Dendrochronological Comparison of Methods of Determining Spruce Budworm Outbreaks in Cape Breton, Nova Scotia

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Abstract

Eastern spruce budworm (*Choristoneura fumiferana* Clem.) is an insect known for its destructive impact on coniferous forests across the Canadian Maritimes. Trees experience considerable stress during spruce budworm outbreaks as the budworm defoliates vast tracts of forest stands, leading to the reduction or elimination of individual tree's annual-growth ring. Outbreaks have traditionally been identified through comparison of the radial-growth patterns of a species unaffected by the budworm (non-host) to that of an affected species (host). However, where no reliable non-host species is available, an alternate method has been developed involving the application of a running mean to the non-host chronology. The outbreak detection accuracy of both methods were compared to each other and to forest survey records using tree core samples collected in Cape Breton, Nova Scotia. Comparison of the traditional method against the historical record indicates that the traditional method lacks accuracy in the detection of extremely severe outbreak events, particularly the 1974-1983 outbreak across Cape Breton Island. The running mean method was found to correctly identify the large-scale 1974-1983 outbreak event but was less sensitive to lower-intensity outbreaks, such as the 1960-1963 event. The breakdown in accuracy of the traditional method is hypothesized to result from the impact of climate on the non-host species during these severe outbreaks, causing a reduction in the accuracy of the traditional method. Application of a running mean to the non-host chronology compensates for the climatic response of the non-host and improves program OUTBREAK's detection accuracy. The importance of climate in spruce budworm outbreak detection is supported by the strong correlation between the Atlantic Multidecadal Oscillation (AMO) and standardized tree growth, as well as the illustrated relationship of the AMO with known outbreak events.

Introduction

Eastern spruce budworm (*Choristoneura fumiferana* Clem. (Lepidoptera: Tortricidae)) is an integral natural disturbance in spruce-fir stands of the boreal forest and is considered to be as important (or more) to forest productivity as fire (Morris, 1958; Blais, 1983; Belle-Isle and Kneeshaw, 2007; Morin et al., 2007). In Eastern Canada, outbreaks of spruce budworm have been found to occur at a frequency of around every 30-40 years during the past century (Royama, 1984; Royama et al., 2005). Severe outbreaks target mature balsam fir (*Abies balsamea* (L.) Mill) and white spruce (*Picea glauca* (Moench) Voss) stands, causing devastating defoliation damage particularly when they occur in large contiguous stands (Swaine and Craighead, 1924; Graham and Orr, 1940; Mott, 1963; Blais, 1983; MacLean, 1984; Morin, 1994; Bergeron et al., 2002). The high vulnerability of this stand type is due to the defoliation preference of spruce budworm to balsam fir and white spruce as host species, though black spruce (*Picea mariana* (Mill.) B. S. P.) and red spruce (*Picea rubens* Sarg.) also suffer from defoliation by spruce budworm (Blais, 1962; Greenbank, 1963; Mott, 1963; Royama, 1984; Nealis and Régnière, 2004; Morin et al., 2007). Due to this preference in host species, damage during severe outbreaks is greater in stands with a higher composition of balsam fir and spruce trees (Blais, 1962; Blais, 1983).

Spruce budworm is usually present in spruce-fir stands at low endemic population levels until conditions within the forest and atmosphere are favourable to the budworm's life cycle, allowing their population to increase rapidly (Morris, 1963). As an outbreak progresses, the compounding effects of defoliation on new growth increases and often leads to tree mortality, seen in most forests by the fifth or sixth year of an outbreak (Morris, 1963). In the case of severe outbreaks, mass defoliation on a landscape level regularly results in vastly increased host mortality, particularly of balsam fir trees (Morris, 1963; Morin et al., 2007). Through these mass mortalities, severe outbreak events alter the composition and functioning of a forest in a way that is secondary only to fire disturbance (Morin and Laprise, 1990; Kneeshaw, 2001). The regular disturbance caused by outbreak events are important to allow regeneration of balsam fir stands, as the death of the overstory allows the seedlings in the understory to grow and mature (Morin, 1994; Morin and Laprise, 1997; Parent et al. 2003). This cycle of outbreak-regeneration maintains the forest complement in much of the eastern boreal forest (MacLean, 1984; 1988; Morin, 1994).

In Eastern Canada, spruce budworm outbreak events are well documented for the past 200-300 years (Blais, 1983). Historical data for regions of southern Ontario, southern Quebec, New Brunswick, the north shore and Gaspe regions of Quebec, and Newfoundland document three severe, wide-ranging, outbreaks (Blais, 1983). In the 1910s, a severe outbreak occurred in most of southern Quebec, New Brunswick, and in Cape Breton (Morris, 1958; Nova Scotia Department of Lands and Forests (NSDLF), 1977). In the 1940s, an event was again initiated in southern Quebec and New Brunswick (Morris, 1958), which was repeated in the 1970s across Quebec, New Brunswick, Cape Breton and Newfoundland (NSDLF, 1977; Blais, 1983; Kettela, 1983). In all of these events, spruce budworm affected vast tracts of forested land throughout these provinces, with about 11 million ha influenced in the 1910s event, 25 million ha in the 1940s, and 58 million ha in the 1970s infestation (Blais, 1983; Kettela, 1983). Each of these 20th century outbreaks had devastating effects on the forested landscape within the course of a single decade.

