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Original article

Stadium Woods: A dendroecological analysis of an old-growth forest fragment on a university campus

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ABSTRACT

On the Virginia Tech campus, adjacent to the football stadium is a 4.6-ha forest fragment that contains a population of unusually large white oak (*Quercus alba* L.) trees. We used dendroecology and sampled vegetation in fixed area plots to reconstruct the disturbance history of this forest fragment and compared the radial-growth averaging criteria and the boundary-line release criteria for identifying canopy disturbances. Structurally, the Stadium Woods has an inverse-J diameter distribution and trees present in all canopy strata. The oldest white oak had periods of asynchronous suppression and release indicating a closed canopy forest with periodic canopy disturbances. The boundary-line release criteria detect a broader range of growth releases, whereas the radial-growth averaging criteria are more specialized for capturing canopy gaps. Release events identified with the boundary-line release criteria lagged an average of 5.8 years behind those identified with the radial-growth averaging criteria because the boundary line release criteria identifies the year of maximum percent growth change, whereas the radial-growth averaging criteria identifies the first year with a detectable increase in radial growth. The Stadium Woods represents a unique collection of unusually large white oak trees growing in a heavily populated area and reveals the importance of long-term tree-ring chronologies stored within urban forest fragments.

Introduction

Much of our knowledge of forest stand dynamics and historical disturbance regimes originates from dendroecological analysis of tree-ring records from old-growth forests (Fritts and Swetnam, 1989; Lorimer and Frelich, 1989). Frequency and intensity of natural disturbances such as wind throw, ice storms, insect outbreaks, and fires can be reconstructed by dating scars, growth releases, or cohorts of tree establishment that followed disturbance events (Shumway et al., 2001; Jeffries et al., 2006; Lafon, 2006; Greenberg et al., 2011). Tree-ring patterns can also record the history of human activities such as logging, grazing, and the location of historical transportation routes (Ericsson et al., 2003; Motta et al., 2006; Cowell and Hayes, 2007).

The distribution and history of eastern old-growth forests in North America generally follow two patterns: (1) trees that were never cleared during European settlement because they were growing on very steep slopes or on soils unsuitable for agriculture (Therrell and Stahle, 1998) or (2) small old-growth forest fragments surrounded by land that has been heavily impacted by humans (Abrams and Copenheaver, 1999). Most eastern old-growth forests fit the former pattern (Muller, 2003; Pederson, 2010) and the few old-growth forest fragments in populated areas typically contain informal trails, exotic species, and a lower native biodiversity (Matlack, 1997; Jim, 2004). However, these forest fragments contain tree-ring records that often pre-date the fragmentation of the forest and can be used to reconstruct long-historical records of stand and gap dynamics (Lorimer, 1985).

The two most common techniques for reconstructing stand dynamics are the radial growth averaging criteria and the boundary-line release criteria. The radial-growth averaging criteria was developed by Nowacki and Abrams (1997) to identify canopy disturbances in mixed oak (*Quercus*) stands in the central Appalachian Mountains and targets increases in radial growth rate that persist in the tree ring record for a minimum period of time (10 years), corresponding to typical gap closure time for this forest type. The boundary-line release criteria developed by Black and Abrams (2003) to identify growth releases caused by canopy disturbance based on the growth potential for a given species and prior growth exhibited for an individual tree, such that trees with rapid growth

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rates must experience relatively smaller percent growth change as an indication of a release compared to trees with extremely slow growth rates. The inclusion of prior growth rates assumes that trees growing extremely fast are growing close to their biological maximum, and even under improved growing conditions are unable to demonstrate proportionally the same increase in growth as a tree released from suppressed conditions (Phipps, 2005). A recent study indicates that at extremely low productivity sites, the boundary-line release criteria underestimates the frequency of release events in sites (Ziaco et al., 2012).

On the campus of Virginia Tech, a large land-grant university in the southeastern United States, is a remnant old-growth white oak (*Quercus alba* L.) stand. Although this forested stand is heavily impacted by undergraduate forestry laboratories, military training exercises for the Virginia Tech Corps of Cadets, and by students walking between the town and the university, it contains an unusually high density of large white oak trees. This site provides the unique opportunity to explore the dendroecology of heavily disturbed old-growth fragment. Thus, the objectives of this research were to: (1) use structural data and tree-ring releases to reconstruct the disturbance history of Stadium Woods, and (2) contrast the radial-growth averaging criteria (Nowacki and Abrams, 1997) with the boundary-line release criteria (Black and Abrams, 2003).

