

# Identifying growth releases in dendrochronological studies of forest disturbance<sup>1</sup>

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**Abstract:** Information on historical disturbances is vital to our understanding of current forest conditions. Dendrochronological methods provide one means of reconstructing disturbance histories in temperate and boreal forests. In particular, the dates of significant growth releases recorded on surviving trees provide strong inferential evidence of past disturbance events. The most common method of detecting releases (the percent-increase method) expresses the postevent growth increase as a percentage of the preevent rate. Despite its widespread use, the method is known to be overly sensitive at low rates of prior growth and overly stringent at high rates. We present an alternative method that directly follows the percent-increase method, but instead of dividing the postevent growth rate by the preevent rate, we simply subtract the two. If the difference exceeds a predetermined species-specific threshold, the event is considered a release. This absolute-increase method has convenient properties that remedy the shortcomings of the percent-increase method. We tested the validity of the absolute-increase thresholds by binary logistic regressions, and we compared the absolute- and percent-increase methods by various methods. We conclude that for the species evaluated in this study, the absolute-increase method represents an improvement over the standard percent-increase method.

**Résumé :** Il est vital de posséder des informations au sujet des perturbations passées pour comprendre l'état actuel de la forêt. La dendrochronologie fournit une façon de reconstituer les perturbations passées dans les forêts boréales et tempérées. En particulier, la date des dégagements significatifs de croissance qui sont enregistrés dans les arbres qui ont survécu fournit une preuve par inférence solide des perturbations passées. La méthode la plus commune de détection des dégagements (la méthode de l'augmentation relative en pourcentage) exprime l'augmentation de croissance postérieure à une perturbation comme un pourcentage du taux de croissance antérieur à cette perturbation. Bien qu'elle soit largement utilisée, on sait que cette méthode est trop sensible lorsque le taux de croissance antérieur à la perturbation est faible et trop stricte lorsqu'il est élevé. Les auteurs présentent une méthode alternative qui découle directement de la méthode de l'augmentation relative en pourcentage mais au lieu de diviser le taux de croissance postérieur à la perturbation par le taux de croissance antérieur à celle-ci, ils soustraient simplement l'un de l'autre. Si la différence dépasse un seuil prédéterminé propre à chaque espèce, il s'agit d'un dégagement. Cette méthode de l'augmentation absolue a des propriétés intéressantes qui comblent les lacunes de la méthode de l'augmentation relative en pourcentage. Les auteurs ont testé la validité des seuils de la méthode de l'augmentation absolue à l'aide de régressions logistiques binaires et ils ont comparé les méthodes de l'augmentation absolue et relative en utilisant divers moyens. Les auteurs concluent que pour l'espèce évaluée dans cette étude, la méthode de l'augmentation absolue constitue une amélioration par rapport à la méthode standard de l'augmentation relative en pourcentage.

[Traduit par la Rédaction]

## Introduction

Natural disturbances strongly influence species composition, structure, and function of forests. In temperate and boreal forests, dendrochronology (tree-ring analysis) provides a means of reconstructing historical disturbances. Tree ages, fire or impact scars, and significant increases in radial growth provide the primary information needed for such reconstructions. Radial growth increases are often referred to as re-

leases, because following disturbance, subcanopy trees are released from suppression of former canopy trees. By tallying dated growth releases from numerous tree-ring series, one can reconstruct the history of canopy disturbance in a given forest stand. This approach emphasizes shade-tolerant trees species, as shade-intolerant species would not typically endure the period of suppression prerequisite for release.

In practice, detecting growth releases presents numerous obstacles. First, radial growth varies with temperature and precipitation, so any attempt to isolate disturbance-related responses must filter out effects of weather. Second, the pattern of response varies with tree species, prior growth rate, diameter, and perhaps age. Third, a tree's response to disturbance varies according to the type, magnitude, and duration of the disturbance. The great variety of release-detection methods applied to this problem clearly reflects the difficulty presented by these factors.

Much of the early assessment of radial-growth releases was no doubt done visually, that is, without quantitative criteria. Though this method has received little use in recent

Received 16 November 2004. Accepted 21 April 2005.  
Published on the NRC Research Press Web site at  
<http://cjfr.nrc.ca> on 20 August 2005.

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decades (but see Oliver and Stevens 1977; Winter et al. 2002), it remains applicable in situations where the worker is familiar with the autecology, sensitivity, and range of growth anomalies expected for a given species. Henry and Swan (1974) appear to be the first to use the percent-increase method of release detection, which is currently the most widely used method. In its current form, the postdisturbance growth increase is expressed as a percentage of predisturbance growth; if the percent exceeds a predetermined threshold, the response is considered a valid release. More recently, Black and Abrams (2003) presented a boundary-layer method, which scales the percent-increase threshold according to a tree's growth rate prior to disturbance. If a percent increase exceeds a predefined percentage of the observed maxima for a given rate of prior growth, the response is considered a valid release. Additional methods exist for detecting releases from standardized mean chronologies (i.e., not intended for individual tree-ring series). Kitzberger et al. (1995) present a release enhancement filter to detect stand-wide response to tectonic activity, and Downing and McLaughlin (1990) propose intervention detection, a time series technique, to evaluate stand- or region-wide growth responses. All release-detection methods share the need to establish thresholds beyond which a given event is deemed a valid release.