Cape Breton Island, Nova Scotia is one area of eastern Canada where outbreak records date back 250 years (NSDLF, 1977). In Cape Breton, severe outbreaks have occurred more frequently than in other areas of eastern Canada due to its high concentration of vulnerable spruce-fir stands (Swaine and Craighead, 1924; Graham and Orr, 1940; Morris, 1963; NSDLF, 1977; Blais, 1983; Bergeron et al., 2002). In the past century, severe stand-altering outbreaks have occurred across the entire Island from 1911-1915 (Morris, 1958; NSDLF, 1977), 1922-1927 (Swaine, 1933; Hawboldt, 1955; NSDLF, 1977), 1951-1956 (Morris, 1958; NSDLF, 1977), 1960-1963 (NSDLF, 1977), and the most severe of the century from 1974-1983 (NSDLF, 1977; Blais, 1983; Kettela, 1983; Ostaff and MacLean, 1989; Piene, 1989; Hudak, 1991). The outbreak lasting from 1922-1927 was described by Swaine (1933) as peaking in 1927 with 80% parasitism, providing an indication of the severity of this outbreak though it is not well described.

The most recent, and most severe, outbreak from 1974 to 1983 reduced the number of mature merchantable spruce and fir trees from 416 million to 122 million, a reduction totalling approximately 71% of the total living merchantable trees in Cape Breton (MacLean and Ostaff, 1989; Hudak, 1991; Forest Research Report (FRR), 1994). A reduction to 272 million trees was anticipated through other natural causes by this time but the drop still equalled a 55% increase over the anticipated loss (MacLean and Ostaff, 1989; Hudak, 1991; FRR, 1994). The severity of this outbreak was due to the emergence of spruce budworm larvae from hibernation two weeks prior to the emergence of bud burst in the preferred host, balsam fir trees (NSDLF, 1977). In order to survive, the new larvae fed on the older foliage and later switched to the new foliage once it had emerged (NSDLF, 1977). This caused severe stress to the trees as the budworm returned to eating old-growth needles once the new growth had been stripped away, leaving nearly all host trees sparsely foliated (NSDLF, 1977). By its peak in 1976, 1.22 million ha of host trees were moderately to severely defoliated on Cape Breton Island (Magasi et al., 1976).

Records of past outbreaks are valuable in predicting the responses of spruce-fir forests to spruce budworm outbreaks. As the Eastern Canadian forest industry is largely based around softwood species, knowledge about the response of these species is valuable to forest industry groups (Blais, 1983). In this regard, analyses of past outbreaks are often used to evaluate the impact of many external factors; from climatic conditions leading up to severe infestations, to the role of forest management practices on the frequency, severity, duration, and extent of each spruce budworm outbreak (Blais, 1983). These analyses can further be used to inform forest managers about the current conditions that are contributing to the next potentially severe outbreak.

In order to facilitate these analyses, spruce budworm outbreaks are identified in tree-ring growth patterns, frequently using the computer program OUTBREAK (Holmes and Swetnam, 1996; Speer, 2010). The program compares the radial-growth patterns of a spruce budworm host species to that of a non-host species and determines the presence of outbreaks based on defined parameters and growth reductions in the host that are not seen in the non-host (Speer, 2010). Program OUTBREAK assumes that regional climatic conditions, although driving growth of all forest species, creates the same response for both host and non-host species during an outbreak. This assumption of program OUTBREAK will be tested as identical climatic inputs are known to influence the radial growth of all species to differing levels (Fritts, 1976).

To improve the accuracy of understanding past severe spruce budworm outbreaks, this research looks into the strengths and weaknesses of program OUTBREAK as it attempts to detect the most severe, stand-altering infestations. Cape Breton, with its well documented records of 20th century events, and five severe Island-wide infestations during this time, will be used as a case study. Traditional host/non-host analyses will be compared against newer regional averaging methodologies to determine the strengths and weaknesses of each method.

We hypothesize that the ability of program OUTBREAK to accurately detect extremely severe outbreaks may be reduced because of the increased role that climate plays in severe outbreaks (Gray, 2008) and the subsequent enhanced influence climate will have on the radial growth of both the host and the non-host species (Gray et al., 2004; Phillips, 2009). This research will better inform forestry officials about past outbreak episodes and, if future episodes can be predicted based on cyclic climate variations, will better inform their future forest management practices.

Study Sites

Samples were collected from four sites across Cape Breton Island in July of 2011. The sites were located at the north, south, east, and west points of the island in order to provide a comprehensive representation of spruce budworm activity across all of Cape Breton. A fifth site, previously sampled in 2005, was added to the analysis in order to increase the sample depth and spatial coverage of the analysis (Fig.1, Table 1). All sampled sites were located relatively near to the coast to reduce variability in micro-climate effects and were collected at elevations ranging from approximately 20 m to 247 m above sea level. Each site was at a minimum of 80 km away from the nearest other site.