Materials and methods

Study area

Stadium Woods is an isolated patch of old-growth forest covering approximately 4.6 ha located east of Lane Stadium on the campus of Virginia Tech in Blacksburg, Virginia. The university leased Stadium Woods and 66 ha of surrounding agricultural land in 1915, and later purchased the property in 1920 (Virginia Agricultural and Mechanical College and Polytechnic Institute, 1925). In the 1915 lease agreement, Stadium Woods is described as "that other portion of the land. . .known as the woodland, which contains twelve acres (4.8 ha) by recent survey" (Eggleston's Presidential Files, Special Collections, Virginia Tech). An aerial photograph from 1937 and a 1947 campus map confirm that Stadium Woods was slightly larger prior to the construction of Lane Stadium in 1965 (Wallenstein, 1997). The current overstory is dominated by large-diameter white oaks and the mid-canopy and understory are a mixture of native and invasive trees and shrubs. The total annual precipitation of 1010 mm is evenly distributed throughout the year. The average winter temperature is 0 °C and the average summer temperature is 19 °C. Although there is some topographic relief within the woods, slopes do not exceed 10% and the average elevation of the area is 640 m asl. Stadium Woods soils are a Groseclose-Urban land complex with a rooting zone that exceeds 1220 mm and a moderate available water capacity (Creggar and Hudson, 1985). The Stadium Woods has a site index of 26, meaning even-aged white oak trees will reach 26 m in height within 50 years after germination (Olson, 1959). The high number of unusually large and old white oak are a rare characteristic for this region and classify Stadium Woods as eastern old-growth forest (Hunter and White, 1997).

Field and laboratory work

To quantify structural characteristics within Stadium Woods, thirty 100 m^2 fixed-area plots were randomly located and within each plot, height to top of live crown, diameter at breast height (dbh, 1.4 m), and tree species were recorded on all stems > 10 cm dbh. An increment core was extracted from each tree at 0.5 m above the root collar. While sampling the vegetation plots, we extracted cores from a total of 16 white oak trees. To capture the disturbance history of Stadium Woods, we supplemented the initial collection of white oak increment cores with cores from an additional 17 white oaks. We targeted trees with characteristics associated with older trees, e.g., blocky bark, sinuous trunk, and broken top branches (Pederson, 2010). Some larger white oaks had substantial root buttressing and basal rotting. To avoid boring into rotten sections and to avoid ring width variations caused by buttressing, we cored these stems at 1.4 m. All increment cores were air-dried and glued to wooden holders. Each core was sanded with progressively finer grit sandpaper until it was possible to see the cellular structure of the wood under a microscope.

Within species groups, tree cores were visually crossdated using patterns of narrow and wide ring widths to accurately date the annual rings (Schweingruber et al., 1990). Due to small sample size, the northern red oak (*Quercus rubra* L.), scarlet oak (*Quercus coccinea* Münchh.), and black oak (*Quercus velutina* Lam.) cores were combined into a single red oak group for visual crossdating because a prior study from this region had shown that these three species crossdated well (White et al., 2011). To reduce crossdating problems caused by small sample size, we also combined box elder (*Acer negundo* L.), Norway maple (*Acer platanoides* L.), and red maple (*Acer rubrum* L.) and we created a third group from sweet cherry (*Prunus avium* L.) and black cherry (*Prunus serotina* Ehrh.). After visual crossdating, ring widths from all cores were measured with a TA Tree-Ring Measurement System (Velmex, Inc., Bloomfield, NY). We used the crossdating verification program, COFECHA, available through the Dendrochronology Program Library (Grissino-Mayer, 2001). We had difficulty crossdating understory trees because the common climatic signals used for crossdating were weak relative to tree-specific competition signals and because the tree-ring series were very short (15–20 years). Therefore, we were unable to crossdate 16 of the 46 understory tree cores and these cores were eliminated from further radial-growth analysis. For six species, we had five or fewer cores and this was not a large enough sample size to crossdate properly. Therefore, we did not date or measure ring widths for American beech (*Fagus grandifolia* Ehrh., 1 tree), black locust (*Robinia pseudoacacia* L., 3 trees), black walnut (*Juglans nigra* L., 1 tree), flowering dogwood (*Cornus florida* L., 5 trees), little leaf linden (*Tilia cordata* Mill., 3 trees), and white ash (*Fraxinus americana* L., 1 tree). The remaining increment cores (79 trees) had sufficiently strong common signals and large enough sample size that we were confident in our dating (Table 1).

Data analysis

To quantify the ecological importance of each tree species in Stadium Woods, we calculated an importance value (Barbour et al., 1999). The importance value for each species was an average of the relative frequency (# plots that a species occurs in and therefore a measure of how widely distributed a species was within the stand), relative density (# of stems/ha), and relative dominance (basal area as calculated from the dbh measurements).

We contrasted the radial-growth averaging criteria (Nowacki and Abrams, 1997) and the boundary-line release criteria (Black and Abrams, 2004) for differences in how these methods identified growth releases. The raw tree-ring width measurements from the white oak cores were analyzed to identify percent growth change following Nowacki and Abrams (1997):

$$\%GC = \left[\frac{M_2 - M_1}{M_1}\right] \times 100$$

where %GC is the percent growth change of the average ring width from the previous 10 years (M_2) and the average ring width of the subsequent 10 years (M_1). This process excludes the first and last

Table 1
Tree-ring characteristics of species sampled from Stadium Woods, Virginia. *Quercus* spp. includes *Q. coccinea*, *Q. rubra*, and *Q. velutina*. *Acer* spp. includes *A. negundo*, *A. platanoides*, and *A. rubrum*. *Prunus* spp. includes *P. serotina* and *P. avium*.