Despite its widespread use and intuitive appeal, the percent-increase method is known to have significant shortcomings. We present here an alternative method, that of the absolute increase, which has convenient mathematical properties that remedy these shortcomings. We tested the validity of the method by applying logistic regression to a data set including growth responses of a subset of small trees growing either in recently formed gaps or under intact canopies. We then compared the absolute- and percent-increase methods by applying them to numerous individual tree-ring series and tallying the differences. We conclude that for the species tested, the absolute-increase method represents a significant improvement over the standard percent-increase method.

### The standard percent-increase method

When first published, the percent-increase method appeared as a ratio (Henry and Swan 1974); however, it is now commonly expressed as a percentage, formalized as follows by Nowacki and Abrams (1997):

$$[1] \quad \text{Percent increase} = \frac{\text{Mean}_{t_2} - \text{Mean}_{t_1}}{\text{Mean}_{t_1}} \times 100$$

where  $\text{Mean}_{t_1}$  is the mean radial growth during the time window prior to the event, and  $\text{Mean}_{t_2}$  is the mean radial growth following the event. By using a temporal window of reasonable length, this method filters out the response to short-term changes in temperature and precipitation (Lorimer 1980; Lorimer and Frelich 1989; Nowacki and Abrams 1997). In practice, the percent increase is often calculated for all possible pairs of consecutive pre- and post-windows, shifting 1 year at a time, and the results of all pairwise comparisons are scanned for values exceeding a predetermined threshold. A review of the literature reveals a wide variety of threshold values, ranging from 25% (Nowacki and Abrams 1997; Winter et al. 2002) to 250% (Stewart and Rose 1990; Stewart et al. 1991; Veblen et al. 1991). Likewise, the literature reports a

variety of window lengths, ranging from 4–5 years (Henry and Swan 1974; Payette et al. 1990; Schweingruber et al. 1990; Merrens and Peart 1992) to 15 years (Lorimer 1980; Lorimer and Frelich 1989; Frelich and Lorimer 1991). Perhaps the most common criteria in use are the 10-year window (for both pre- and post-event) and a 100% threshold, which is generally meant to signify the loss of the overhead canopy.

The percent-increase method is known to be overly sensitive (accepting false positive releases) at low growth rates and overly stringent at higher rates (producing false negative releases). As an example of its oversensitivity, for a mean prior growth rate of 0.15 mm/year, not uncommon for shade-tolerant species, an increase to 0.3 mm would result in a 100% increase. This “postrelease” growth rate, however, is too low to be considered a valid release; it simply represents minor fluctuations around a low mean rate. The zero values added to account for missing rings when cross-dating further exacerbate this problem. As an example of its overstringency, for a mean growth rate of 1.5 mm/year, an increase to 3.0 mm would be required to meet the 100% increase threshold. Although we feel that a valid release could occur during a growth rate of 1.5 mm/year, a sustained increase to 3.0 mm would be quite uncommon for many relatively slow-growing, shade-tolerant species.

Recognizing this limitation, several researchers have simply raised or lowered the release criteria on various portions of a given tree-ring series to accommodate changes in prior growth (Lorimer 1980; Glitzenstein et al. 1986; Dahir and Lorimer 1996; Storaunet et al. 2000; Groven et al. 2002; Black and Abrams 2003). The magnitude of release also varies by species, given the differences in mean growth rate and sensitivity (sensu Fritts 1978). Recognizing that species respond differently, Canham (1985, 1990) established separate release criteria for sugar maple (*Acer saccharum* Marsh.) and American beech (*Fagus grandifolia* Ehrh.). Black and Abrams (2003) developed different criteria for each of three species under study. Table 1 lists the sensitivities and mean ring widths for the six species evaluated in the present study.

### An alternative method: the absolute increase

The initial calculations needed for the absolute-increase method are identical to those of the percent-increase method. However, instead of dividing the postevent growth rate by the preevent rate (or establishing a percent increase), we simply subtract the two (i.e.,  $\text{Mean}_{t_2} - \text{Mean}_{t_1}$  from eq. 1 above). If the difference exceeds a predetermined species-specific threshold, the event is considered a release. The selected thresholds are meant to detect overhead canopy disturbances, likely equivalent to the “major” releases commonly referred to in the literature. This method is not to be confused with that of Canham (1985, 1990), in which releases are deemed as such if the growth rate simply exceeds a predetermined value, regardless of the magnitude of the change.

