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Spatial extent of winter thaw events in eastern North America: historical weather records in relation to yellow birch decline

CHARLES P.-A. BOURQUE*, ROGER M. COX†, DARREN J. ALLEN‡, PAUL A. ARP* and FAN-RUI MENG*

*Faculty of Forestry and Environmental Management, University of New Brunswick, P.O. Box 44555, Fredericton, NB, Canada E3C 6C2, †Natural Resources Canada, Canadian Forest Service – Atlantic Forestry Centre, P.O. Box 4000, Fredericton, NB, Canada E3B 5P7, ‡Natural Resources Canada, Canadian Forest Service – Great Lakes Forestry Centre, 1219 Queen Street E., Sault Ste. Marie, ON, Canada P6A 2E5

Abstract

An algorithm (*Weather Reader*) was developed and used to analyze daily weather records from all existing Canadian and American weather stations of eastern North America (in excess of 2100 stations), from 1930 through 2000. Specifically, the Weather Reader was used to compile daily minimum, mean, and maximum air temperatures for weather stations with at least 30 years of data, and was used to calculate accumulated degree days for winter thaw–freeze events relevant to yellow birch (*Betula alleghaniensis* Britt.) from beginning to end. A thaw–freeze event relevant to yellow birch was considered to take place when (i) the station daily maximum temperature reached or exceeded $+4\,^{\circ}$C after being below freezing for at least 2 months of the winter, (ii) sufficient growing degree days accumulated (>50 growing degree days) to cause the affected yellow birch trees to prematurely deharden, and (iii) the daily minimum temperature dropped below $-4\,^{\circ}$C causing roots and/or shoots of dehardened trees to experience freeze-induced injury and possibly dieback. The threshold temperature of $+4\,^{\circ}$C represents the daily temperature above which biological activity occurs in yellow birch. The station growing degree day summaries were subsequently spatially interpolated with the Kriging function in GS+™ and mapped in ArcView™ GIS in order to display the geographic extent of the most severe thaw–freeze events. The ArcView™ maps were then compared with the extent of historically observed yellow birch decline. It was found that the years 1936, 1944, and 1945 were particularly uncharacteristic in terms of region-wide winter thaw–freeze extremes, and also in terms of observed birch decline events during 1930–1960. An overlay of suspected accumulated birch decline based on thaw–freeze mapping and observed decline maps prepared by Braathe (1995), Auclair (1987), and Auclair *et al.* (1997) for 1930–1960 demonstrated similar geographic patterns. The thaw–freeze projection for 1930–1960 was shown to coincide with 83% of the birch decline map appearing in Braathe (1995) and 55% of the geographic range of yellow birch in eastern North America. Thaw–freeze mapping was also applied to two significant events in 1981. Greatest impact was recorded to occur mostly in southern Quebec and Ontario, and several American Great Lake States, specifically in northern Michigan and New York, where the greatest growing degree day accumulation prior to refreeze in late February (February 28th) was projected to have occurred; and in southern Quebec, most of Atlantic Canada, and Maine, prior to a late spring frost in mid-April (April 17).

Keywords: base temperature, climate change, computer programming, degree-day accumulation, geographic information systems (GIS), geo-statistics

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Correspondence: Roger M. Cox, tel. + 1506 452 3532, fax + 1506 452 3525, e-mail: rcox@NRCan.gc.ca

Introduction

Dieback of yellow birch (*Betula alleghaniensis* Britt.) and paper birch (*B. papyrifera* Marsh.) trees has been a major problem in eastern North America (Balch, 1944; Sinclair, 1952; Pomerleau, 1953; Walker *et al.*, 1990; Pomerleau, 1991; Ward & Stephens, 1997). Widespread decline of birch, exhibited as branch dieback and mortality, was first recorded during the 1930s in central and southern New Brunswick (NB), Canada. Since then, severe birch dieback has been noted from the Maritime region (Pomerleau, 1953) to eastern Ontario (ON) (Sinclair, 1952; Walker *et al.*, 1990). Birch decline has lead to a 19% loss of the $368 \times 10^6\,m^3$ growing stock of yellow birch in North America (Ward & Stephens, 1997). The estimated value of timber volume loss during the 1935–1955 period was $\$60 \times 10^9$ (current value CND funds) as of 1987 (LRTAP 1986).

Prolonged winter thaws followed by sharp freezing have been recognized as an important mechanism to incite shoot dieback in northern hardwood species (Auclair, 1987; Pomerleau, 1991; Auclair *et al.*, 1992; Auclair *et al.*, 1996; Auclair *et al.*, 1997). For example, soil freezing (Hepting, 1971), winter root thaw–freeze events, and late spring frosts (Braathe, 1957; Braathe, 1995; Auclair *et al.*, 1996; Cox & Malcolm, 1997; Zhu *et al.*, 2000; Zhu, 2001; Zhu *et al.*, 2001; Zhu *et al.*, 2002) have all been found to be inciting factors for dieback in yellow and paper birch. Accumulated effects of winter cavitation (i.e., winter-induced xylem embolism in *B. cordifolia* Regel (Sperry, 1993), *B. occidentalis* Hook (Sperry *et al.*, 1994) and *B. alleghaniensis* (Zhu *et al.*, 2000; Zhu *et al.*, 2001; Zhu *et al.*, 2002) have also been considered to be a factor in birch dieback because of potential disruption of water transport in affected trees. A field investigation of *Fagus grandifolia* Ehrh. demonstrated that residual winter cavitation causes considerable crown dieback (Sperry, 1993).