Species	Time span	Series intercorrelation	Mean sensitivity	Average ring width (mm)
Acer spp.	1965–2011	0.425	0.334	1.883
Prunus spp.	1937–2011	0.410	0.303	1.967
Q. alba	1697–2011	0.577	0.208	1.798
Quercus spp.	1895–2011	0.517	0.233	2.039
Sassafras albidum	1967–2011	0.446	0.251	1.421

decade of each tree-ring series because a minimum of 10 years is required for calculating the running average, which is why we only used the white oak tree-ring series and excluded the shorter lived understory species from this analysis. Release events were identified as periods when the percent growth change exceeded 25% for a minimum of 10 years and the release year was identified as the first year in this period of higher growth.

The boundary line equation to identify release events in white oak had already been developed by Black and Abrams (2004) and successfully applied in another study from Virginia (Copenheaver et al., 2009). The species-specific white oak boundary line was constructed from 164,867 growth increments that had been collected across 24 sites and the boundary line was calculated as (Black and Abrams, 2004)

$$y = 527.22e^{-0.787x}$$

where y represents percent growth change (%GC from the radial growth averaging equation presented earlier) and x represents prior growth (represented as M_2 in the % GC formula presented earlier). A moderate release is identified when %GC falls within 20–49.9% of the established boundary line for white oak and a major release is identified when %GC falls within 50–100% of the boundary line for white oak. We identified both moderate and major releases in our analysis. When an extended series of years exceeded the release criteria, the maximum %GC was identified as the release year when the tree recorded a canopy disturbance event that was substantial enough to have allowed that individual tree to respond to the increase in available light and space through a corresponding increase in radial growth (Black and Abrams, 2003).

Results

Structure and history of Stadium Woods

Stadium Woods has an inverse-J diameter distribution (Fig. 1A) with many small-diameter trees and fewer large-diameter trees. The stand contains a number of large-diameter white oaks with the largest being 115 cm dbh. The large size of the white oak trees led to it being the most important species in the stand (Table 2). Sweet cherry was the second most important species because it had the highest density and frequency (Table 2). Oaks dominated the overstory positions and sweet cherry and flowering dogwood were common understory species (Fig. 1B).

The oldest white oaks in Stadium Woods all had initial periods of extremely slow growth rates (Fig. 2). This initial period of sustained suppressed growth did not cover a common time period for all trees, but ranged from a maximum of 110 years (Fig. 2A) to the shortest period of 34 years (Fig. 2B). The periods of suppressed growth were preceded by and followed by periods of more rapid growth. Most of the transition periods between slow and fast growth spanned a couple of decades (Fig. 2A). However, a few trees demonstrated abrupt transitions, e.g., Fig. 2B: where in 1939, the tree put on 0.39 mm of radial growth and by 1942 it formed 2.76 mm of radial growth. It was not uncommon for the white oaks

Table 2
Relative frequency (number of plots), relative density (# stems), relative dominance (basal area), and importance value for tree species >10 cm in diameter at breast height at Stadium Woods, Blacksburg, Virginia.

Species	Relative frequency	Rel. density	Relative dominance	Importance value
Q. alba	16	16	57.4	30
P. avium	22	30	7.8	20
Q. rubra	7	9	17.1	11
C. florida	10	8	1.3	7
P. serotina	9	7	1.7	6
S. albidum	9	6	0.7	5
A. rubrum	7	6	1.4	5
R. pseudoacacia	4	3	2.8	3
Q. velutina	1	2	5.0	3
T. cordata	4	3	0.8	3
Q. coccinea	3	2	0.6	2
J. nigra	1	1	2.2	2
F. grandifolia	1	1	0.9	1
A. platanoides	1	1	0.3	1
F. americana	1	1	0.2	1
A. negundo	1	1	0.1	1

