was around -0.01 for the Lyford plot. Trees

353 identified as released by absolute-increase methods had a significantly lower CIC ( $p < 0.001$ ) than  
 354 those identified as not released, where negative values of CIC indicate decrease in competition.  
 355 Radial-growth averaging method identified the highest number of growth releases (n=13 Hurricane  
 356 pulldown, n=8 Lyford plot) while time-series identified the least (n=8 Hurricane pulldown, and n=3  
 357 Lyford plot).

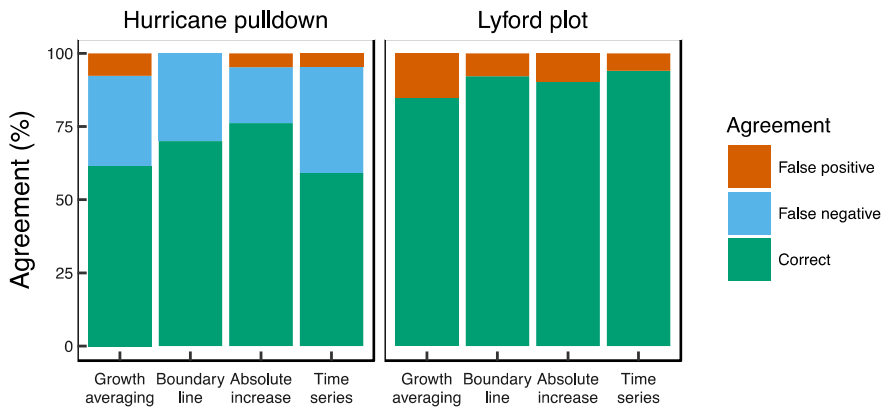


358  
 359 **Fig. 1** Competition index change (CIC) of trees identified as released (orange) and not released  
 360 (blue) based on the four disturbance detection methods at the Hurricane pulldown experiment (left  
 361 panel) and the Lyford plot (minor 1938 hurricane damage, right panel). The solid black line  
 362 represent median, the box represents 25 and 75 quantiles. CIC was calculated based on the  
 363 inventory data (see methods). Note the different scales on the two y-axis.

364  
 365 The accuracy of the four disturbance detection methods (measured as trees with an  
 366 identified release from those with a significant change in CIC identified as having been released  
 367 through SVM analysis) was 60-76% for Hurricane pulldown, and 85-94% for the Lyford plot, the  
 368 forest with the lowest disturbance rate (Fig. 2). False negatives were more common than false  
 369 positives for the Hurricane pulldown, but false negatives were not detected in the Lyford plot  
 370 (meaning that all trees estimated to have been released by the SVM analysis were also detected by  
 371 the tree-ring method). The radial-growth averaging method had the highest prevalence of false  
 372 positives in both stands (up to 15%). The time series method had the highest accuracy for the