Because the absolute-increase threshold is a constant (e.g., 0.58 mm for red spruce (*Picea rubens* Sarg.), the criteria for release are effectively scaled to account for prior growth, making the criteria more stringent at low rates of prior growth and more lenient at relatively high rates. This property can

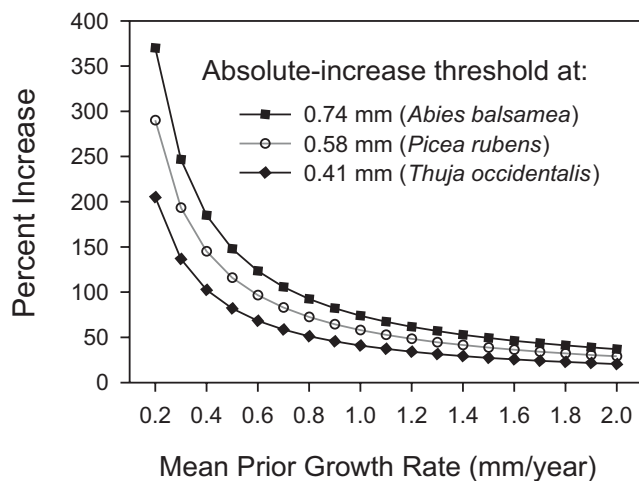
**Table 1.** Attributes used for release detection for the six species under study.

Species	Mean sensitivity	Mean ring width (mm)	Absolute-increase threshold (mm)	1.25 × SD	90% quantile	<i>n</i> *
<i>Picea rubens</i>	0.284	0.94	0.58	0.59	0.56	1189
<i>Abies balsamea</i>	0.246	1.35	0.74	0.78	0.79	523
<i>Thuja occidentalis</i>	0.205	0.90	0.41	0.36	0.36	319
<i>Acer saccharum</i>	0.300	0.98	0.52	0.51	0.52	288
<i>Fagus grandifolia</i>	0.277	0.97	0.56	0.56	0.63	338
<i>Betula alleghaniensis</i>	0.306	1.17	0.67	0.69	0.69	172

Note: SD, standard deviation.

\*Number of cores evaluated to determine the absolute-increase threshold.

**Fig. 1.** Absolute-increase thresholds for selected species, after conversion to percentages. The thresholds become more lenient with increasing rates of prior growth, thereby correcting the principal shortcoming of the standard percent-increase method.



best be appreciated in Fig. 1, where absolute increases have been converted to the corresponding percentages for comparison with the percent-increase method. At a mean prior growth rate of 0.25 mm/year, an increase of 0.58 mm results in a 232% increase; for a prior growth of 0.50 mm/year the increase is 116%; and for a prior growth of 0.75 mm/year the increase is 77%. Thus, the absolute-increase threshold provides the scaling factor that adjusts the percent-increase threshold across a continuous range of prior growth rates.

We point out that this method, or at least the underlying concept, is not necessarily new. Several authors have evaluated differences (by subtraction) in growth rates before and after disturbance. Merrens and Peart (1992) evaluated pre- and post-disturbance “growth differences” (although on annual growth averaged for groups of cores) to evaluate the response to a particular hurricane. Kitzberger et al. (1995) used the differences between mean growth rates (after multiplication by an enhancement factor) in their “release enhancement filter”. Their filter, however, was applied to standardized mean chronologies, not individual tree-ring series.

Importantly, the absolute-increase method shares with its alternatives the necessity of establishing a threshold above

which a given event is considered a valid release. The optimal threshold is one that minimizes both false-positive and false-negative releases. We present an empirical approach for determining the appropriate species-specific absolute-increase threshold. Its use, however, requires knowledge of growth responses expected for a given species and necessarily includes subjectivity. For this reason, we tested the validity of the thresholds by applying logistic regression to growth-response data from small trees occurring in recently formed gaps.

## Materials and methods

### Field and laboratory procedures

The dendrochronological material used in this study resulted from a larger, related project addressing patterns of natural disturbance in old-growth forests of the Big Reed Forest Reserve of northern Maine, USA (see Fraver 2004). The 2000-ha reserve (centered at 46°20'N and 69°05'W) shows little or no evidence of timber harvesting (Cogbill 1985<sup>4</sup>; Widoff 1985<sup>5</sup>). Mean annual precipitation is 1058 mm, and mean annual temperature is 5.3 °C (Baron et al. 1980; Millinocket station). That project included 37 plots (30 m by 50 m) located in a stratified (by forest community type) random manner in the reserve's five community types: mixed-wood forest (*N* = 21 plots), northern white-cedar (*Thuja occidentalis* L.) seepage forest (*N* = 5), red spruce forest (*N* = 4), hardwood forest (*N* = 4), and northern white-cedar swamp (*N* = 3). Community nomenclature generally follows that of the Maine Natural Areas Program (1991). Plot basal areas (overall mean = 31.2 m<sup>2</sup>/ha) and densities (mean = 521 trees/ha) are typical for old-growth forests of the region (Lutz 1930; Leopold et al. 1988; Ziegler 2002). Plot elevations ranged from 330 to 520 m above sea level. On each plot, all trees were uniquely numbered and tagged, and diameter and species were recorded for each. We considered trees as living stems ≥10 cm diameter at breast height (1.37 m). We also noted whether trees were located in relatively recent canopy gaps (small trees only), on gap borders, or formed part of intact canopies. We extracted one increment core at breast height from all trees. Cores were mounted and sanded to a fine polish using standard methods. Ring widths were measured on a Velmex sliding-stage stereomicroscope to the nearest 0.01 mm. Cross-dating was conducted using meth-