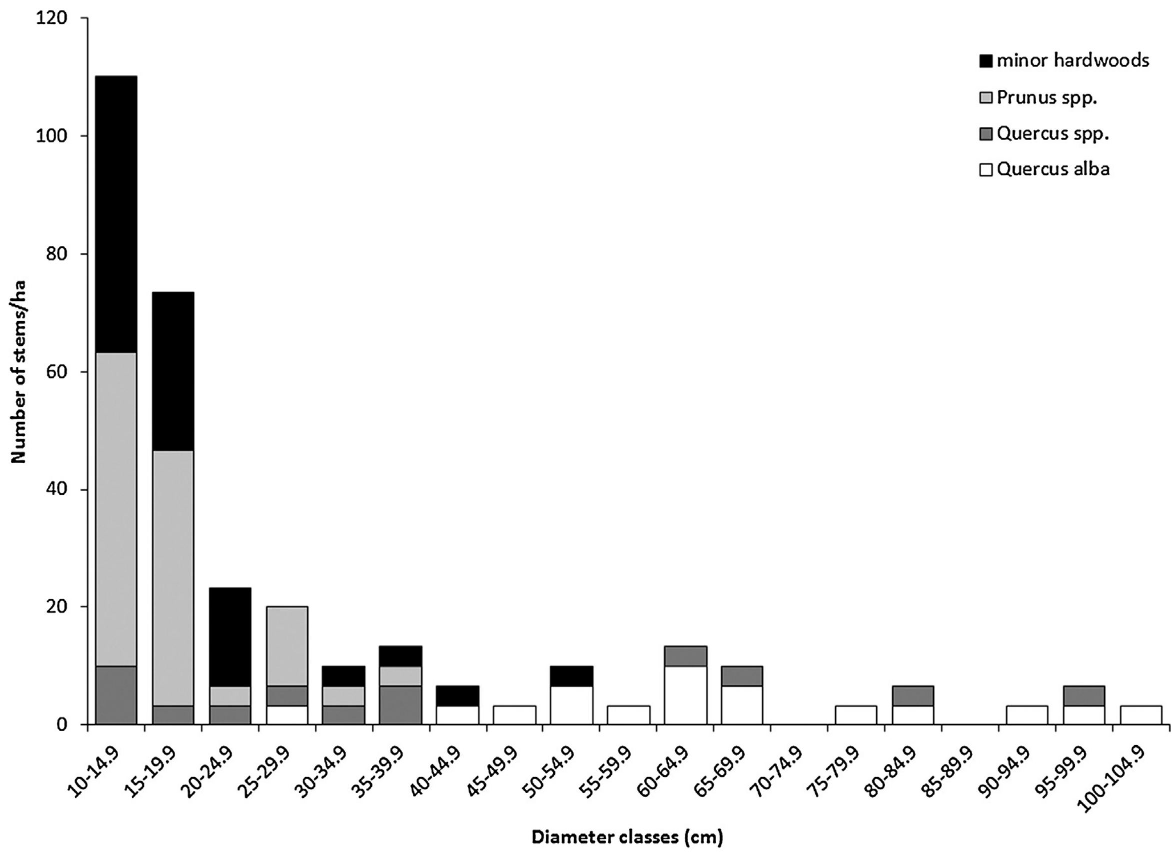
to exhibit their most rapid growth rates late in life (Fig. 2A) and no overstory trees exhibited the negative exponential growth curve associated with open-grown trees. The understory trees in Stadium Woods had strongly individualistic growth patterns (Fig. 2B and C) with tree-level competition clearly being the primary driver in growth rate.

Stand-level disturbances can be identified when multiple trees experience a growth release within the same decade. Stadium Woods appears to have had three and at most four periods when there was some degree of stand-level disturbance: early 1700s, early 1800s, early 1900s and to a lesser degree the mid-1900s (Fig. 3). However, in all of these common disturbances, less than 50% of the trees experienced a release in growth; therefore, the disturbance was either not stand-wide or may have disproportionally influenced trees of a specific size or canopy position.

Radial-growth averaging criteria vs. boundary-line release criteria

The radial-growth averaging criteria identified fewer overstory disturbance events than the boundary-line release criteria (Figs. 3 and 4). From the 33 white oaks sampled in Stadium Woods, the boundary-line release criteria identified a total of 90 release events, while the radial-growth averaging criteria identified a total of 43 release events. Every release identified with the radial-growth averaging criteria was also identified as a release in the boundary-line release criteria; however, the boundary line release criteria identified additional release events that were not detected by the radial-growth averaging criteria.

Release events identified by the boundary-line release criteria lagged an average of 5.8 years behind release events identified with the radial-growth averaging criteria (Table 3). For example, in Fig. 4A, the radial-growth averaging criteria identified a release event in 1935, but the boundary-line release criteria identified this release event as 1940. Similarly in Fig. 4B, the radial-growth



