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ARTICLE

Application of a *u-w* method for the detection of boreal forest response to environmental changes in Canada

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ABSTRACT
To better understand the long-term response of boreal forests to increasing environmental changes, we applied the *u-w* method to detect growth changes triggered by environmental factors. Three species (*Picea mariana, Picea glauca*, and *Populus tremuloides*) of various sizes and ages were sampled in a boreal forest in northern Canada. Several stem disks were collected from the base to the crown of seven or eight trees in each of ten plots and ring width was measured to estimate the annual volume growth of each tree. Growth shifts, or changes in the phase of volume growth, were observed in every tree, and some shift years were common to the plots and species, suggesting the same environmental impact on trees. More frequent growth shifts were observed in the smallest trees in the black spruce plots, but showed no common patterns among the trees of different ages/sizes and species. Common growth shifts across species and plots were observed after severe drought years associated with fire incidences. We concluded that the u-w method is useful for detecting multi-year climate impacts on tree growth.

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Climate changes; boreal forest; tree ring; stem volume; growth shifts

Introduction

Boreal forests are sensitive to global climate change (Serreze et al. 2000; Intergovernmental Panel on Climate Change 2007) as the mean global surface temperature has risen by an estimated 0.74°C over the past century (Intergovernmental Panel on Climate Change 2007), altering forest dynamics in numerous ways (Soja et al. 2007). The global warming rate is greater in the circumpolar region (Food Agriculture Organization 2008) and is projected to rise due to the increase in greenhouse gases (Wigley et al. 1980; Intergovernmental Panel on Climate Change 2014). Climate change is expected to influence forest disturbances such as fire, insect outbreaks, and invasive species in forest biomes (Dale et al. 2001). The intensity and frequency of these disturbances are likely to rise (Millar and Stephenson 2015) and may cause a change in the forest structure (Taylor 2010).

There is substantial evidence of the impact of climate change on forest trees. Previous tree ring research on western Canadian aspen forests showed that drought and insect defoliation have led to growth decline at a regional scale (Hogg et al. 2005) along with increased aspen mortality and biomass declines along the southern edge of the Canadian boreal forest (Michaelian et al. 2010). Likewise, satellite image analysis and tree ring analysis indicated drought-induced productivity decline across Alaska (Beck et al. 2011) and a decline in the radial growth of white spruce in western Canada (Hogg et al. 2017), and black spruce in most regions across northern Canada (Girardin et al. 2015).

However, it is not easy to predict the influence of climate on forests. Several studies have reported that trees of different species and different sites often respond differently to the same climatic conditions (Martín-Benito et al. ; Way and Oren 2010; Andreu-Hayles et al. 2011), and the response of trees to climate varies throughout the year (Garrett et al. 2006). Similarly, trees display physiological limitations to coping with the pace of climate change (Renwick and Rocca 2015; Ols et al. 2016), and physiological responses are highly related to limiting factors (Boisvenue and Running 2006). Nevertheless, understanding and predicting the potential consequences of climate change may be one of the challenges because of inadequate understanding of the mechanistic process in forests, and between forest and atmosphere (Ryan 1991; Cannell and Thornley 2003; Boisvenue and Running 2006). Thus, further investigation of the impacts of climate on forest structure is imperative (Bonan 2008) for forest management protocols and terrestrial carbon sequestration in the face of increasing climate change.

Various tree-ring-based methods have been applied to investigate the impact of environmental factors (temperature, precipitation, moisture, and other disturbances) on the response of forest growth at different times and spatial scales. The dendrochronological technique is a useful approach for assessing the radial growth response of trees to variability in their environment in short-term change. The key purpose of this method has been to reconstruct previous climate records rather than to explicate the growth trends of trees in typical forest systems (D’Arrigo et al. 2005; Carrer 2011; Nehrbass-Ahles et al. 2014; Jr et al. 2016). Climate signals may be explained reasonably from radial growth increment (Hc 1983). Alternatively, tree or stand volume is an important tool for the observation of changes in trees and is the basis for forest management planning around the world (Boisvenue and Running 2006). Furthermore, it has been reported that growth at the lower and upper parts of the stem

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section responds differently to specific climatic conditions (Chhin et al. 2010). Despite the difference in stem growth, the dendrochronological technique chiefly focuses on radial growth and does not consider vertical growth; therefore, the response of trees to environmental changes may not be clearly understood. Stem analysis, a more detailed approach where trees are sectioned at regular intervals so that whole tree growth can be better quantified directly (Thomson and Van Sickle 1980; LeBlanc et al. 1987), may improve on the standard approach of quantifying growth at breast height only.

In this study, we applied the *u-w* method (Hozumi 1985) to investigate environmental impacts on the stem volume growth of trees. The change in tree growth appears as a conspicuous shift of growth phase in the *u-w* curve. This approach has some advantages, especially for detecting relatively long-term growth changes due to environmental factors at the individual and stand levels (Hozumi 1987). This study aimed (1) to detect and examine the effects of drought on the growth of three main species, black spruce (*Picea mariana*), white spruce (*Picea glauca*), and quaking aspen (*Populus tremuloides*), in Northwest Territories, Canada. Also, (2) to explore relationships of growth shifts with fire events, associated with drought. We determined the relationship among growth shifts, drought events, and fire events, using events coincidence analysis (Donges et al. 2016). At the same time, we examined the species' sensitivity to environmental changes detectable by the *u-w* method and climate effects from the perspective of the differences in species, age, and size.

Materials and methods

Site description

The study site was on flat terrain (60°1′14″N, 112°19′43″W, 180 m a.s.l.) situated in the boreal ecozone, along the Salt River, about 20 km west of the town of Fort Smith, Northwest Territories, Canada (Figure 1). Regional climate exhibits strong seasonal variation with short, moderately warm summers and long cold winters (Köppen climate classification Dfb or Dfc), with a mean annual temperature of −2.9 °C and mean annual precipitation of 344 mm from 1985 to 2014, based on records at Fort Smith A (https://climate.weather.gc.ca). Black spruce, often associated with white spruce, and quaking aspen are the dominant species in this site (Figure 1 right). Black spruce and quaking aspen are fire-adapted and often regenerate after fire disturbance to develop an even-aged stands (Jayen et al. 2006).Ten study plots established at the site were classified into three age classes based on the oldest tree in each plot (Table 1): 60 years old (four black spruce and two aspen plots), 160 years old (one black spruce and one mixed spruce plots), and 230 years old (two mixed spruce plots). The four 60-year spruce plots have developed on a bog, resulting in their slow growth and the remaining 6 stands established on well-drained sites.