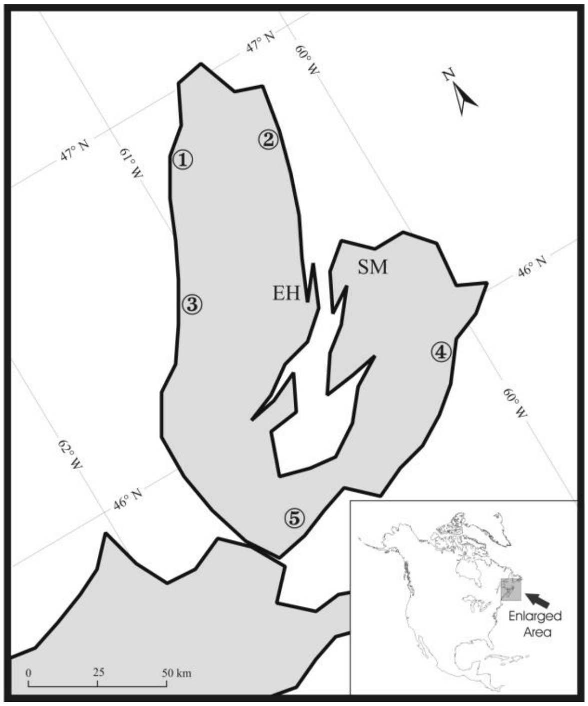


Fig. 1 – The location of study sites in Cape Breton is indicated by numbers which correspond to sample site codes in Table 1. The EH and SM labels indicate the location of the non-host chronologies used in this study.

Table 1 – The geographic locations of the study sites in Cape Breton, N.S. Study site number refers to their location in Fig. 1.

Study Site	Site Code	Latitude	Longitude	Elevation (m)
1	05AYL000	46° 47' N	60° 51' W	247
2	11TL000	46° 45' N	60° 19' W	20
3	11UL000	46° 19' N	61° 12' W	36
4	11VL000	45° 53' N	60° 10' W	64
5	11WL000	45° 37' N	61° 6' W	82

Methods

At each sampling location, balsam fir and the dominant spruce species present were sampled. Spruce was chosen as a secondary species at each site because they are the next preferred host species of spruce budworm and they are more capable of surviving severe outbreaks while still experiencing severe radial-growth reductions (Blais, 1983; Morin et al., 2007). Using a 5.1 mm increment borer, 40 core samples were taken from 20 trees of both species, resulting in a total of 80 cores from each site. Two increment cores were taken from opposite sides of each tree at breast height and were placed into individual labelled straws for transportation. At each site, only trees whose cores visually appeared to be more than 40 years old were sampled in order to ensure the detection of the most recent severe outbreak.

Samples were brought back to the Mount Allison Dendrochronology Laboratory (MAD Lab) for further processing. Each sample was glued into a wooden mount and allowed to set. Once the glue was dry, the samples were sanded with progressively finer grit sandpaper (80-400 grit) in order to increase radial-ring boundary definition and clarity. Visual crossdating was conducted on the sanded cores (Stokes and Smiley, 1968) and then the distance between annual-ring boundaries was measured to an accuracy of 0.001 mm using a Velmex measuring system attached to a 63X microscope. Following ring-width measurement, each site was statistically crossdated using the computer program COFECHA (Holmes, 1983; Grissino-Mayer, 2001). COFECHA assigns a correlation value to each sample core based on how well it correlates with a master chronology made up of all input samples.

Tree-ring data was used to determine the occurrence of past spruce budworm outbreak events using two statistical methods: 1) the host versus non-host method (Swetnam et al., 1995) and; 2) the host versus running mean of the non-host method (Nishimura, 2009). The host versus non-host method (herein referred to as the traditional method), compares the ring-width chronology of each tree of a species which is a host of spruce budworm, to the master chronology of a species that is not a host. Host versus non-host analysis assumes that both species will have similar radial-growth patterns and that through comparison, the only difference between them will be the radial-growth reduction in the host species due to defoliation by spruce budworm (Speer, 2010). The host versus running mean of the non-host method was adapted from the host versus running mean of host method developed in Labrador where no non-host tree species grew (Nishimura, 2009). The adapted running-mean method (herein referred to as the running-mean method) compares individual samples of the host species to a running mean of the regional master chronology of the non-host species. A running mean of 25 years was placed through the ring-width measurements of the master chronology of the non-host species as it was deemed to be about 1.5 times the length of an average spruce budworm outbreak event (Nishimura, 2009).

Prior to host/non-host analysis, the crossdated samples for each non-host species were compiled then standardized and detrended using a negative exponential curve in program ARSTAN (Cook, 1985). This was done to create a single standardized ring-width regional master chronology for both non-host species, as it is required for analysis using the traditional method within program OUTBREAK (Holmes and Swetnam, 1996). To facilitate use of the running-mean method, the standardized and detrended non-host master chronologies were smoothed by adding a 25-year running mean to the ring-width data. This 25-year running mean made the value of each ring-width measurement the average of the preceding 12 years, and of the succeeding 12 years (Nishimura, 2009). In this research, the non-host species used were eastern hemlock (*Tsuga Canadensis* (L.) Carrière) and sugar maple (*Acer saccharum* Marshall), both originating from Cape Breton (Fig. 1).

The individual crossdated host samples were compiled into a single file of spruce samples and a single file of balsam fir samples for OUTBREAK analysis. Compilation was done prior to comparison to the non-host chronologies in order to provide a more comprehensive

Island-wide representation of outbreaks by reducing any localized radial-growth variation between sites (Blais, 1962). Standardization using the same parameters as with the non-host species was conducted in program ARSTAN on the compiled spruce and fir chronologies to create regional master chronologies of each species in order to facilitate statistical comparison with climate data (Cook, 1985).