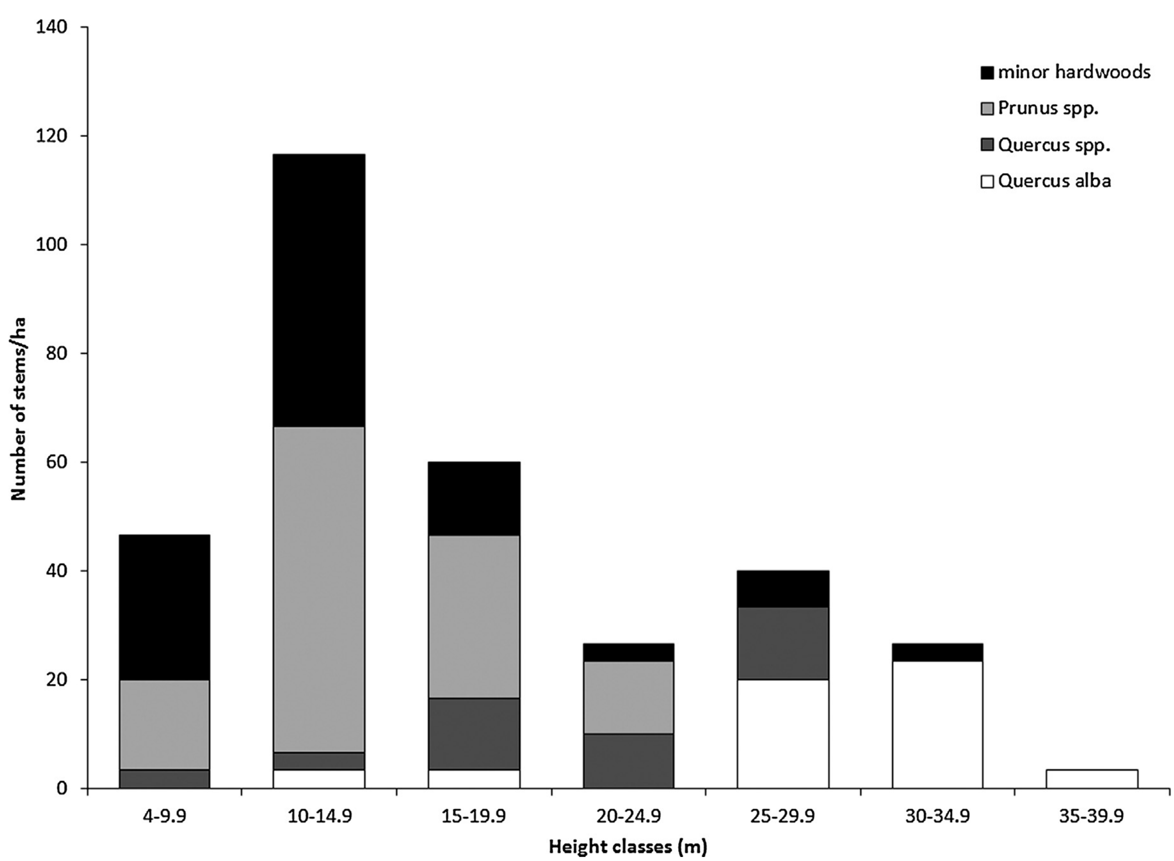


Fig. 1. Stand structural characteristics measured in Stadium Woods, Blacksburg, Virginia in spring 2012. (A) Stand density by diameter class and (B) stand density by height class.

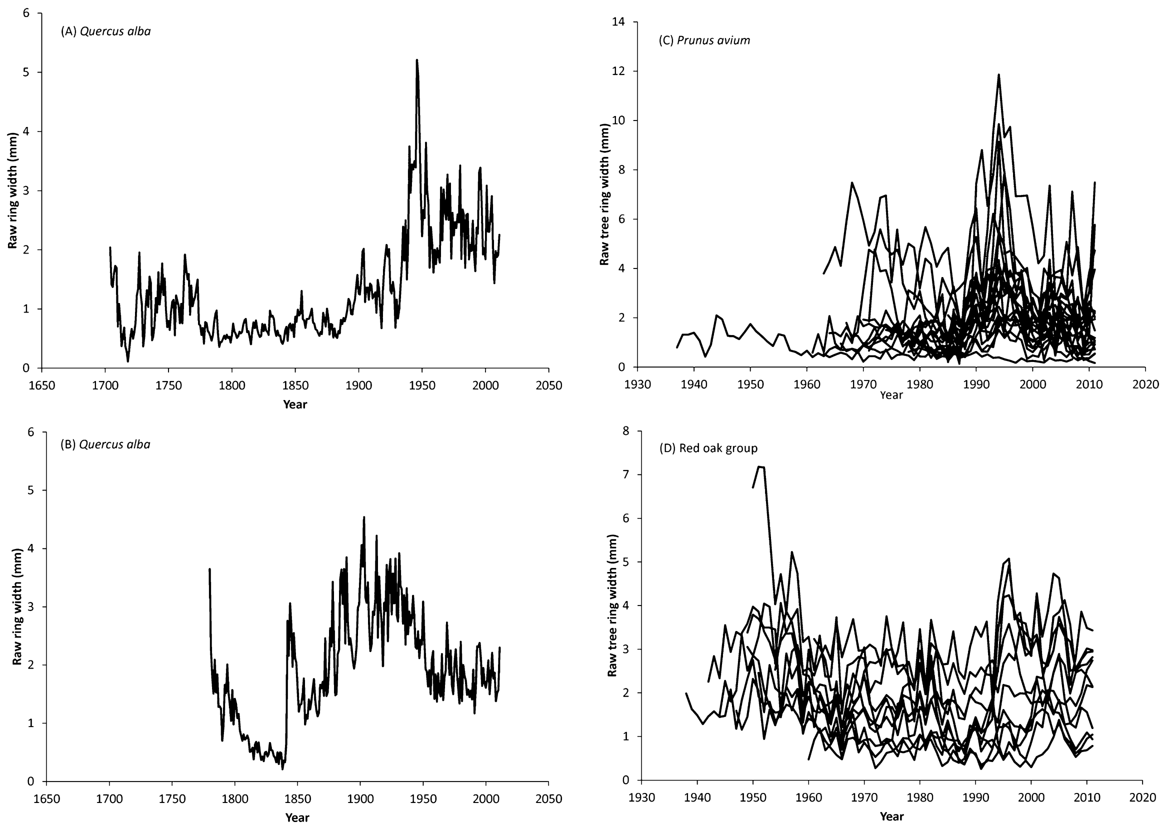


Fig. 2. Tree-ring series from two overstory, white oak trees (A and B) and superimposed tree ring series from (C) 21 sweet cherry and (D) 11 trees from the red oak group from Stadium Woods, Virginia.

Table 3
Lag in the identification of canopy disturbance events between the boundary-line release criteria and the radial-growth averaging criteria.

Lag between disturbance events identified with the boundary line vs. radial-growth average	
Average	5.8 years
Minimum	2 years
Maximum	10 years

averaging criteria identified a release event in 1934, but the boundary-line release criteria identified this release event as 1942. This same pattern is seen in Fig. 4C, where the radial growth averaging criteria identified a release event in 1840, but the boundary-line release criteria identified this release as 1847.