Sampling

Eight black spruce plots were sampled, of which three co-occurred with white spruce, and two plots were sampled for quaking aspen (Table 1). At each plot, tree height and stem diameter at breast height (DBH) and/or stem diameter at 0.2 m height were measured on each sample tree.

Following plot measurements, 7 or 8 trees, spanning the range of tree DBH at each plot were felled for stem analysis. Sample disks were collected from different heights of a tree stem according to the tree height typically as follows; small trees (less than 2 m): at 0 m (i.e. ground level) and every 0.2 m to the top; medium trees (2 to 8 m): at 0, 0.3, 1.3 and every 1 m to the top; and large trees (more than 8 m): at 0, 0.3, 1.3 and every 2 m to the top. Sample disks were air-dried and polished with a mechanical sand-belt first and then with progressively finer grades of sandpaper (80–1200 grit). After polishing, ring widths were measured along two to four radii in each disk to an accuracy of 0.01 mm, using the Velmex TA

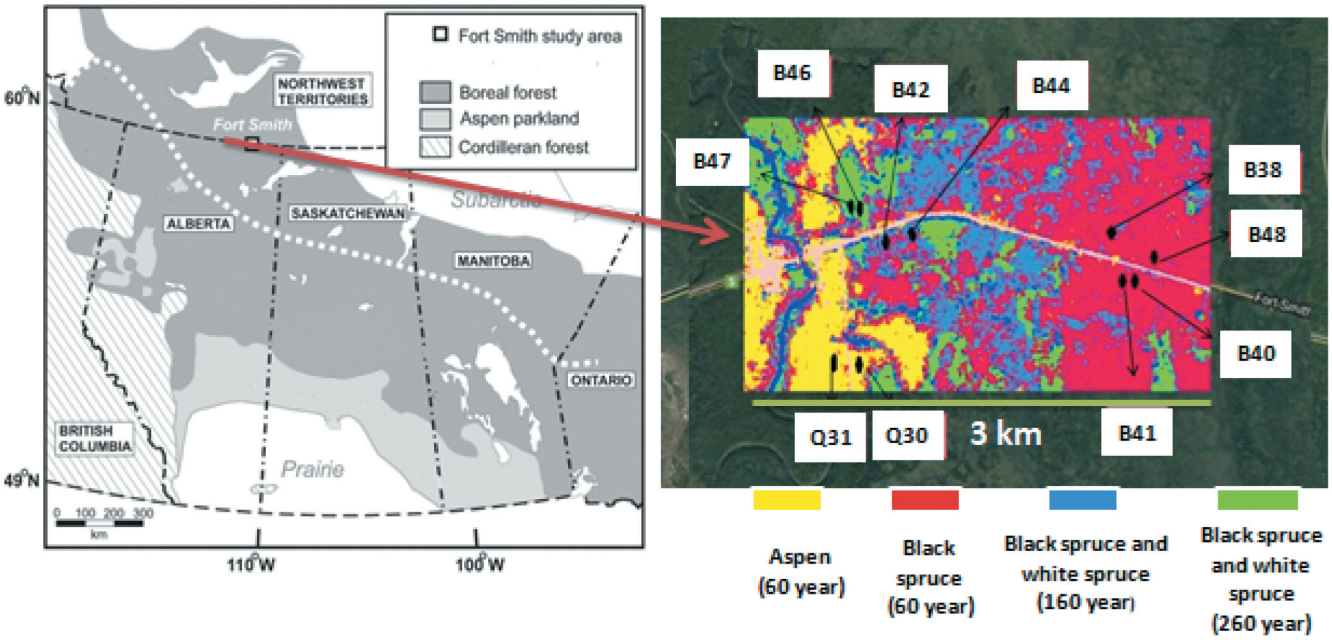

Figure 1. Location of the study site (Left) and the vegetation map of the site (Right). Left: prepared from Hogg et al. (2013) under the permission of authors. Right: prepared using Sentinel 2 image, and processed using COPERNICUS/S2 (ImageCollection ('COPERNICUS/S2', filter date (2018-3-10 to 2018–12-20)), supervised classification and random forest classifier.

Table 1. Sample plots and trees.

Plot	Plot size (m^2)	Density (stem m^{-2})	Sample trees	DBH (cm)	Height (m)	Tree age (year)
Q30	593	0.15	7	15.2 (9.3, 21.7)	17.4 (13.1, 19.4)	66 (66, 68)
Q31	567	0.17	7	14.1 (5.9, 24.5)	16.0 (10.4, 21.1)	67 (66, 68)
B38	225	0.73	7	5.7 (3.6, 7.7)	4.9 (3.5, 6.6)	64 (58, 71)
B40	4.5	26.2	7	1.0[b] (0.3, 2.0)	0.5 (0.2, 0.9)	46 (36, 59)
B41	45.9	2.21	7	5.1[b] (2.6, 8.5)	3.2 (1.2, 6.2)	59 (57, 63)
B48	48.1	1.83	7	4.9[b] (1.8, 10.2)	3.2 (0.8, 6.3)	58 (55, 61)
B42[a]	359	0.28	8	14.6 (3.0, 26.8)	11.7 (2.8, 17.6)	156 (141, 169)
B44	232	0.58	8	9.1(3.4, 19.3)	8.3 (3.4, 14.5)	156 (141, 167)
B46[a]	887	0.09	8	22.1 (9.8, 35.9)	18.1 (8.2, 23.6)	190 (161, 229)
B47[a]	1127	0.10	8	20.4(4.7, 36.3)	16.4 (4.1, 25.6)	172 (94, 242)

Values for DBH, height, and age are mean (minimum, maximum) of each plot. Q: Quaking aspen, B: Blake spruce, a: Black and white spruces mixed. b: Stem diameter measured at 0.2 m above ground. All plots were sampled in 2010, but plot B38 is sampled in 2019

system (Velmex Inc, Bloomfield, NY, USA) and the tree ring measuring program, MeasureJ2X (VoorTech Consulting, NH, USA) or WinDendro (Regent Instruments, Quebec, Canada). For samples with less clear rings, a cross-section (40 μm thick) was prepared from each disk using a sliding microtome and stained with safranin. Each section was then mounted on a glass slide, and the ring width was measured. Finally, the tree ring width series were cross-dated with COFFECHA (Holmes 1983), to confirm that all true growth rings were measured and assigned the correct calendar year.