Program OUTBREAK was then used to locate the timing of outbreak events for both the traditional and the running-mean method through identification of areas in the ring-width sequences which have experienced growth depressions due to spruce budworm defoliation (Holmes and Swetnam, 1996). An outbreak was defined as a period where growth reduction lasts at least 5 years and is characterized by 8-12 years of reduced growth followed by 8-12 years of increased growth (Swetnam et al., 1985, Swetnam et al., 1995). The output of program OUTBREAK details the number of individual trees affected by budworm and the relative frequency of trees affected by budworm for each year of growth for the compiled samples. Note that defoliation does not cause immediate growth reductions in balsam fir and spruce, as there is a lag of 2-4 years before suppression is usually seen in the ring pattern (Blais, 1962).

Although both types of OUTBREAK analyses were run over the entire 20th century, the focus of this research centered on the most recent severe outbreaks in Cape Breton from 1960-1963 and from 1974-1983 due to potential sample depth limitations. Results of the OUTBREAK analysis for both methods were compared to the known dates of the most recent outbreaks to allow evaluation of the accuracy of both methods in determining severe outbreak occurrences. Based on a two-level defoliation scale used by the Nova Scotia Department of Lands and Forests (1977), a three-level defoliation scale used by Krause (2003), and a five-level defoliation scale used by the Quebec Department of Natural Resources (Gray, 2000), a four-level scale was developed in this study to rank the intensity of each detected outbreak event based on the relative frequency of trees affected. Spruce budworm populations were considered to be at endemic levels when the relative frequency of trees affected was 25% or below. Detection of a weak outbreak was delineated where 26-50% of the trees on the Island detected signs of budworm, a moderate outbreak from 51-75%, and a severe outbreak from 76-100%. This is comparable to other studies, such as Dumaresq (2011), who considered a relative frequency of <50% trees affected to constitute an outbreak event and Robert et al. (2012) who considered a frequency of <25% of trees affected to constitute an outbreak.

Radial growth and spruce budworm outbreaks are both related to climatic events (Fritts, 1976; Gray et al., 2004; Gray, 2008), and in Eastern Canada, this means relationships to the ocean-atmosphere driven climatic variations of the Atlantic Ocean (Phillips, 2009). We selected the Atlantic Multidecadal Oscillation (AMO) Index as a proxy for this type of cyclical variation affecting the forests of Eastern Canada. The AMO Index consists of monthly smoothed sea surface temperature (SST) values spanning from 1856 to present and cycles between negative cool phases and positive warm phases over a 65-80 year period (Kerr, 2000; Enfield et al., 2001). The values were retrieved from online sources of the Physical Sciences Division of the Earth System Research Laboratory (ESRL) of the National Oceanic and Atmospheric Administration

(NOAA). Smoothed monthly AMO Index values were averaged for each year and plotted against the standardized regional master chronologies of the host and non-host species, as well as against the date ranges of historically documented outbreaks found in the Nova Scotia Department of Lands and Forests (1977) spruce budworm report. A two-tailed Pearson product-moment correlation coefficient (r-value) was calculated to quantify the relationship between radial-tree growth and differently lagged AMO values (*c.f.* Phillips, 2009). The correlation between the AMO Index and radial growth was tested from a 1-year lag to a 10-year lag in order to find the strongest relationship between radial growth and climate.

Results

Samples were crossdated both visually and using the computer software program COFECHA. All chronologies, at each site, were found to correlate above the 99% significance level (ranging from 0.425 to 0.562) (Table 2). The compiled spruce cores correlated at 0.404 and the compiled fir cores correlated to 0.345, again above the 99% confidence interval (Table 2) (Holmes, 1983). The final Island-wide sample depth for the outbreak analysis contains a total of 206 spruce cores and 212 fir cores (Table 2). The eastern hemlock non-host chronology contained 38 samples and crossdated with a mean series correlation of 0.643, well above the 99% level (Table 2). The sugar maple non-host chronology contained 46 samples and also crossdated above the 99% significance level with a correlation of 0.375. All correlation values were assigned based on overlapping 50-year segments (Table 2).

Table 2 – Sample statistics describing chronology length, time span of chronology, sample depth, and correlation (correlation values above 0.3281 are significant at the 99% confidence interval based on overlapping 50-year segments; Holmes, 1983).