Discussion

Disturbance history of Stadium Woods

The disturbance history for Stadium Woods involves frequent, small-scale canopy disturbances (Fig. 4) with a limited number of disturbances that influenced larger portions of the stand (Fig. 3). Stadium Woods lacks the synchronized period of releases associated with a large-scale timber removal (Abrams and Copenheaver, 1999); however, studies in other forest types have shown that small-scale harvesting (removal of 6–18% of the basal area) does not trigger a release in radial growth that is detectable as a release event using the radial-growth averaging criteria (Perez-de-Lis et al., 2011). Therefore, it is possible that Stadium Woods may have periodically served as a source of firewood for local inhabitants since the first Europeans explored this area in 1654 and a short-lived settlement (Draper's Meadow) was established in 1748 (Johnston, 1906).

The oldest white oaks in Stadium Woods experienced very slow growth when they were young and later in life had periods of more rapid growth (Fig. 2A and B). Two other old-growth white oak stands with similar growth patterns were the 250-year old white oak stand at Great Falls National Park, Virginia (Abrams and Copenheaver, 1999) and the 426-year old white oak stand at Ander's Run, Pennsylvania (Ruffner and Abrams, 2002). All three old-growth white oak stands had a similar pattern of canopy-level white oaks that had spent over a century in understory positions producing very narrow annual growth rings, but once released from a suppressed canopy position the trees were able to double or triple their growth rates. At Great Falls, white oak remained in the understory for 125 years (growing less than <0.5 mm per year), before experiencing an abrupt increase in growth following logging (Abrams and Copenheaver, 1999). At Ander's Run, the oldest white oak spent over 300 years with an extremely slow growth rate (<1 mm yr^{-1}) before logging opened up the canopy and the tree doubled its growth rate (Ruffner and Abrams, 2002).

Radial-growth averaging criteria vs. boundary-line release criteria

The two approaches for identifying canopy release events, radial-growth averaging criteria (Nowacki and Abrams, 1997) and boundary-line release criteria (Black and Abrams, 2003), provided slightly different reconstructions of the canopy disturbance history at Stadium Woods (Figs. 4 and 5) with the boundary-line release criteria identifying a higher frequency of disturbances. Release criteria are developed to mathematically quantify canopy disturbances as reflected in changes of radial growth rates; however,