Stem volume growth estimates

Stem volume was estimated using the Stem4r program developed by Ishizuka and modified by Miyaura (http://www.est.ryukoku.ac.jp/est/miyaura/kenkyu/program/program.html).

In the program, the total volume (V) of a log is calculated based on Smalian's formula:

$$V = \frac{B1 + B2}{2} \times L$$

,

where $B1$ and $B2$ are the cross-sectional areas inside the bark at the lower and upper end of the log, respectively, and L is the log length. For the top part of a stem, V is estimated as a cone as follows:

$$V = \frac{B1}{3} \times L$$

.

The past stem volume of each tree was estimated in the same manner as above, based on the ring width data of the disks collected at different heights in the tree.

U-w approach

The u-w method (Hozumi 1985) is a tool for analyzing stem volume growth of a tree, based on the characteristic of the curve depicted by the stem volume w and the value u defined as follows. Given the growth rate of a stem as dw/dt, the relative growth rate of w is $(dw/dt)/w$. Then, u is defined as the ratio of the relative growth rate $(dw/dt)/w$ to w, as equation (1)

$$u = \frac{1}{w}\left(\frac{1}{w}\frac{dw}{dt}\right)(1)$$

The basic equation of the growth curve of w is presented in equation (2).

$$u = \frac{1}{w^2}\frac{dw}{dt} = Aw^{-c}\left(1 - \left(\frac{w}{W}\right)^m\right)(2)$$

where W is the asymptote of w, t is the time after the observation of an initial value of w; A, m, and c are constants (Hozumi 1987). An example of the growth curve, or called u-w diagram, is illustrated by comparing it with a standard w-t growth curve in Figure 2. The change in tree growth is observed as the shift of one curve to the next in Figure 2a. The growth shifts observed in Figure 2a are more conspicuous than the slope changes of the w-t growth curve in Figure 2b.

Hozumi (1987) demonstrated that growth model considered in the u-w method is equivalent to Bertalanffy's growth model (Bertalanffy 1949), which was proposed based on the balance of two physiological processes (anabolism and catabolism). Also, Miyaura and Hozumi (1993) estimated experimentally the aboveground weight of a tree by the Bertalanffy's growth model, indicating that stem volume growth can be described by using the u-w method.

Detection of growth shift by u-w diagram

In the analysis, u and w are calculated as equations (3) and (4), respectively. w_1 and w_2 are the stem volume of a tree at t_1 and t_2, respectively.

$$u = \frac{(logw_2 - logw_1)^2}{(w_2 - w_1)(t_2 - t_1)} \quad (3)$$

$$w = \frac{w_2 - w_1}{logw_2 - logw_1} \quad (4)$$

We used the program developed by Aoki (2008, unpublished, http://www.est.ryukoku.ac.jp/est/miyaura/kenkyu/program/program.html) to calculate and plot the u-w diagram. Growth shift detection relies on visual inspection, as shown in Figure 2a, which is composed of four growth phases. The inception of each curve following the first curve shows a point of growth shift indicated by arrows in a given year, meaning a certain change in the tree's growing environment leading to an increase of the carrying capacity. As a result, the tree's growth goes into a different phase.

Climate moisture index (CMI) and Fire data

Climate moisture index and fire data relating to the study site were reconstructed; both variables were used to examine relationships of growth shifts with drought and fire incidences. Climate data at Fort Smith A was obtained from the official site of the Government of Canada (https://climate.weather.gc.ca), and subsequently, CMI (cm $month^{-1}$) values were calculated as precipitation (cm $month^{-1}$) minus potential evapotranspiration (PET), based on Eh (1997). PET, estimated in cm $month^{-1}$, is the

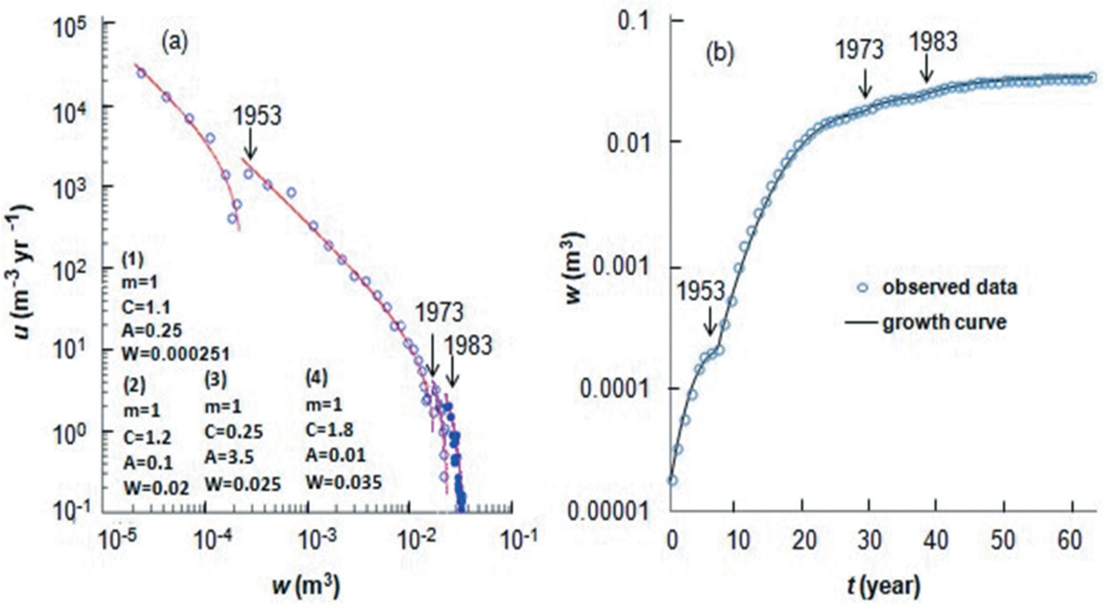

Figure 2. Growth shift observed in 65-year quaking aspen in two different growth curves. (a) u-w curve; (b) log w-t curve. Each arrow shows a growth shift year.

expected rate of water vapor loss to the atmosphere, calculated from mean daily maximum and minimum temperature (°C) for every month. In this study, we used a window of 15-month for CMI calculation, from June of preceding year to August of the current year, because the climate condition of the previous year significantly influences the tree growth in the current year. Then, CMI was calculated using the sum of the monthly CMI values over 15 month periods. Negative CMI values mean dry conditions, whereas positive ones denote moist conditions.