373 Lyford plot (94%), but showed the highest value of false negatives (36%) for the Hurricane  
 374 pulldown.



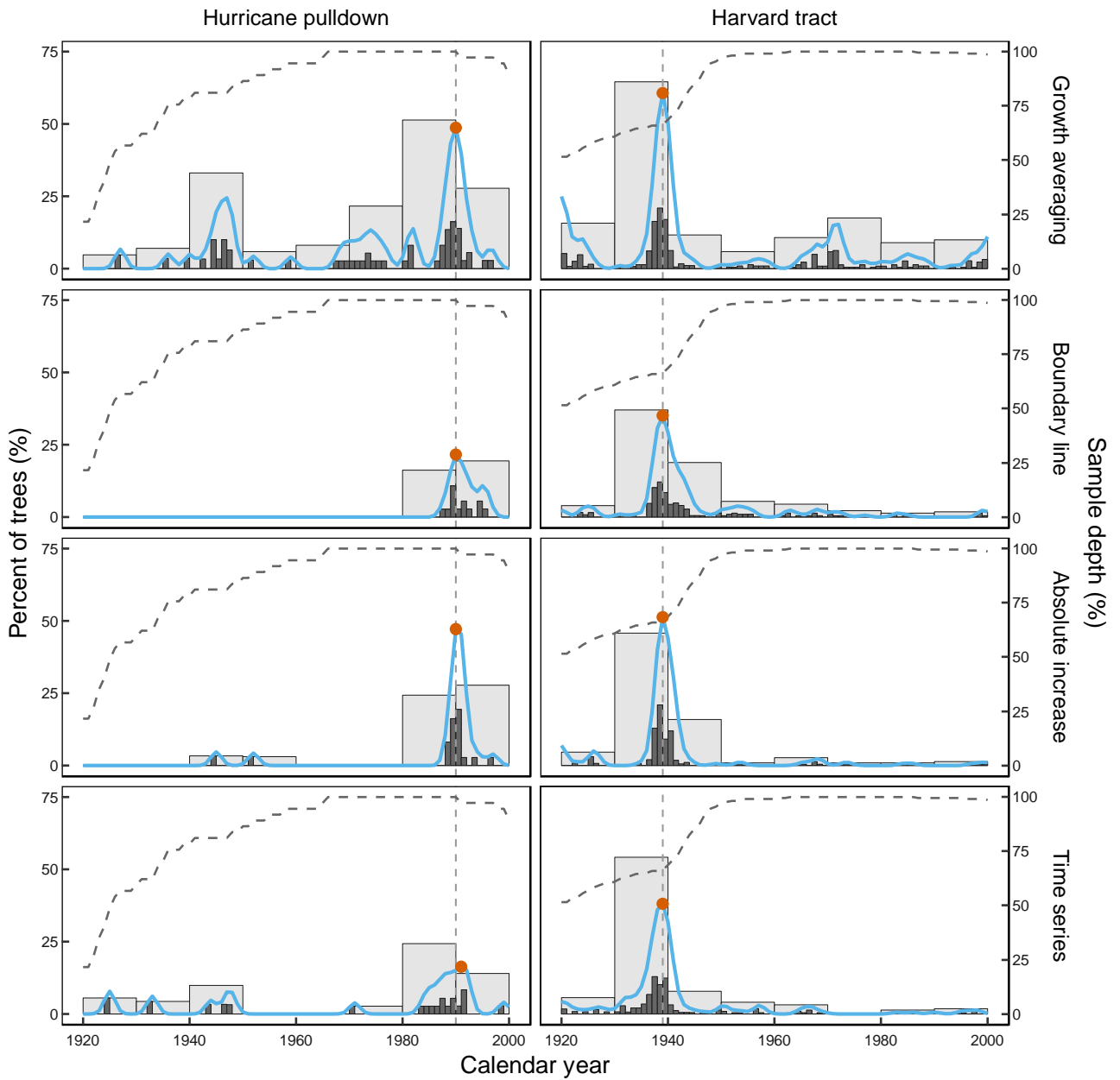
375  
 376 **Fig. 2** Agreement between the classification of tree growth from the Hurricane pulldown  
 377 experiment (left panel) and the Lyford plot (minor 1938 hurricane damage, right panel) using  
 378 support vector machine analysis and the four disturbance detection methods tested for this study.

379  
 380 *Event Detection at the Stand Level*

381 The performance of each method regarding the timing and severity of detected disturbance  
 382 events at the stand level was evaluated using data from the Hurricane pulldown experiment (Fig. 3)  
 383 and the Harvard tract. While all methods identified peaks in disturbances within a year of the  
 384 known event (1990 for the Hurricane pulldown and 1938 for the Harvard tract), the temporal offset  
 385 of all series analyzed ranged from -6 years (six years prior to the event) to +7 years (7 years after  
 386 the event). The absolute-increase method had the best temporal accuracy overall showing the lowest  
 387 standard deviation (Hurricane pulldown=1.88; Harvard tract =1.31), positive or neutral skewness  
 388 (1.85; -0.13 respectively), and low kurtosis for the Harvard tract (3.4; 0.04 respectively) in  
 389 identifying the correct year of disturbance, suggesting correct identification of most releases. Here,  
 390 a lower standard deviation shows greater temporal precision, positive skewness more detections in  
 391 the years following the event and low kurtosis light tails or lack of outliers. In comparison, other  
 392 methods had higher standard deviation (e.g. time-series method 2.7, boundary-line 2.5) or negative

393 skewness (time-series method -0.96), reflecting a wider temporal spread of detected releases and  
394 releases detected several years before the actual disturbance.

395           The absolute-increase and the radial-growth averaging methods identified the highest  
396 severity of disturbance at the Hurricane pulldown experiment (i.e., peaks of the kernel density  
397 function, 47% and 49%, respectively). In contrast, the estimated severity of disturbance for the  
398 time-series and boundary-line methods showed roughly half those values (16% and 22%  
399 respectively). Differences among methods in estimating the severity for the 1938 event at the  
400 Harvard tract were lower, but still notable.