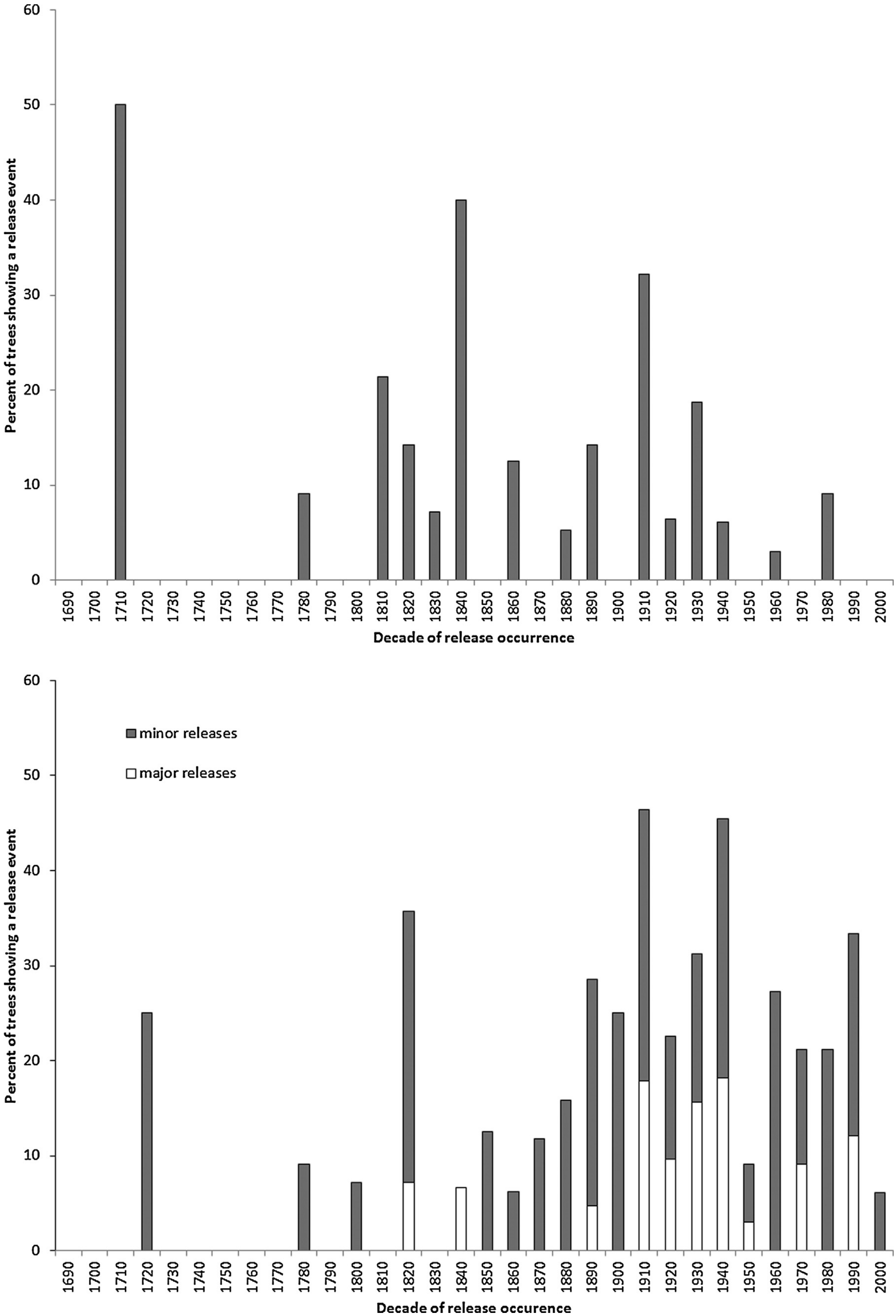


Fig. 3. A comparison of the synchrony of release events found in Stadium Woods, Blacksburg, Virginia as calculated by the (A) radial growth averaging criteria and (B) the boundary line release criteria.

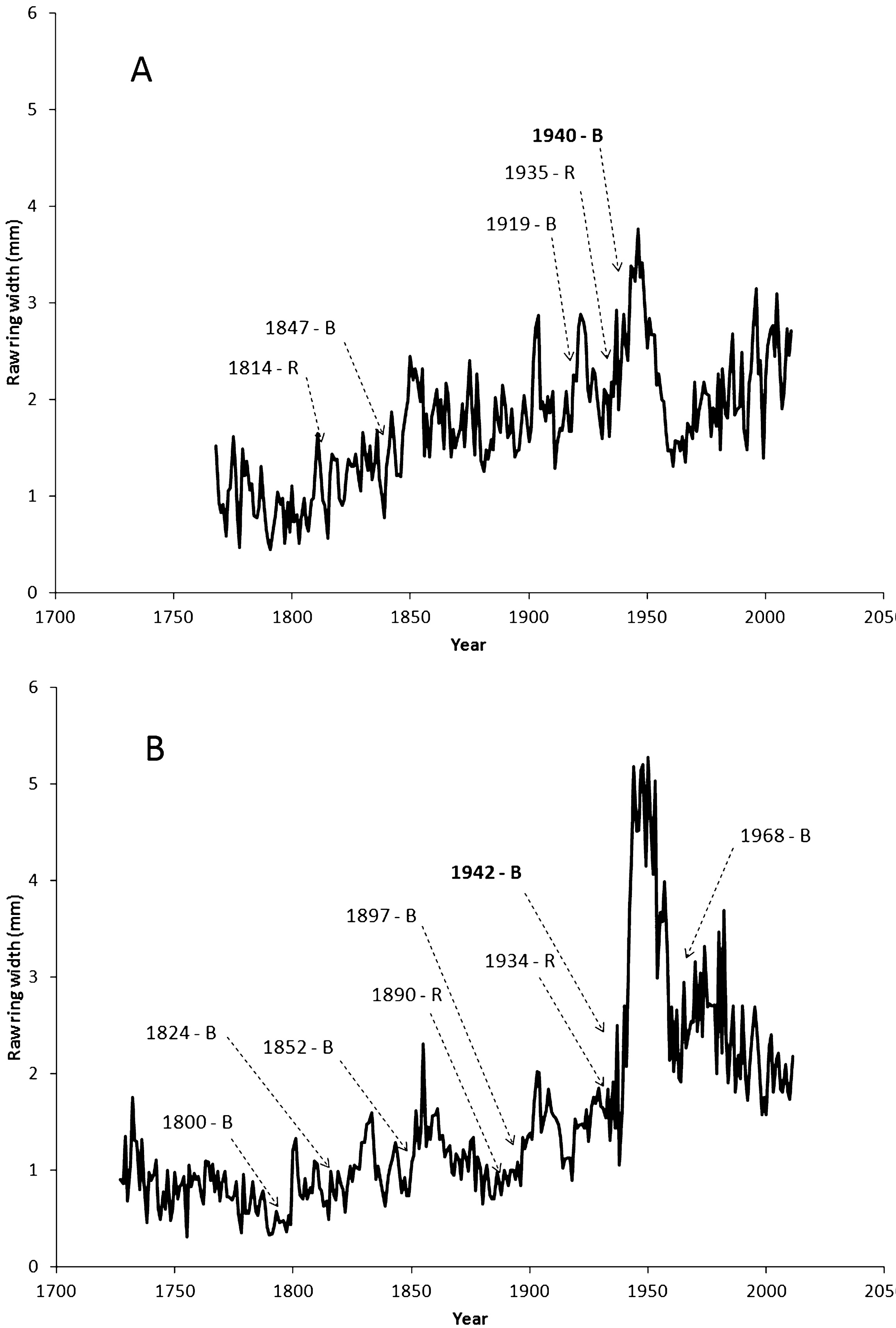


Fig. 4. Example of radial growth from three white oak trees in Stadium Woods in Blacksburg, Virginia. Release events marked with the year and an 'R' indicates releases identified by the radial growth averaging criteria. Release events marked with the year and a 'B' indicates releases identified by the boundary line release criteria. Major releases identified with the boundary line release criteria are shown with bold text.