In addition, we included the fire incidence data in the analysis as an indicator of drought which was followed by a fire in the study area. Fire data was downloaded from the Canadian National Fire Database (CNFDB) provided by the Government of Canada (http://cwfis.cfs.nrcan.ca/ha/nfdb). QGIS software was used (QGIS.org 2019) to extract and calculate retrospective fire area and fire frequency in the area including Wood Buffalo National Park adjacent to the research site and a circle with a radius of 50 km, where the center of the radius (60° 01′N, 112°19′W) was located in our study area.

Event coincidence analysis (ECA)

To investigate the relationship of growth shifts with drought events indicated by CMI, and with spatial fire events as a proxy of severe droughts, we conducted an event coincidence analysis (Donges et al. 2016), using the R package CoinCalc (Siegmund et al. 2017). ECA calculates the empirical fraction of co-occurrences in a two series of event observations, e.g. event series A and B, which is referred to as the event coincidence rate (ECR). The notion of event coincidence is not symmetric, i.e. it always takes one of the two event series as a reference to which the second is compared; commonly, in this context type B events are considered as possibly influencing the timings of type A events (Siegmund et al. 2017). In this study, events A and B are growth shifts and drought, respectively.

The event coincidence rate (ECR) takes values between 0 and 1, where 0 means that A and B never occurred simultaneously, and 1 means that A and B always occurred simultaneously. For calculating the relationships between two event series A and B, ECA performs two different test setups to address type B events as the precursors and the triggers of type A events, respectively. Firstly, the precursor coincidence rate (PCR) is defined as the quotient of the number of coincidences in type A and type B events and the number of type A events, measuring the fraction of type A events that are preceded by at least one type B event. Secondly, the trigger coincidence rate (TCR) is described as the number of event coincidences in type A and type B divided by the number of type B events, quantifying the fraction of type B events that are followed by at least one type A event. Differentiating between PCR and TCR allows quantifying the strength, directionality, and time lag of statistical interrelation between event series (Donges et al. 2016). We examined the statistical significance of both test setups between the growth shifts and drought – and fire-events in the period between 1950 and 2010. Furthermore, we used the lowermost 10 percentile threshold for drought and the uppermost 90 percentile threshold for growth shifts and fire events for the coincidence analysis.

Results

Growth shifts of trees

Growth shifts were observed in most of the trees in common periods especially after 1950 (e.g. early 1980s) with some inconsistencies among the trees within each plot and between the plots (Figure 3). The bulk of the trees experienced growth shifts in the first three years of the 1950s, 1970s, and 1980s. Also, growth shifts were seen in nearly half of the trees in 2004, and this is explicitly seen in old tree plots (B42, B44, B46, and B47). However, some visual differences related to the synchronicity of growth shifts in the plots and between the plots also were observed. For instance, relatively more synchronous growth shifts observed in quaking aspen plots (Q30 and Q31) than those of other plots; by

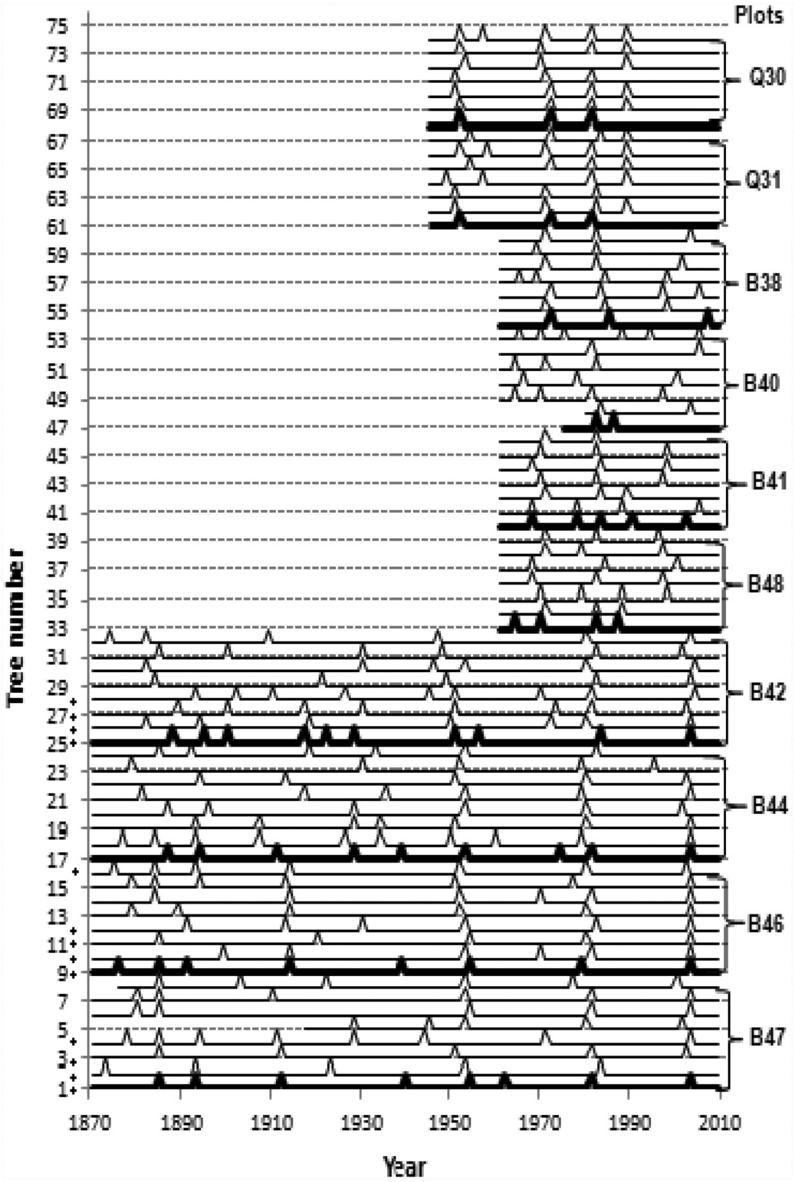

Figure 3. Growth shifts phases of trees in 10 plots. Q: Quaking aspen plot; B: Black spruce plot. Trees are numbered from the smallest to the largest in height in each plot. Peaks in each line show growth shifts; + indicate white spruce.

contrast, young black spruce trees (B38, B40, B41, and B48) appeared to show more or less inconsistent and asynchronous growth shifts. On the other hand, growth shifts in old black spruce trees (B42, B44, B46, and B47) were not synchronized in the former 80 years (1870–1950), and thereafter started to show synchronous growth shifts in the later 60 years (1950–2010). Overall, the synchronous growth shifts among and between plots suggests that certain common regional factors may have triggered these growth shifts.