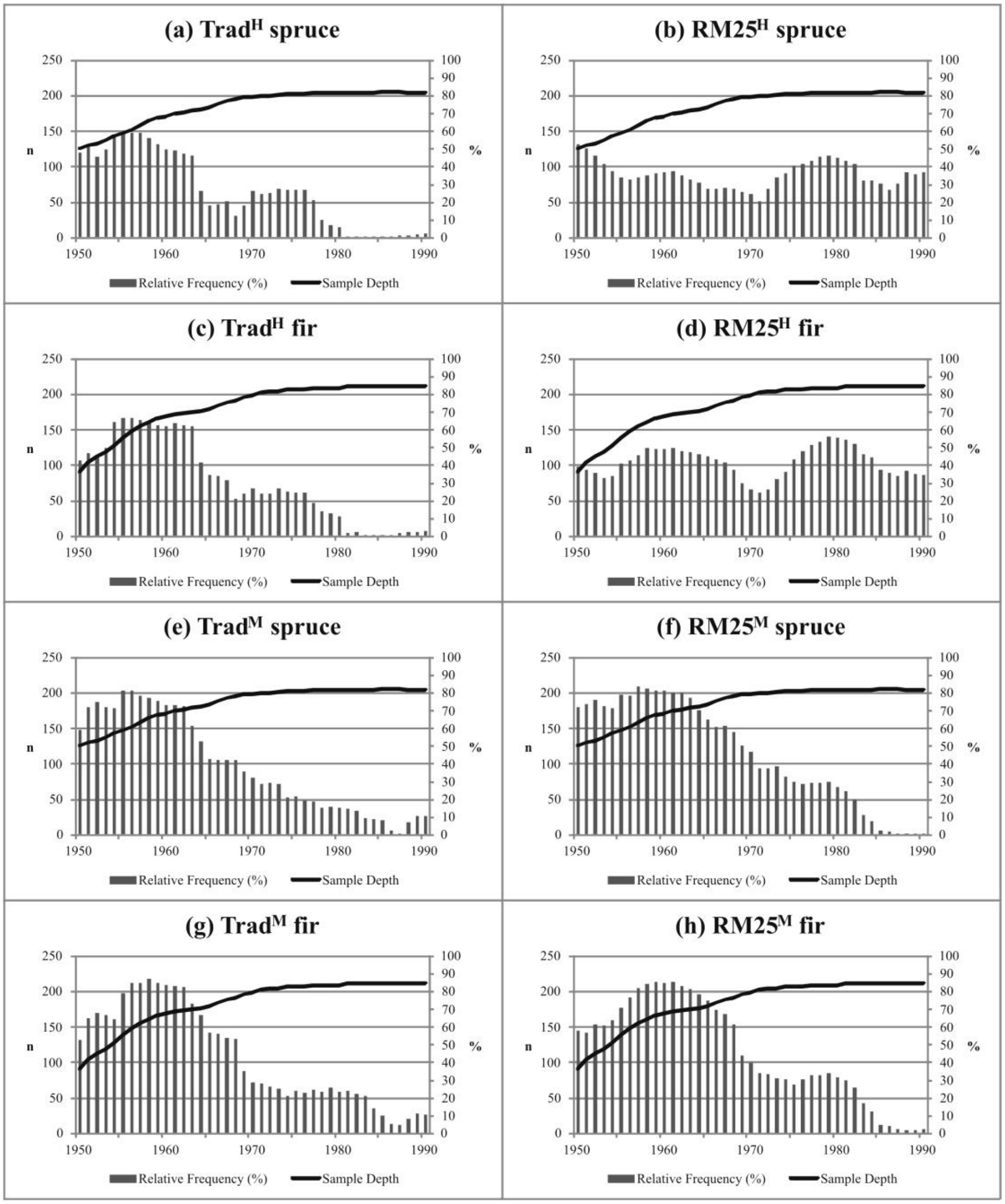
Site Identification Code	Species[a]	Mean Correlation to the Master Chronology	Length of Chronology (Years)	Time Span of Chronology	Number of Cores
11TL200	WS	0.492	98	1913-2010	40
11TL300	BF	0.432	91	1920-2010	38
11UL100	BS	0.562	121	1890-2010	40
11UL300	BF	0.444	68	1943-2010	40
11VL200	WS	0.490	120	1891-2010	40
11VL300	BF	0.460	92	1919-2010	38
11WL900	RS	0.444	110	1901-2010	46
11WL300	BF	0.423	72	1939-2010	38
05AYL100	BS	0.538	106	1899-2004	40
05AYL300	BF	0.449	78	1927-2010	58
Compiled Spruce	S	0.404	121	1890-2010	206
Compiled Fir	BF	0.345	92	1919-2010	212
07AHL800	EH	0.643	348	1692-2006	38
09ASLE00, 09ATLE00, 09FLE00	SM	0.375	249	1761-2009	46

[a] BF = Balsam fir, BS = Black spruce, RS = Red spruce, WS = White spruce, S = Compiled spruce, EH = Eastern hemlock, SM = Sugar maple

Analysis of tree-ring data using the traditional method and the running-mean method is displayed in Fig. 2 for the most highly replicated period from 1950-1990. There is evidence of a moderately severe outbreak in the early 1960s as detected by both the running-mean method and the traditional method (Fig. 2). When eastern hemlock is used as a non-host species, 46-64% of the trees were affected by spruce budworm when using the traditional method, and a lower 15-38% of the trees were affected when using the running-mean method over the length of the 1960s outbreak (Fig. 2a-d). Sugar maple depicts increased severity for the 1960s event compared to the eastern hemlock non-host chronology, with the traditional method identifying a range of 61-84% of the trees affected, and a higher 70-85% of the trees affected during this same time span (Fig. 2e-h). Based on historical records of this outbreak, the severity of this event was accurately detected by both methods (NSDLF, 1977).

A distinct difference between the results of the traditional and of the running-mean method is depicted during the 1974 to 1983 severe outbreak event (Fig. 2; Table 3). The results of the traditional method using eastern hemlock as a non-host species illustrates that endemic to weak infestations were detected in the ring-width data for both the spruce and balsam fir during the most severe outbreak known (1-27 %) (Table 3). The intensity of the detected outbreak is increased when the running-mean method is applied, indicating a weak outbreak in fir (32-47%)

and a severe outbreak in spruce (64-84%) (Table 3). When sugar maple is used as a non-host species using the traditional method, the detection signal only illustrates weak endemic levels of spruce budworm activity (10-26%). Again, when a 25-year running mean is applied to the sugar maple master chronology and run against the spruce and fir samples, a higher level of outbreak signal emerges (11-34%) (Table 3).