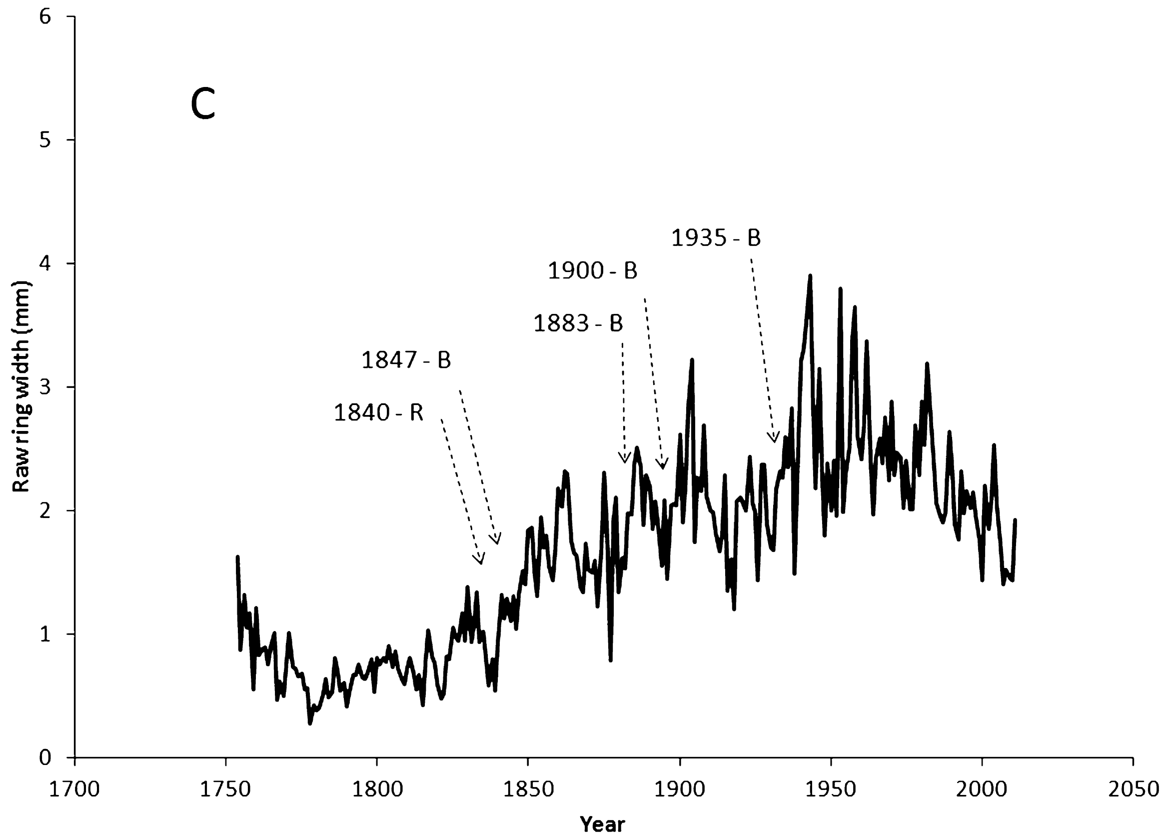


Fig. 4. (*Continued*).

the boundary-line release criteria was more liberal in identifying releases in white oak, e.g., in Fig. 5B the boundary-line approach identified six release events (5 minor and 1 major), whereas the radial-growth averaging technique only identified two release events in the same tree. The difference between these two approaches appears to stem from the difference in the sustainability (10-year minimum) required of the percent growth change by the radial-growth averaging technique. Many trees had time periods where the growth rates exceeded the 25% increase, but this percent growth change was not sustained for 10 years. Nowacki and Abrams (1997) included the 10-year requirement to separate growth increases caused by ideal climatic conditions (usually shorter in duration) from increased light and space resources due to a canopy gap (usually longer in duration). Thus, by not including a duration aspect in the boundary-line release criteria, the approach is broader in terms of what growth releases it captures and it may be detecting increases caused by environmental changes other than canopy disturbances.

The release events identified by the boundary line release criteria lag on average 5.8 years behind those identified by the radial-growth averaging criteria. This difference is because the boundary-line release criteria identifies the release event year as the year with the maximum percent growth change, whereas the radial-growth averaging criteria identifies the event year as the first year that exceeds a 25% increase in the percent radial growth change that is sustained for a minimum of 10 years. Given that the first year to exceed the 25% level is seldom the year with the highest percent growth change, there is always a lag in tagging the release year associated with the boundary-line release criteria. Therefore, the radial-growth averaging criteria identifies the earliest year when a growth response can be detected in tree-ring width data, but the boundary-line release criteria identifies the year when the tree experiences the most rapid increase in growth rate in response to changed environmental conditions.

Conclusions

Stadium Woods appears to have been forested for at least three centuries and the dendroecological analysis of the overstory white oak trees reveals frequent small gap disturbances, but only a limited number of disturbances that influenced larger portions of the stand. The boundary line release criteria identified a twice as many release events for the site compared to the radial-growth averaging criteria. Additionally, the release events identified by the boundary-line release criteria lagged behind the events identified by the radial growth averaging criteria by an average of 5.8 years because the boundary line release criteria identifies the year with a maximum increase in growth and the radial-growth averaging criteria identifying the first year with a detectable increase in growth.

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