Common temporal patterns of growth shift occurrences were observed between plots despite the difference of species and age (Figure 4). Besides, the patterns of growth shifts appeared to be more similar between the plots of the same species and similar age than those of different species or age. For example, the growth shifts of quaking aspen plots (Q30 and Q31), young black spruce plots (B38, B40, B41, and B48), and old black spruce plots (B42, B44, B46, and B47) show a similar pattern in each group. On the other hand, some apparent differences were seen in their growth shift patterns when comparing young black spruce plots with those of old black spruce or comparing quaking aspen plots. Growth shifts in the young black spruce plots (B38, B40, B41, and B48) were more frequent than in other plots but less synchronized within each plot. Despite the differences in age and species, common growth shift patterns were observed across the plots especially in the early 1950s (old spruce and quaking aspen plots), 1970s (young spruce and quaking aspen plots), 1980s (across all plots) and 2000s (old spruces plots).

Additionally, the size-related trend of growth shifts was observed for spruce trees (Figure 5). A significant difference in growth shifts frequency was seen in old black spruce plots ($p = 0.01$) where trees less than 5 m displayed higher occurrence of growth shifts than those of larger trees, but no significant differences were observed among the other four height classes greater than 5 m (Figure 5c). Trees in young black spruce plots showed no significant differences in growth shift frequency among three size classes although a decreasing trend of growth shift frequency was observed with increasing height (Figure 5b). The mean frequency of the growth shifts in each of three height classes of young spruce plots was greater than those of height classes over 5 m in old spruce plots (Figure 5b and 5c). Thus, as observed above, the smaller spruce trees with heights less than 5 m

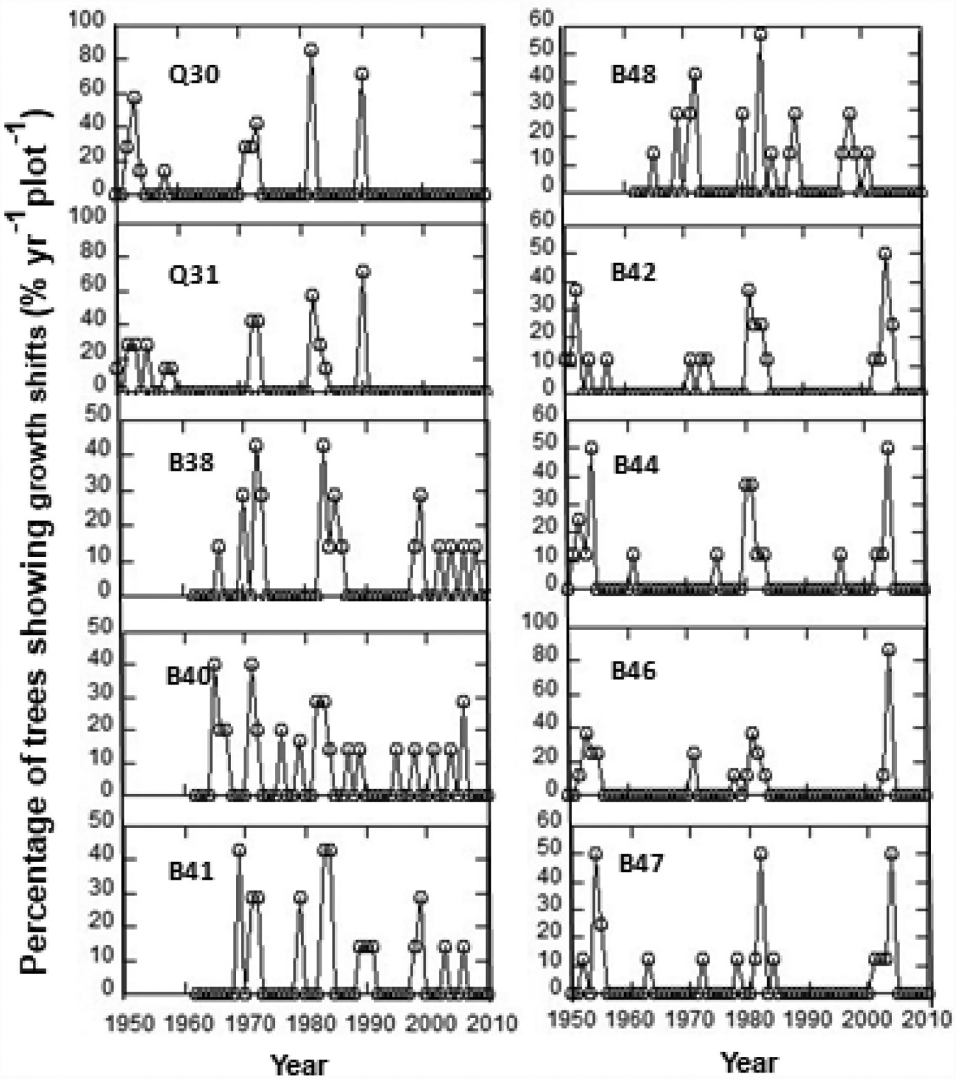

Figure 4. Percentage of trees exhibiting growth shifts in each plot.

tended to show more frequent growth shifts than the larger spruce trees. On the other hand, size-related differences were not observed in quaking aspen trees.