<sup>4</sup>C.V. Cogbill. 1985. Evaluation of forest history and old-growth nature of the Big Reed Pond Reserve, T8 R10 and T8 R11 W.E.L.S., Me. Report prepared for the Maine Nature Conservancy.

<sup>5</sup>L. Widoff. 1985. The forest communities of Big Reed Pond Reserve, T8 R10, T8 R11, Maine: results of field work, summer 1985. Unpublished report.

ods of Yamaguchi (1991), with verification by COFECHA (Holmes 1983).

For the present study, we returned to these same plots to determine the date on which gaps were formed, as this information was needed for analyzing growth responses by logistic regression (see below). We dated 22 gaps with confidence, following the methods of Dynesius and Jonsson (1991), Hytteborn et al. (1991), and Runkle (1992). Many of these gaps resulted from the August 1983 thunderstorm that affected much of the reserve and surrounding areas. Gaps included single or multiple tree falls. We focus the present study on the reserve's six dominant tree species (listed in decreasing order of abundance): red spruce, balsam fir (*Abies balsamea* (L.) Mill.), American beech, northern white-cedar, sugar maple, and yellow birch (*Betula alleghaniensis* Britt.). These six species represent 93% of all trees sampled in the reserve. Five of these species are rated as shade tolerant (Burns and Honkala 1990); the sixth, yellow birch, is rated as tolerant (Graves 1899) to intermediate (Burns and Honkala 1990).

Given the random plot locations, the exhaustive sampling of trees on confined plots, the large number of cores (ca. 3000), and the variety of conditions in which the trees were growing, the growth rates and patterns observed here likely represent the full ranges possible for these species under natural forest conditions.

### Selecting the absolute-increase threshold: an empirical approach

The method of establishing an absolute-increase threshold begins by setting the threshold to a reasonable value (e.g., 0.5 mm for species in this study) then refining it by successive applications to actual tree-ring series. To this end, we wrote several in-house programs that automatically produce time-series graphs for each increment core showing ring widths, percent-increase functions, absolute-increase functions, and the tentatively chosen absolute-increase threshold. All programming was done in SAS/GRAPH version 8.1 (SAS Institute Inc. 1999). We continually adjusted the absolute-increase threshold, reproduced the graphs, and evaluated the outcomes based on our knowledge of each species' sensitivity, mean growth rate, and range of growth responses. After many iterations applied to hundreds of tree-ring series for each species, threshold values emerged that best separated valid releases from lesser fluctuations in growth. In all cases, threshold selections were tempered by comparisons with the percent-increase criteria, once modified to account for prior growth rates (see below).

### Testing the absolute-increase thresholds: logistic regressions

To further test the validity of the absolute-increase criteria, we applied binary logistic regression to a subset of the above data, limited to the growth responses of small trees found in recently formed dated gaps (i.e., exposed trees) and similarly sized trees found under intact canopies. Logistic regression allowed not only a test for differences in growth between exposed trees and intact-canopy trees, but also the selection of optimal absolute-increase values that minimized both false-positive and false-negative releases. Constructing the data set required that for each exposed tree, we select a

control tree of the same species from the intact-canopy portion of the plot. Controls were selected so as to have a diameter most closely matching that of the exposed trees. For both exposed and control trees, the mean growth rate 10 years before and 10 years after gap formation was determined, and the absolute increase was calculated as described above. We assume any differences in growth response between the two groups of trees to be the result of gap formation. Although 70 exposed trees representing nine species were located during fieldwork, limited sample sizes permitted statistical analyses of only three species: American beech ( $N = 26$ ), red spruce ( $N = 21$ ), and balsam fir ( $N = 17$ ). Logistic regressions were conducted in SAS version 8.1 (SAS Institute Inc. 1999).

### Comparing the absolute- and percent-increase methods

We compared the absolute- and percent-increase methods by applying each to a large number of cores and determining under what conditions the methods agree and disagree. For both methods, we used 10-year windows, and for the standard percent-increase method we used a 100% threshold, largely by convention. We also include in the comparisons a modified version of the percent-increase method, in which we have made release criteria more stringent for low rates of prior growth and more lenient at relatively high rates. First, for mean 10-year prior growth rates of less than 1.0 mm/year, we set a percent-increase threshold at 100%, with the added stipulation that the mean postrelease growth rate must exceed 0.75 mm/year. The 1.0 mm/year requirement used by Dahir and Lorimer (1996) seemed overly stringent for species in this study. Second, for mean prior growth rates equal to or greater than 1.0 mm/year, the threshold was relaxed to 50% (as per Lorimer 1980; Glitzenstein et al. 1986; Storaunet et al. 2000; Groven et al. 2002).