(a) Trad^{H} spruce

(b) RM25^{H} spruce

(c) Trad^{H} fir

(d) RM25^{H} fir

(e) Trad^{M} spruce

(f) RM25^{M} spruce

(g) Trad^{M} fir

(h) RM25^{M} fir

Fig. 2 – The graphs illustrate the sample depth and number of affected trees for a) spruce using the traditional method with eastern hemlock as the non-host, b) spruce using the running-mean method with eastern hemlock as the non-host, c) balsam fir using the traditional method with eastern hemlock as the non-host, d) balsam fir using the running-mean method with eastern

hemlock as the non-host, e) spruce using the traditional method with sugar maple as the non-host, f) spruce using the running-mean method with sugar maple as the non-host, g) balsam fir using the traditional method with sugar maple as the non-host, and h) balsam fir using the running-mean method and sugar maple as the non-host.

Table 3 – Results of the OUTBREAK analysis comparing the results of the traditional and running-mean methods to the most severe outbreak event in Cape Breton history from 1974-1982. The percentage of affected trees is shown for each year with shading indicating the severity of the outbreak based on the percentage of affected trees. White = endemic levels (0-25%), light gray = weak outbreak (26-50%), medium gray = moderate outbreak (51-75%), dark gray = severe outbreak (76-100%).

Method	**1974**	**1975**	**1976**	**1977**	**1978**	**1979**	**1980**	**1981**	**1982**	**1983**
Trad^{H} Fir	26	25	25	19	14	13	11	2	2	1
Trad^{H} Spruce	27	27	27	21	10	7	6	1	1	1
RM25^{H} Fir	36	40	42	44	46	47	45	43	41	32
RM25^{H} Spruce	64	75	81	83	84	84	82	81	80	74
Trad^{M} Fir	21	24	23	25	23	26	23	24	22	21
Trad^{M} Spruce	21	22	20	19	16	16	16	15	14	10
RM25^{M} Fir	31	28	31	33	33	34	32	30	26	17
RM25^{M} Spruce	33	30	29	29	29	30	27	25	20	11

Radial-tree growth was found to be significantly correlated to lagged variations in the AMO Index in all sampled species when a two-tailed Pearson product-moment correlation coefficient (r-value) was calculated for lagged AMO Index values. R-values were determined for the balsam fir regional master chronology for the period from 1919-1990 and from 1900-1990 for the spruce, eastern hemlock, and sugar maple regional master chronologies. Balsam fir was found to be significantly correlated only to a 6-year lag of the AMO (r-value = 0.275; p = 0.02) while spruce, eastern hemlock, and sugar maple were found to be significantly correlated to the AMO at all 10 tested lags. At a 6-year lag of the AMO, correlation coefficients were significant for spruce (r-value = 0.565; p = 0.01), eastern hemlock (r-value = 0.736; p = 0.01), and for sugar maple (r-value = 0.514; p = 0.01). The relationship between radial-tree growth and the AMO Index lagged 6 years is illustrated in Fig. 3. Note that the balsam fir sample depth is less than 30 cores prior to 1936 and spruce sample depth is less than 30 cores prior to 1913.