Growth shifts coincidence with climate effects

The occurrence of growth shifts visually showed synchrony with events of drought, fire frequency, and fire area in common periods (the early 1950s, 1970s, 1980s, and the 2000s in Figure 6). ECA indicated that the years of growth shifts were largely related to drought and to both fire variables, although some differences were observed in their PCR and TCR values (Figure 7). PCR test shows significant ($p< 0.05$) relationships between fire events and growth shifts where 5 out of 7 growth shifts corresponding with both fire variables (PCR = 0.714, Figure 7b, and 7c). However, the PCR test indicated no significant relationships of growth shifts ($p= 0.1$) with drought events despite 4 out 7 growth shifts corresponding with episodes of droughts especially in the first three years of the 1950s and 1970s (Figure 7a). Additionally, similar PCRs (0.714) were observed in both fire variables with growth shifts. It shows that the number of corresponded growth shifts is equal with each of the fire variables. The statistics of the PCR test suggests that both fire variables were related as a precursor to growth shift and show correspondence interrelationships between them. Also, in the TCR test, insignificant relationships ($p= 0.1$) were seen between growth shifts and drought episodes and fire frequency, while showing significant relationships with fire areas ($p = 0.04$) . It means that the number of events of fire areas corresponding with growth shifts is greater than those of drought episode and fire frequency (Figure 7d, 7e, and 7f). TCR test implies a possible causal influence of both fire and drought events. It means that, in most cases, occurrences of drought episodes and fire events were followed by one or two growth shifts in an interval of about 2 or 3 successive years, and it suggests a possible lag effect on growth shifts. Overall, Coincidence rates in both tests are comparable; it implicitly suggests that drought followed by fire led to correspondence relationships with growth shifts.

Discussion

Factors causing growth shifts

Our study shows drought causes growth shifts in boreal forest trees, which is indicated in the correspondence of growth shifts (e.g. the early 1950s, 1970s, 1980s, and 2004) with drought episodes and fire events. The tree species and tree individuals sensitive to drought stress die because of severe drought episodes or prolonged dry periods, which

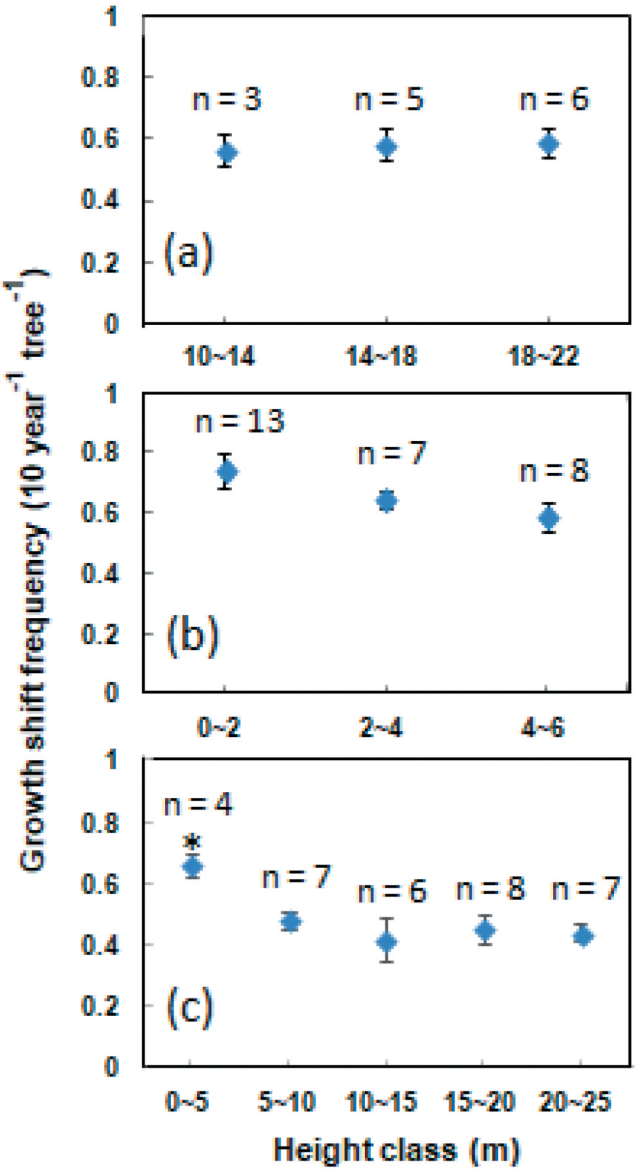

Figure 5. Comparison of growth shift frequency among different tree-height classes. (a) Quaking aspen (Plots Q30 and Q31); (b) Young black spruce (Plots B38, B40. B41, and, B48); (c) Old black spruces (Plots B42, B44, B46, and B47); (n) number of trees in each height class; vertical bar shows standard error; * Significantly different (Tukey's test, $p < 0.05$).

enables the survived trees to utilize more resources leading to their temporal active growth, i.e. growth shift. This interpretation is exhibited in Figure 2a; a growth shift always accompanies an increase of *w*, meaning that the carrying capacity for survived trees temporally increases. The active tree growth often shows a one or two-year lag as indicated in Figures 6 and 7. It is noteworthy that even though the drought is not very severe, continuous dry years can cause trees' death and survivors' growth shift as indicated in the early 1980s and 2000s, during which four or five dry years continued (Figure 6a and 6d).

Drought effects in Canadian boreal forests have been widely reported as, the massive mortality of aspen following severe drought along the southern edge of the Canadian boreal forest (Michaelian et al. 2010), a decline in drought-related radial growth of black spruce (Deslauriers et al. 2014), and climatic drying-induced reduction of white spruce in western Canada (Hogg et al. 2017). Based on our results, drought-induced growth reductions and growth release in surviving trees following drought-related mortality episodes would lead to growth shifts in each tree and stand.

The mechanism of trees' growth reduction by drought is water shortage leading to low stomatal conductance and subsequently to low photosynthesis, but forest fires associated with drought also may affect tree growth as indicated by the relationships between growth shifts and fire data (Figure 7). Fire smoke and combustion particles may limit stomatal functions, resulting in the growth reduction of trees. We lack experimental evidence to show if growth shifts occurred due partially to fire smoke although coincidence tests were significant (Figure 7). Effects of fire smoke remained unanswered and may warrant further investigations in the future.