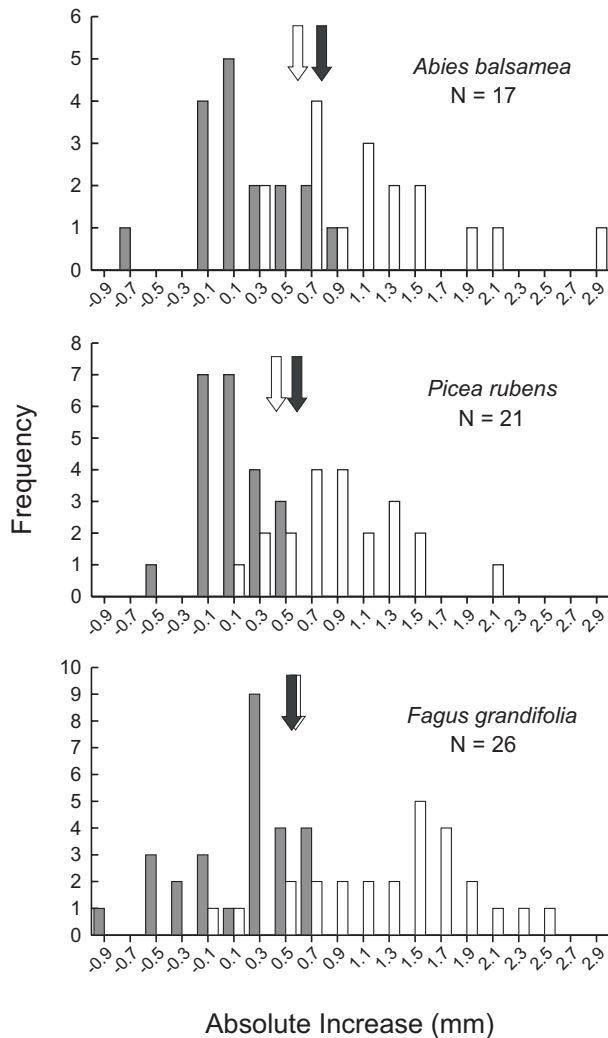
As such, we have three release-detection methods for comparison: the standard percent increase, the modified percent increase, and the absolute increase. Increment cores (i.e., tree-ring series) from five of the 37 plots in our concurrent study provide data for these comparisons. The plots selected represent those with the longest chronologies from each of the five community types, thereby ensuring adequate temporal depth and variety of species. Each of the 550 tree-ring series from these plots was evaluated for growth release using the three methods.

## Results

### Empirical approach

The absolute-increase thresholds determined by the empirical approach for the six species are presented in Table 1. Thresholds range from 0.41 mm (northern white-cedar) to 0.74 mm (balsam fir), with values generally increasing with increasing mean growth rate and mean sensitivity. The approach works best when a large number of cores are available and when the researcher is familiar with the growth responses and sensitivities of the species under investigation. During exploratory analyses and data summaries, we observed that the absolute-increase threshold for each species roughly corresponded to 1.25 times the standard deviation of absolute increases, where the standard deviation is calculated for the absolute increases determined for all possible years for all

**Fig. 2.** Distribution of absolute increases, showing the greater response of trees in recent gaps (open bars) when compared with trees under intact canopies (shaded bars). Arrows show the absolute-increase thresholds that best separate the two groups of trees. Solid arrows indicate thresholds determined empirically; open arrows indicate thresholds suggested by logistic regression;  $N$  is the number of exposed trees in recent gaps.



canopy trees. Similarly, it roughly corresponds to the 90% quantile for absolute increases thus calculated. We suggest that for uncommon species or for species otherwise unfamiliar to the researcher, either of these approximations may provide reasonable threshold values. These approximations are listed in Table 1.

### Logistic regressions

The distribution of absolute increases from exposed trees and those under intact canopies is shown in Fig. 2. As expected, the absolute increases from exposed trees were greater than those from trees under intact canopies (American beech logistic regression likelihood ratio  $\chi^2 = 41.6$ ,  $P < 0.001$ ; red spruce  $\chi^2 = 41.9$ ,  $P < 0.001$ ; and balsam fir  $\chi^2 = 26.5$ ,  $P < 0.001$ ). For each species, the optimal absolute increase that best separated the two distributions was taken as the value associated with the graphed intersection of specificity (an

expression of the likelihood of false negatives) and sensitivity (an expression of the likelihood of false positives; Hosmer and Lemeshow 2000). For American beech, the absolute-increase threshold resulting from this optimization (0.58 mm) and that determined by our empirical approach (0.56 mm) were nearly identical. However, for the other species, the two estimates differed by larger amounts (0.44 vs. 0.58 mm for red spruce, and 0.57 vs. 0.74 mm for balsam fir; see Fig. 2). Despite these differences, the percentage of cores correctly assigned to gap or intact canopies (estimated by the same logistic regression) using these thresholds differed very little. For red spruce, the estimated percentages were 87% correct (optimal threshold determined by logistic regression) and 85% correct (threshold determined by the empirical method); for balsam fir they were 89% and 86% correct.