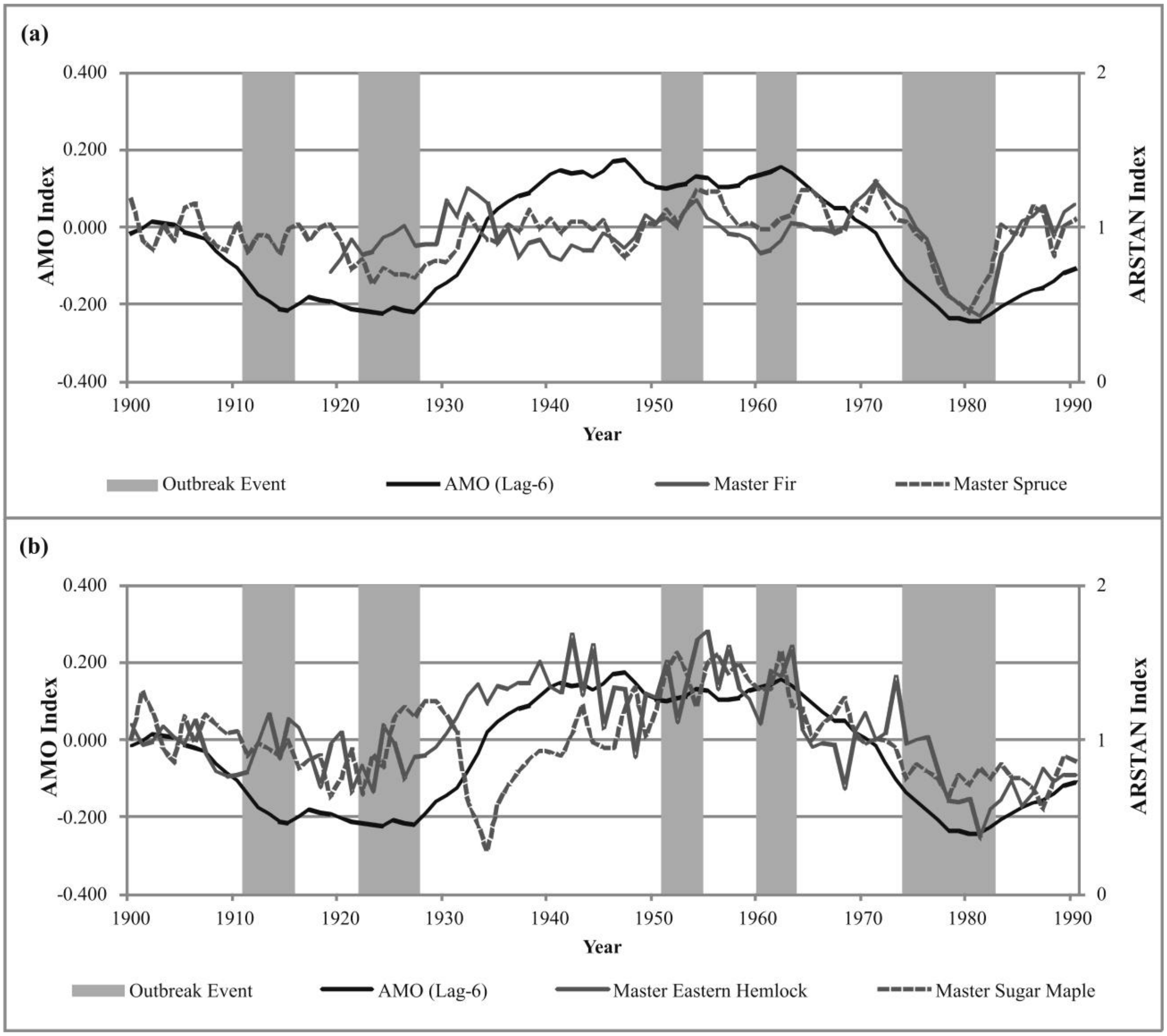


Figure 3 – The AMO Index from 1900-1990 with a 6-year lag applied plotted against a) the standardized index of the regional spruce master chronology and the standardized index of the regional fir master chronology, and; b) the standardized index of the regional eastern hemlock master chronology and the standardized index of the regional sugar maple master chronology. Vertical bars represent the historically documented outbreak events from 1900-1990 in Cape Breton.

Historical spruce budworm outbreak events for the 91-year period from 1900-1990 occur during relatively cooler phases of the AMO (Fig. 4). Each recorded outbreak event was preceded by several years of a negative phase of the AMO SSTs which tended to extend into the early years of the outbreak. This trend is seen strongly in the 1911-1915, 1922-1927, and 1974-1983 outbreak events, and more weakly in the 1951-1956 and 1960-1963 events. During the 20th century, values of the AMO Index only drop below -0.200 on three occasions and in each case a sustained outbreak event follows. The most severe 1974 to 1983 outbreak was characterized by the lowest recorded AMO values ranging from -0.209 to -0.245. The 1951 to 1956 and 1960 to 1963 outbreaks occurred during a positive warm phase of the AMO, but were still characterized by a drop in SSTs prior to and during the early outbreak events compared to surrounding values.

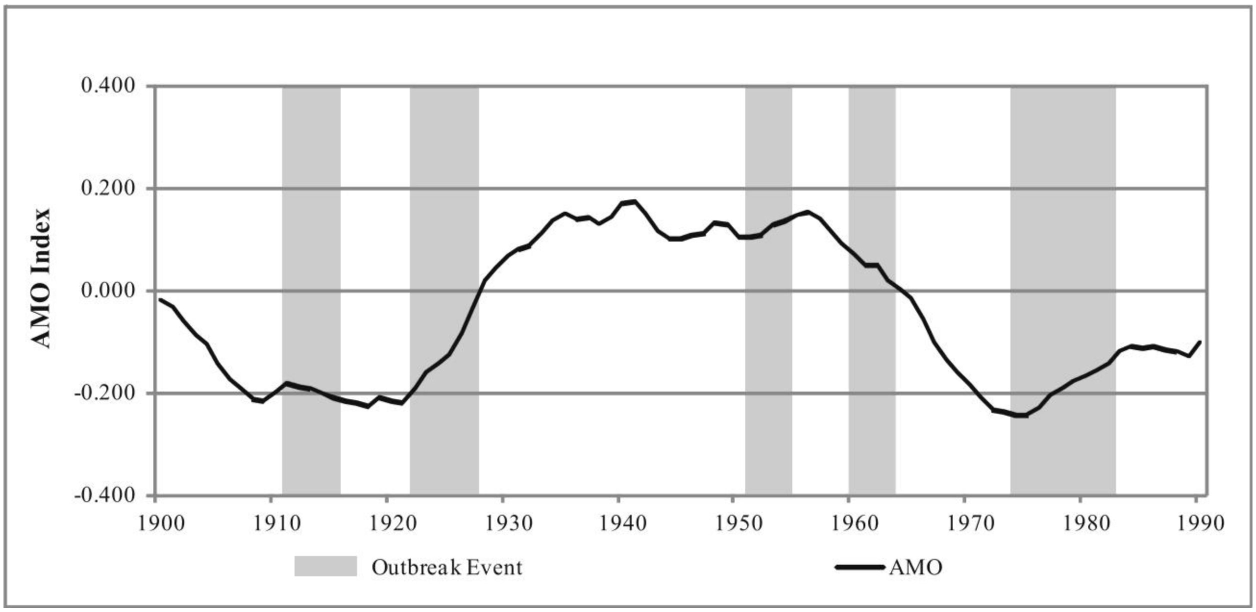


Figure 4 – The non-lagged AMO Index from 1900-1990 plotted against historically documented Island-wide outbreak events.