402

403 **Fig. 3** Plot-level disturbance history in response to a simulated hurricane in 1990 (left panel) and  
 404 natural hurricane at the Harvard tract in 1938 (right panel). The proportion of trees responding to  
 405 disturbances is binned by year (black bars) and decade (grey bars). Peaks of disturbances (solid  
 406 orange circles) were identified based on the standardized running kernel density estimation function  
 407 (solid blue line). Accuracy, precision, and severity of release events (orange error bars) are  
 408 identified here based on different window lengths. The dashed grey line shows sample depth (as a  
 409 percent).

410

411 Our sensitivity analysis of all methods at the stand level showed that the boundary-line  
 412 method was the most sensitive to changes in window length parameters and threshold levels within  
 413 pre-established ranges (Table 1), showing the widest range of temporal detection (-1 to 5 years)  
 414 (Fig. 3). Variation in detected severity of the event was greater than variation in temporal accuracy,  
 415 and deviated from the default settings for up to 35% (radial-growth averaging), when within 14%  
 416 from the default. In all methods, increasing the window length and minimum threshold for releases  
 417 resulted in decreases of estimated disturbance severity ( $p < 0.001$ ).

418

### 419 Discussion

420 Our comparison of four commonly used methods of disturbance detection from forests with  
 421 well-documented past disturbance revealed a wide range of efficacy among the methods. Despite  
 422 only minor differences in the temporal accuracy in the detection of a disturbance event between  
 423 methods, pronounced differences were observed in estimating the stand level severity of  
 424 disturbance (up to 1.9 times higher). Performances improved (i.e. greater precision rates) and  
 425 differences among methods were minor in a stand with a relatively low rate of canopy disturbance  
 426 (Table 2). Our results showed that these uncertainties were greatest with the boundary-line and  
 427 time-series methods.

428

429 **Table 2** Comparison of the efficacy of each method to various parameters of disturbance detection.

<b>Parameters</b>	<b>Radial- growth Av.</b>	<b>Radial- growth Av. Original</b>	<b>Boundary- Line</b>	<b>Absolute- Increase</b>	<b>Time- Series</b>
Correct					
Hurricane pulldown	61%	73%	70%	76%	59%
Lyford plot	85%	96%	95%	90%	94%
False Positive					
Hurricane pulldown	8%	4%	0%	5%	5%
Lyford plot	15%	4%	5%	10%	6%

False Negative					
Hurricane pulldown	31%	23%	30%	19%	36%
Lyford plot	0%	0%	0%	0%	0%
Temporal Precision					
of Disturbance (range, in years)	-1 – 1	-1 – 1	-1 – 5	0 – 1	-1 – 2
Calculated severity					
Hurricane pulldown	49%	41%	22%	47%	16%
Harvard tract	61%	49%	35%	52%	38%
Sensitivity to					
Parameter	high	high	high	low	high
Thresholds					
Large Amount of Data Required	no	no	yes	yes	no
<i>A priori</i> Information					
Required	no	no	yes	yes	no
Additional					
Information Returned	no	no	no	no	yes

430

431

Uncertainties in temporal accuracy of release events at tree level resulted in large

432

uncertainties in reconstructed disturbance severity at the stand level (Fig. 3). Temporal precision

433

was higher with the absolute-increase and radial-growth averaging methods and lower with

434

boundary-line and time-series methods. All methods showed a substantial limitation in

435

reconstructing the estimated severity of canopy disturbance. Although the radial-growth averaging

436

and absolute-increase methods estimated a disturbance severity of just 50% of the trees in the

437

Hurricane pulldown, that severity was more than twice the value estimated with the other two

438

methods. While each method may detect the same number of trees showing a release around the

439

time of a known disturbance, variations in temporal precision influenced the estimation of

440

disturbance severity by nearly 1.9 times. It is clear that temporal precision of the various methods

441

needs to be considered carefully when estimating disturbance severity and, equally important, when

442

identifying agents of past disturbance events (Fritts 1976; Black *et al.* 2016). Additional sources of

443

information, such as growth suppression, tree injuries, death dates, may also be used to precisely

444 estimate the date of disturbance and potentially determine the agent of disturbance that affected the  
445 forest.

446 Parameter setting (window lengths and thresholds) is among the most critical and still  
447 largely unsettled issues in disturbance analysis from tree rings as it influences the precision and  
448 accuracy in releases and ultimately lead to over- or under-estimations of severity of disturbance  
449 events (Rubino & McCarthy 2004; Bouriaud & Popa 2007; Copenheaver *et al.* 2014). Thus, it is  
450 important to consider the existing trade-off between the higher probability of obtaining more false-  
451 positives with short window lengths and low thresholds or more false-negative with longer window  
452 lengths and more strict thresholds. The sensitivity to changes in parameters also depends on the  
453 method and our sensitivity test showed that the absolute-increase and radial-growth averaging  
454 methods were least sensitive to changes in parameter selection.