### Method comparisons

In Fig. 3 we present two tree-ring series that illustrate the concepts of false-positive and false-negative releases. In each panel we present the series twice, once for the standard percent-increase method and once for the absolute-increase method. In both panels the solid line represents ring width, the dotted line, a particular threshold, and the broken line, the percent- or absolute-increase function. In the strict use of these methods, releases are considered valid when these functions exceed their respective thresholds.

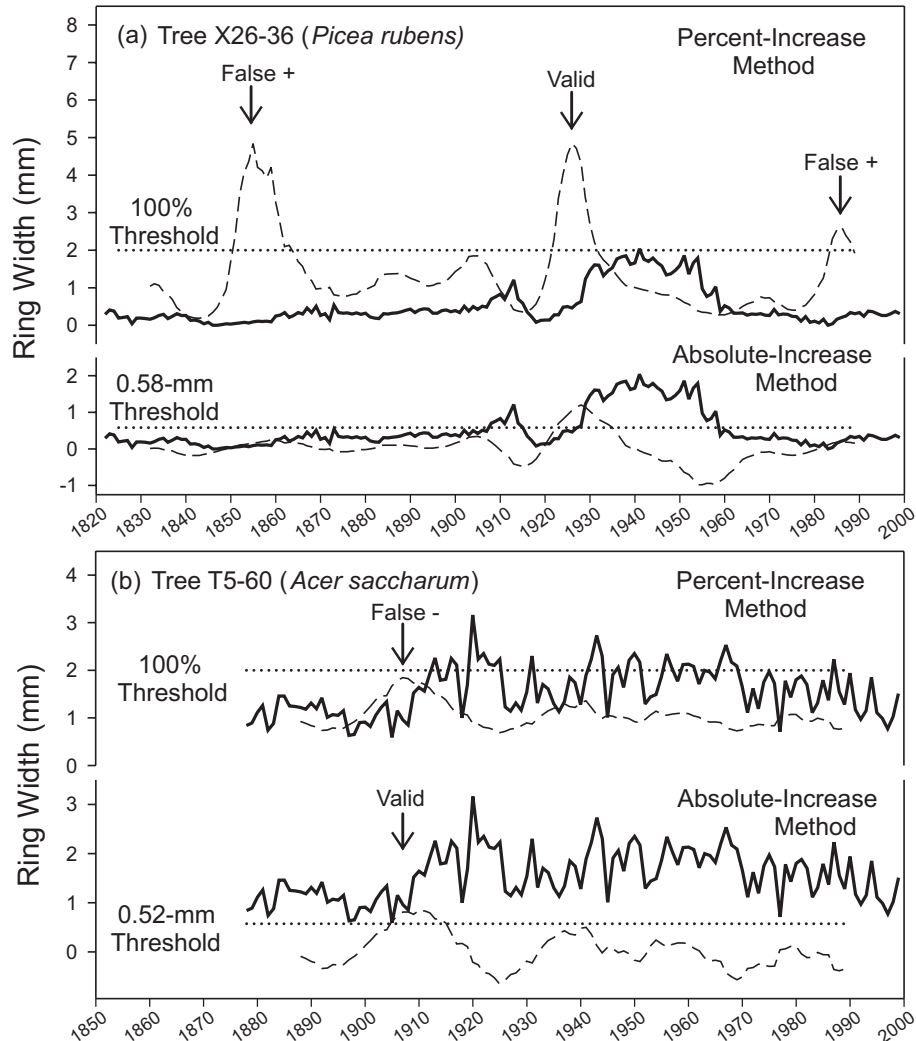
The standard percent-increase method's oversensitivity at low rates of prior growth can readily be seen in Fig. 3a. While both the percent- and absolute-increase methods correctly identify the release ca. 1925, the percent-increase method detects questionable releases ca. 1855 and 1985. These peaks result from minor fluctuations around low growth rates, which can easily result in a doubling (100% increase) in growth. We consider these two questionable releases to be false positives, given that the "postrelease" growth rates remain quite low. The growth increase beginning ca. 1905 is of insufficient duration to be considered a release by either of these methods.

The standard percent-increase method's overstringency can be seen in Fig. 3b, where what appears to be a valid release beginning ca. 1908 is not detected (i.e., a false negative) because the prior growth rate is too high to attain the doubling necessary using this method. The absolute-increase method identifies this event as a valid release.