Factors affecting growth shift

Some factors are affecting the mechanism through which growth shifts are induced. Tree size appears to be one of the factors affecting the frequency of growth shifts. Relatively more growth shifts were observed in shorter trees than in taller trees when comparing short and tall trees within and across plots (Figure 5b and 5c). Short trees are expected to be more sensitive to slight changes in the local environment (e.g. shading and competition for space and nutrients), which do not have a significant influence on tall trees. This interpretation is supported by the smaller difference in the growth shift frequency among trees in Q30 and Q31 (Figure 5a), where all the aspen trees were taller than 10 meters, which is greater than the 5-meter threshold for high versus low growth shift frequency in spruce (Figure 5c)

Trees at younger ages seem to have experienced growth shifts asynchronously within and across the plots, as seen in the old plots B42, B44, B46, and B47 (Figure 3). Growth shifts seemed less synchronized across the trees before 1950 and then they tended to be more synchronous. It is thought that within-stand factors (i.e. competition, nutrients, and shading) affect the growth in the early to mid-growth stages (Huang et al. 2013), and exogenous factors (i.e. temperature and precipitation) are more likely to affect trees as they age. Also, age-related physiological changes occur in trees that may accrue their sensitivity to external factors. For instance, a shift in carbon allocation to various parts of the tree (Ryan et al. 1997), decreasing photosynthetic efficiency and leaf size, and gas exchange attributes change over time with increasing age (Kull and Koppel 1987). Therefore, the susceptibility and vulnerability of trees to environmentally driven factors are expected to increase as they age. Thus, synchronous growth shifts after 1950 can be ascribed partly to age-induced sensitivity changes to environmental factors and the severity of drought episodes especially after 1950.

Species-specific sensitivity to environmental factors also causes a difference in the growth shift synchronicity among plots. The growth shift synchronicity in two quaking aspen plots appeared more consistent than in the spruce plots (Figure 3). One of the potential causes that led to synchronicity can be the severity of drought as aspen is one of the most drought-intolerant species (Chen et al. 2017). Similarly, Hogg et al. (2002) also observed synchronous biomass decline among aspen trees in northwestern Alberta, Canada and implied that drought and insect defoliation may have been the factors that led to a synchronous decline over vast areas of aspen.

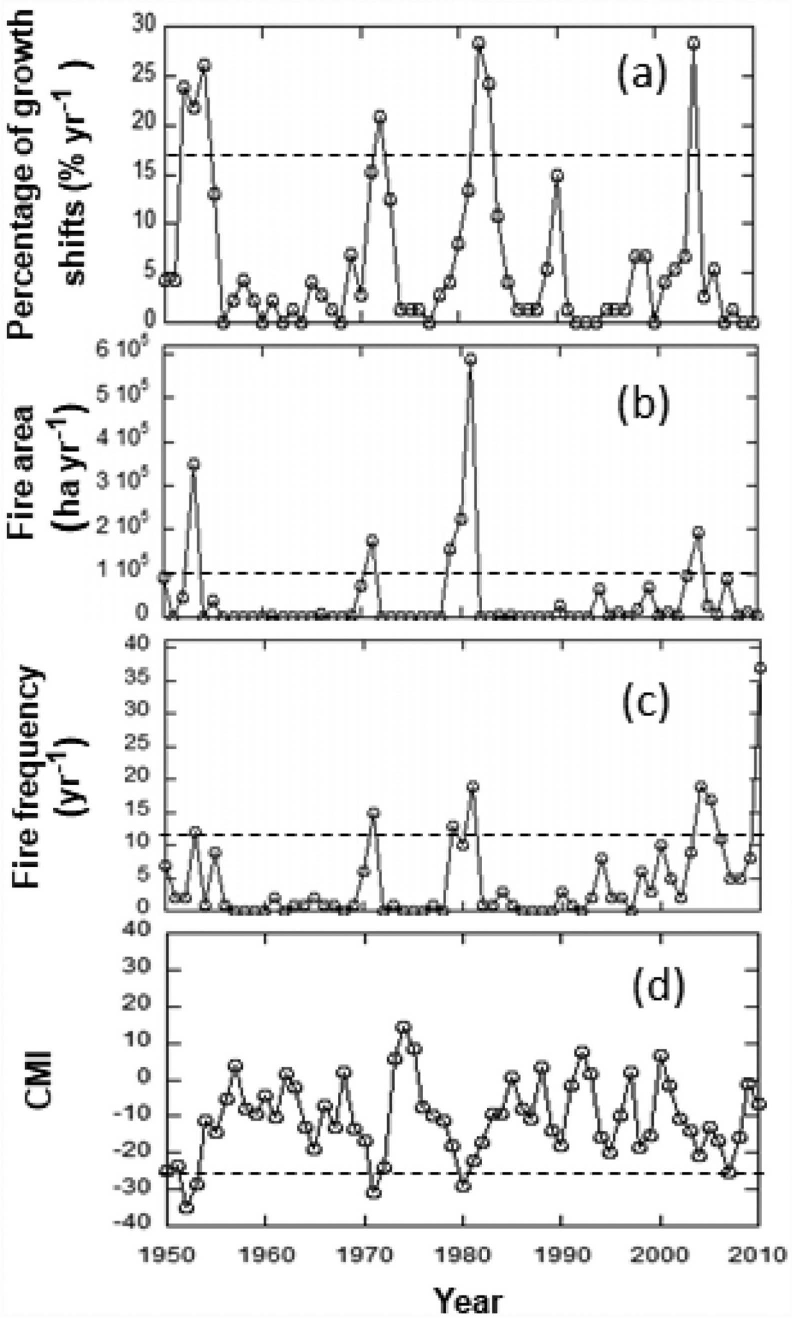

Figure 6. Correspondence of growth shifts with drought and fire events. (a) Percentage of all sampled trees showing growth shifts, (b) Fire area, (c) fire frequency, (d) CMI during the years 1950–2010. (d) Dash horizontal line marks the 10th and 90th percentile thresholds used for event coincidence analysis of growth shift, fire area, and fire frequency and drought.

Application of the u-w method to environmental research

The application of the *u-w* method demonstrated several advantages related to examining the impacts of climate change on forests compared to other conventional methods as dendrochronology, which examines the relationship between climate variables and ring width. These advantages include (1) detecting long-term effects of environmental impacts on stem volume growth, (2) examining the areal forest dynamics by extending from individual tree to a stand, and (3) applicable to various sizes of trees and species. On the other hand, the *u-w* method has some limitations. For instance, it is (1) less suitable for detecting successive growth shifts within a decade, (2) more time consuming for sample preparation and tree-ring measurement (3) and less suited for applying to stands with widely uneven tree ages.