**Spotlight: Examining a legacy of thresholds used for radial-growth averaging analysis**

The original thresholds for the radial-growth averaging method was set at averages over two 15-year windows and a minimum growth increase of 50% between each window (Lorimer 1985; Lorimer & Frelich 1989). Within a decade, lower thresholds of 10 years and a 25% growth increase were designated as a theoretical sensitivity of canopy trees to changes in local competition (Nowacki & Abrams 1997). Both methods have been long used and are popular within the community and the radial-growth averaging default in TRADER (Altman *et al.* 2014) is the 10-year 25% growth increase of Nowacki and Abrams (1997). Our sensitivity analysis gives us the opportunity to compare how release detection differs between these thresholds.

We found an improvement of accuracy to 73% (Lyford plot) and 96% (Hurricane pulldown) using the 15-year, 50% threshold compared to 61% and 85% respectively of the 10-year, 25% threshold (Table 2). One goal of the 15-year, 50% threshold was to take a more conservative approach that would avoid detecting disturbance that could be related to changes in other drivers, such as climatic variability (Lorimer 1985). Our results support this approach. While some events are missed with the 15-year, 50% threshold, it is less likely to identify events that did not occur.

455

456 The boundary-line and absolute-increase methods are constrained by the quantity of data or  
457 expert knowledge required prior to using them for disturbance analysis. These two methods require  
458 a significant amount of *a priori* information while radial-growth averaging and time-series methods  
459 require the least amount. Considering these constraints, the application of the boundary-line and  
460 absolute-increase methods may be primarily limited to large datasets of a single species or to  
461 locations where growth information of many species is already available (Black & Abrams 2003;

462 Fraver & White 2005; Ziaco *et al.* 2012). We view the *a priori* need for large data sets regarding  
463 expected species growth patterns or expert knowledge to be a limitation for studies in forests with  
464 high tree-species diversity or where high tree replication is not feasible (e.g. projects with short  
465 timeframes for completion, protected areas or rare species). Of these methods, radial-growth  
466 averaging appears to be the method requiring the least amount of *a priori* information while still  
467 providing accurate results. We also note that the time-series method is the only one that produces  
468 additional information regarding the magnitude and duration of release events (Rydval *et al.* 2015).

469 Finally, the aggregation of disturbances at the stand level from any of these four methods  
470 affects estimates of disturbance severity and timing and, thus our understanding of stand dynamics.  
471 Our results indicate that annual binning of canopy disturbance, combined with kernel density  
472 estimation, would improve reconstructions of forest disturbance history and understanding of long-  
473 term forest dynamics. We find that decadal binning of disturbances may falsely suggest nearly  
474 continuous canopy disturbance. In contrast, annual binning revealed improved agreement with the  
475 documented events at our study forests and suggested more episodic disturbances.

476 Our study is among the first to compare the four methods of release detection; however, we  
477 are aware of possible limitations of our work, and suggest that future studies include: i) a greater  
478 number of tree species with diverse functional traits (e.g. shade tolerance) and higher sample size,  
479 ii) species-rich forests; iii) a broader range of disturbance severity and agents; and iv) use of  
480 different methods to estimate the likelihood that any given tree has been released from disturbance  
481 based on forest inventories. Nevertheless, our findings will assist on deciding which method to use  
482 and will advance the discussion and motivate researchers to conduct more in-depth comparison  
483 among the methods.

484

## 485 **Conclusions**

486 We found that the radial-growth averaging method and absolute-increase methods had lower  
487 levels of overall error in detecting canopy disturbance events in surviving understory trees with the

488 original radial-growth averaging method producing fewer false positives than the default used in  
489 TRADER. Of the methods tested, radial-growth averaging requires the least amount of *a priori*  
490 information while returning reasonably accurate results. We note that the time-series method is the  
491 only one that produces additional information regarding the magnitude and duration of release  
492 events. The findings of this study can improve researchers' choice of which method to use for the  
493 dendrochronological reconstruction of the past disturbances.

494

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506

#### 507 **Authors' contributions**

508 VT, DD, DM-B and NP conceived ideas and designed the study. DO, DB, AB-P and NP performed  
509 the sampling. VT, DD, DM-B, DB and NP performed the dendrochronological analyses. VT, DD  
510 and DM-B performed data and statistical analysis. VT, DD, DM-B and NP wrote the manuscript  
511 and all authors commented on it. All authors contributed critically to the drafts and gave final  
512 approval for publication.

513



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