The five plots selected for methods comparison yielded 434 purported growth releases that met the release criteria for at least one of the three methods evaluated. Figure 4 shows the tally of disagreements between methods, where the behaviors of the percent- and absolute-increase thresholds are shown as functions of mean prior growth. As in Fig. 1, we have converted the absolute-increase threshold to a percent for the purpose of illustration, and we have shown the threshold for red spruce simply for the purpose of delimiting regions of the graph, noting that each species was tested against its own species-specific threshold. The shaded regions between the two thresholds represent areas of disagreement between the methods.

At low growth rates, 139 events exceeded the standard percent-increase threshold but not the absolute-increase threshold, and at higher rates, 67 events exceeded the absolute-increase threshold but not the standard method's (Fig. 4c). Given the percent-increase method's shortcomings with re-

**Fig. 3.** Behavior of the standard percent-increase and absolute-increase methods when applied to two selected tree-ring series, each shown twice for comparison. Solid lines represents ring width, dotted lines a particular release-detection threshold, and broken lines the percent- or absolute-increase function. Releases are considered valid when these functions exceed their respective thresholds. Figure 3a shows that while both methods correctly identify the release ca. 1925 (“valid” arrow), the percent-increase method detects false-positive releases ca. 1855 and 1985 (“false +” arrows). Figure 3b shows the percent-increase method’s failure to detect what appears to be a valid release beginning ca. 1908 (“false -” arrow), because the prior growth rate is too high to attain the necessary doubling (100% increase).



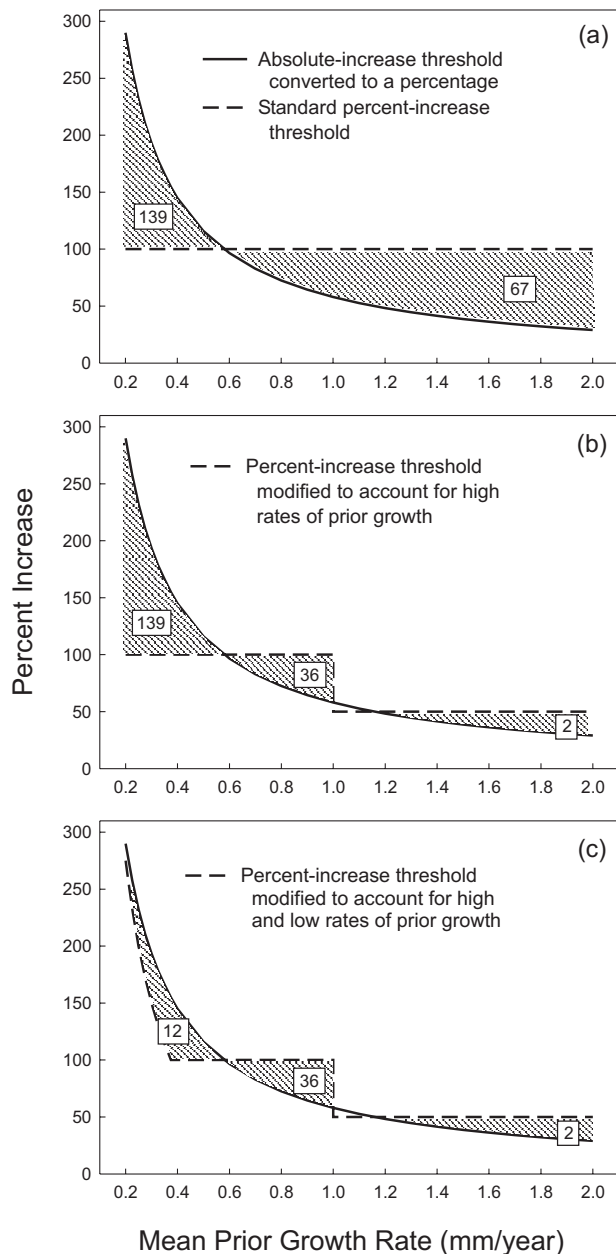
spect to sensitivity, we feel that many of these disagreements represent false-positive and false-negative releases, respectively. Figure 4b shows the effect of lowering the percent-increase threshold for higher growth rates (as per Lorimer 1980; Glitzenstein et al. 1986; Storaunet et al. 2000; Groven et al. 2002). This modification dramatically reduced the number of disagreements in this region. We assume this to represent a reduction of false-negative releases, the intended purpose of the modification. Figure 4c shows the effect of further modifying the threshold (as per Dahir and Lorimer 1996) to make it more stringent for low growth rates. Dahir and Lorimer (1996) required that releases exceed the 100% threshold and achieve a predetermined mean postrelease growth rate (0.75 mm/year in this study). The effect of this second criterion is the raising of the percent-increase threshold at low growth rates. For example, at a prior growth rate of 0.25 mm/year, an increase to the required 0.75 mm/year represents a 200% increase. This modi-

fication dramatically reduced the number of disagreements in the region of slow growth. We assume this to represent a reduction of false-positive releases, the intended purpose of the modification.