Discussion

The comparison of the results of the two methods provides some interesting insights. The analysis illustrated that the traditional method is very good at detecting outbreaks of weak and medium severity (Fig. 2), but did not detect the most severe event of the 1974-1983 outbreak (Fig. 2, Table 3). Conversely, the running-mean method did a poorer job of defining weak and medium severity outbreaks (Fig. 2), but it did highlight an outbreak during the most intense period of known spruce budworm infestation in Cape Breton’s history (Fig. 2, Table 3). There was also a marked increase in outbreak detection accuracy between host species, with the spruce chronology better at defining events than the fir chronology. This may be because balsam fir trees younger than 30 years old are less vulnerable and less damaged by spruce budworm outbreaks (Table 1) (Blais, 1962; Blais, 1983; Morin, 1994), but perhaps more importantly it may be due to the food preference hierarchy of the budworm where many of the older fir died during the severe 1974-1982 event.

The differing accuracy of the traditional method and the running-mean method may be explained by the influence of regional climatic conditions on the non-host species – the same climatic conditions influencing the occurrence of severe spruce budworm outbreaks (Fig. 3, Fig. 4). Eastern hemlock and sugar maple identified outbreaks of differing severity, with eastern hemlock reporting higher intensity outbreaks than sugar maple (Fig. 2, Table 3). During the severe 1974-1983 spruce budworm outbreak, the non-host trees demonstrated growth reductions tied significantly to a negative phase of the AMO, suggesting a reduction in their ability to identify outbreaks using the traditional method (Fig. 3). Application of the 25-year running mean to the non-host regional master chronologies served to increase the detection accuracy through a reduction of the non-host climatic response to the negative phase of the AMO (Fig.2, Table 3).

We hypothesize that climate, spruce budworm, and tree growth are interlinked to such a degree that detection of spruce budworm outbreak events depends on consideration of all three factors. Both radial-tree growth and spruce budworm outbreaks display a relationship with AMO SSTs (Fig.3, Fig. 4). The radial growth of host and non-host species were found to be significantly correlated to AMO variations on a 6-year lag with the strongest correlations calculated for spruce, eastern hemlock, then sugar maple respectively (Fig. 3). Spruce budworm outbreaks also appeared to be linked to AMO variations, as values below -0.200 were always followed by large-scale outbreaks (Fig. 4). This emphasizes the importance of climate in accurate detection of spruce budworm outbreaks.

If climate influences both the occurrence of severe outbreaks and the radial growth of all host and non-host trees, then there is a threshold past which the non-host will be experiencing fundamental changes in their radial growth in response to the extreme climate during the outbreak period (Fig. 3). Once this threshold is exceeded, a breakdown in the accuracy of the traditional method can occur because the basic tenet that deviations in radial growth are driven by the budworm breaks down (Table 3). In the case of the severe 1974-1983 outbreak, such a climate threshold was reached, resulting in low to no detection of the severity of the outbreak when using the traditional method. In contrast, the severity of the 1960 to 1963 outbreak agreed with historical observations when the traditional method was used, probably because it happened during a warm phase of the AMO where the non-host species had not crossed its climatic threshold.

A correction to this breakdown is restored through the different methodological procedures of the running-mean method on the non-host species. The running mean applied to the non-host chronologies dampens the effect of the non-host response to extreme climate and in doing so, increases the differential between host and non-host signals which increases the percentage of detection of past outbreaks. To protect against this type of threshold error, we propose that the running-mean method be used in conjunction with the traditional method when conducting historical analyses of outbreak events. This procedural change would help to pinpoint periods of time when climate may have been more strongly influencing both the growth of the non-host species, as well as making conditions ideal for severe insect outbreaks. The end result will be that the two combined methods will test for a wider range of events and better represent past budworm infestations. In addition, comparison of periods of low AMO SST variations to OUTBREAK results for the Atlantic Canada region would serve to pinpoint areas where outbreaks may have occurred but were not previously detected.

Knowledge of past outbreaks gained through analysis of centuries-old tree samples will increase the predictive power of models projecting forest change. This accentuates the importance of accurate detection methods. The strong relationship between climate and spruce budworm outbreaks seen in AMO fluctuations in Atlantic Canada may also assist in increasing the predictive power of future models. The results of this methodological comparison emphasize the importance of caution in the interpretation of past outbreaks events, particularly when no historical record is available (Swetnam et al., 1985).

Conclusion

The application of the running-mean method to the non-host species chronologies during OUTBREAK analyses can improve the predictive power of the detection model. Weak and endemic levels of outbreak were detected during a well-documented outbreak of high severity using the traditional method while the running-mean method detected higher and more accurate severity levels. Limited results indicate this breakdown in detection may result from crossing a climatic threshold beyond which the traditional method is no longer accurate. In the Maritimes, this climate threshold may be linked to variations in the AMO Index, as values less than -0.200 appear to be linked to severe outbreaks. Reduction of this climate response through the use of the running-mean method has been shown to improve the accuracy of spruce budworm outbreak event detection and will prove valuable in re-assessing past outbreak history and informing future forest management decisions. Consideration of the significant influence of the AMO on radial growth will prove important both in re-assessing past outbreaks and in future forest modelling. The implications of the breakdown in the traditional method should lead to the re-evaluation of past work reconstructing outbreak events based on local annual ocean-atmosphere variations. This will be of importance to forestry management, as when climate thresholds are reached and severe outbreaks go undetected, a valuable source of information about past outbreaks is lost.

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