Sampling is vital for the assessment of the retrospective environmental stresses on forest growth using the *u-w* method. To explain the responses of tree populations to environmental changes, it is crucial to choose representative tree species including various sizes. However, this study suggests that extremely small or large trees in a stand exhibit different growth behaviors from those of other trees. A certain methodological improvement is necessary for dealing with extremely small or large trees for further application of the *u-w* method. Furthermore, it is recommended to avoid the juvenile growth stage in examining the environmental effect of a regional scale because local factors (e.g. competition for space, light, and nutrients) may substantially influence growth during this period.

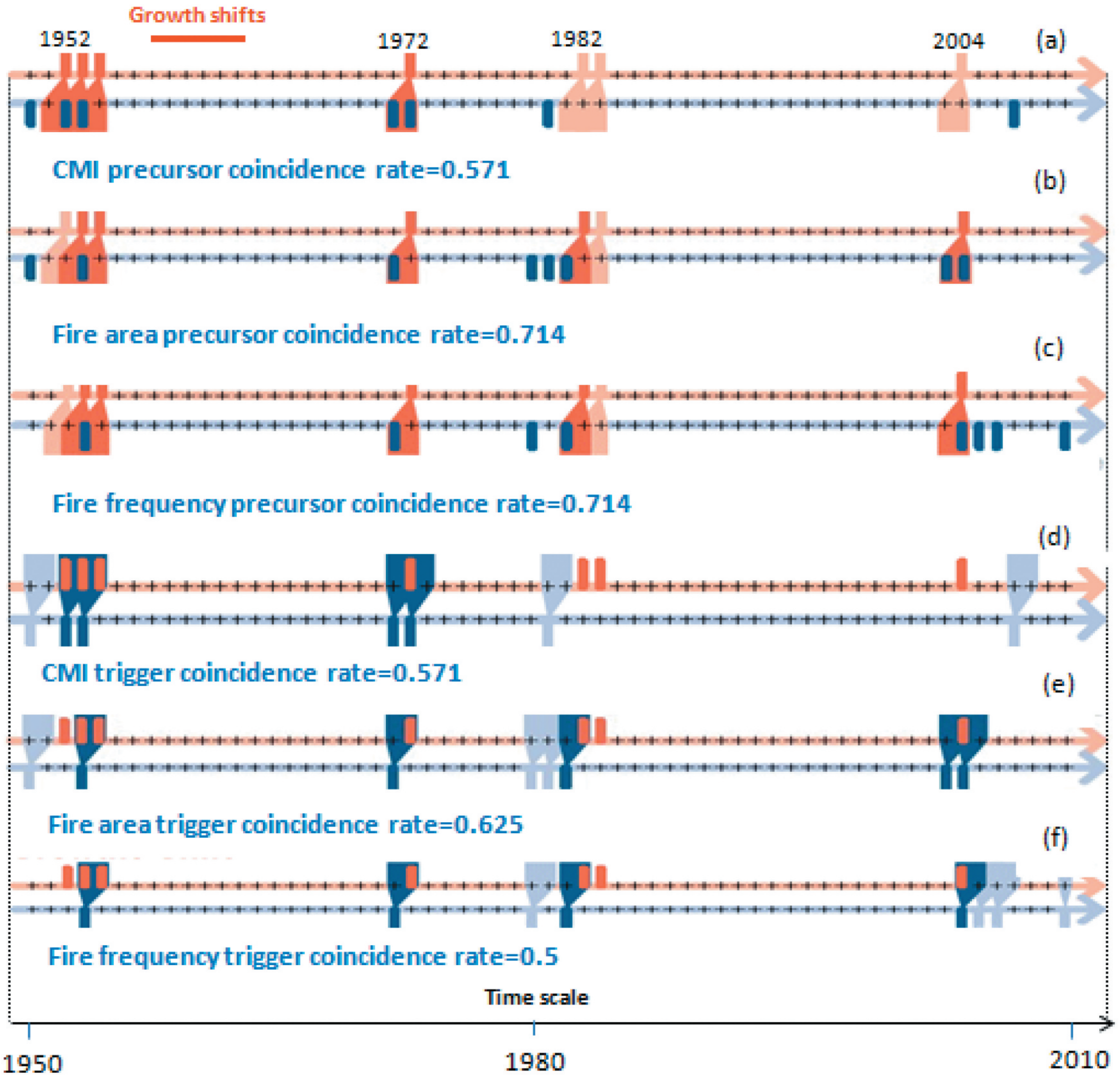

Figure 7. Event coincidence analysis of growth shift and relating factors in the period of 1950 to 2010. CC.plot function of the R package CoinCalc was used to show the coincidences for the growth shifts, CMI, fire area, and fire frequency. (a), (b) and (c) are the precursor coincidence rates (PCR) between growth shifts (red) and relating factors (blue); (d), (e) and (f) are the trigger coincidence rates (TCR) between growth shifts (red) and relating factors (blue). Climate moisture index (CMI) is an indication of drought. Thick blue and red bars mark the coincided events; light color shows events without coincidence. In (a), the PCR of growth shift and CMI is calculated as the ratio of the number of growth shifts preceded by CMI extremes (four red color events) and total growth shifts (four thick red and three light red color events). In (d), the TCR of growth shift and CMI is calculated as the ratio of the number of CMI extremes followed by growth shifts (four blue color events) and total CMI extremes (four thick blue and three light blue color events).

In this study, we confirmed that the *u*-*w* method has a significant potential for detecting the environmental impact on forests, especially on boreal forests which are often composed of trees of even ages due to regeneration after stand-replacing fires. The method needs further improvement for application to wider types of forests but shows potential as a new alternative tool for analyzing forest dynamics in the face of increasing global warming.

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Author contribution statement

Study conception and design: AO. Acquisition of data: AN, AO, NK, TK, and JM. Analysis and interpretation of data: AN, NK, TM, MD, and NO. Drafting of the manuscript: AN and NO. All authors have given consent to the publication of the final version of the draft.

Disclosure statement

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