## Discussion

To some, the empirical approach of selecting the absolute-increase threshold may appear overly subjective. We point out that any release-detection criteria currently in use — including the threshold percentages used in the percent-increase method — must be selected either subjectively or arbitrarily. Our subjectively selected thresholds were based on our experience with these species; for this reason they may well be superior to an arbitrarily chosen and non-species-specific threshold such as the 100% increase often used in the percent-increase method. We feel that any release-detection criteria should be evaluated by application to actual radial-growth data; if the

**Fig. 4.** Graphical representation of the disagreements between release-detection methods. The absolute-increase method is compared with (a) the standard percent-increase method, (b) the standard method modified for high rates of prior growth, and (c) the standard method modified for both high and low rates of prior growth. The shaded regions between the two thresholds represent areas of disagreement; values within the shaded regions provide the number of disagreements in each region. Tallies are based on 434 purported growth releases that met the criteria for at least one of the methods. The absolute-increase threshold for red spruce is shown simply for the purpose of delimiting regions of the graph.



criteria seem overly sensitive or overly stringent, they can be modified as needed. This has been referred to as adjusting the “sensitivity” of the criteria (Lorimer and Frelich 1989; Frelich and Lorimer 1991).

Logistic regressions produced optimal absolute-increase thresholds somewhat different from those determined by the

empirical approach. We attribute the differences to the small sample sizes used in the regressions. However, as stated above, the percentage of cores correctly assigned to gap or intact canopies differed very little between the two threshold values. Thus, we feel that logistic regression reasonably corroborates the thresholds determined by the empirical approach and, in general, lends credence to the approach.

Perhaps the most informative comparison of the methods is simply a tally of their disagreements, with and without the modifications proposed by previous authors, shown as shaded regions in Fig. 4. Various modifications to the original standard percent-increase method have reduced the number of false-positive and false-negative releases. We are aware that the release criteria and modifications used by these authors were intended to serve only as guides. Presenting them as we have in Fig. 4 suggests a rigidity likely unintended by these authors. Nevertheless, the figure clearly shows that experienced workers have recognized the need to modify the threshold to account for the over- and under-sensitivity of the standard percent-increase method. The sequence of modifications (Figs. 4a–4c) suggests a convergence on the absolute-increase method. These modifications, however, produce coarse step functions that are awkward to apply and difficult to justify theoretically. The absolute-increase method performs equally well yet requires no such modification. It automatically and continuously adjusts the threshold’s sensitivity across varying rates of prior growth.

The absolute-increase method has one drawback that warrants noting here. When compared with the percent-increase method, it provides a less reliable estimate of year the release began. Fajvan and Seymour (1993) found that the point where the percent-increase function reaches a local maximum provides a reliable estimate of release initiation. Though in many cases, the percent- and absolute-increase maxima coincide, this is not always so. When the maxima differ, the absolute-increase maximum is always displaced forward in time. For example, Fig. 3b shows that the percent-increase function reaches its local maximum in 1907 (though not exceeding the threshold); the absolute-increase function reaches its local maximum in 1910.

In conclusion, we recommend against the unqualified use of the standard percent-increase method, owing to its propensity for false-positive and false-negative releases. Perhaps its performance with respect to false positives could be improved by raising the percent threshold, but analogous to type I and II error rates in statistics, doing so would necessarily increase the number of false negatives. The method may, however, be appropriate for uncommon species, where little or nothing is known about autecologies and ranges of growth patterns. The trade-off for its use would likely be an increase in error rate when compared with the absolute-increase (or modified percent-increase) method. Conversely, using the absolute-increase method may reduce error, but requires a better knowledge of autecologies of the species under study. In practice, we find it desirable to use the absolute-increase and the modified percent-increase methods simultaneously by viewing them on a single graph for each tree-ring series. For release detection, we rely more on the absolute-increase method; for dating the release we rely more on the percent-increase method. This brings us to a crucial point that has been under-emphasized given our focus on arithme-

tic criteria: regardless of method or thresholds selected, one should view each purported release to make a decision as to its validity. The simultaneous use of the two methods reduces the subjectivity involved. In our view, the methods described here serve as valid guides, yet should not be followed blindly. No arithmetic method is likely to obviate the need to visually inspect each tree-ring series.

## Acknowledgements

This work benefited from discussions with Charles Cogbill, Craig Lorimer, Erika Rowland, and Robert Seymour. We thank Thomas Kitzberger, Ken Olaf Storaunet, and two anonymous reviewers for providing valuable comments on previous drafts of this manuscript, and we thank Brittany Armstrong-Gordon, Rick Dyer, and Duane Fraver for assistance in the field. Funding was provided by The Nature Conservancy's Ecosystem Research Program, the US Environmental Protection Agency (STAR Fellowship provided to first author), and McIntire-Stennis funds. We thank the Maine Chapter of The Nature Conservancy for permission to conduct this work in the Big Reed Forest Reserve.

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