Winter thaw–freeze cycles have been connected to decreased xylem conductivity because of winter cavitation. For example, potted white and yellow birch subjected to experimentally induced winter thaws showed correlations between branch dieback, reduced xylem conductivity, residual xylem embolism, and thaw durations (Braathe, 1995; Braathe, 1996; Cox & Malcolm, 1997; Zhu *et al.*, 2000; Zhu *et al.*, 2001; Cox & Zhu, 2003). When xylem sap freezes, dissolved air forms bubbles in the ice. In turn, these bubbles may nucleate cavitation as negative pressure develops in vessels during thawing (Hammel, 1967; Sperry & Sullivan, 1992; Langan *et al.*, 1997; Robson *et al.*, 1998). Once the air bubbles grow large enough and disrupt the cohesion of water (cavitation), the water column retreats, and vessels become air filled, or embolized (Tyree & Dixon, 1986; Sperry *et al.*, 1988; Jarbeau *et al.*, 1995).

The shallow root systems of birch are likely susceptible to thaw–freeze-induced injuries (Pomerleau, 1991). Such injuries are particularly frequent when snow cover is temporarily lost as a result of extended thaws. The resulting damage by re-freezing of dehardened roots was shown to lead to weak root pressure development during the following spring, which in turn, led to increased dieback (Cox & Malcolm, 1997; Zhu *et al.*, 2000). Critical temperatures for biological processes in trees are temperatures $>4\,^{\circ}C$, which is a common base temperature used to calculate degree days in studies of tree phenology (Braathe, 1995). For freeze-induced injuries following a significant thaw (accumulating more than 40–50 growing degree days; GDDs), $-4\,^{\circ}C$ was chosen as a freezing threshold that corresponded to the air temperature below which the root soil plug froze. This freezing was shown to reduce root and shoot metabolism (triphenyltetrazolium reduction, TTC) after a 6-day thaw ($>4\,^{\circ}C$), compared with the unthawed yellow birch roots (Zhu *et al.*, 2002).

Freezing injury to shoots has been reported to impede the springtime xylem refilling in woody plants (Ameglio *et al.*, 2001) because freezing injuries to parenchyma cells in the xylem of young twigs lead to irreversible damage (George & Burke, 1986). Cold hardiness of yellow birch has been found to be just sufficient to prevent freezing injuries at normal winter temperatures in the Maritime Provinces (Calme *et al.*, 1994). Any significant reduction in cold hardiness because of increased thaw duration, may render yellow birch twigs susceptible to freezing injuries. Mid-winter thaws are common in eastern Canada (Canavan, 1996).

In NB, extensive xylem cavitation was documented in birch with crown dieback (Greenidge, 1951); this, however, was not attributed to winter thaw–freeze cycles at first. Sperry *et al.* (1994) determined that, in the two diffuse porous species, more than 90% of vessels have cavitated by the end of the winter. Auclair (1993) noted that (i) the long interval between winter embolism formation and the development of symptoms, and (ii) the high variation in spring refill makes it difficult to recognize the cause of dieback.

Birch decline has also been noted as a problem in the Ore Mountains in Europe and has been related to prolonged March thawing events in 1997 (Sramek *et al.*, 2001). Zimmerman *et al.* (2002) had also recorded prolonged thaw events in the region during the winter of 1995–1996, which preceded a forest decline of conifers as well as broad-leaved trees (mainly birch) within spruce stands covering over 50 000 ha in the central Ore Mountains and 30 000 ha in the Bohemian portion of the mountain range. Also noted was the fact that the mountains also experienced elevated levels of air pollutants, which may have predisposed the trees to the effects of winter condition by reducing winter hardiness.

Selldén *et al*. (1997) have also reported on birch dieback in Fennoscandia with specific reference to the decline in crown density in birch from 1993 to 1994 in Norway. In Sweden by 1993, 29.2% of the birch monitored throughout the country had 'defoliation' $>25\%$.

Signs of repeated birch dieback and distorted growth have been recorded among plants from 37 seed sources used for reforestation in oceanic Scotland. Investigations by Starti *et al*. (2003) indicated significant differences among seed sources in the timing of spring root pressure development and flushing, a trait important in maintaining frost hardiness of local populations during spring thaw–freeze cycles. This confirms not only the importance of using locally adapted birch populations in reforestation projects, but maintaining useful variation in such traits for potential genetic adaptation to future changes in climate.

Since 1750, atmospheric CO_2 concentration, as shown in the air trapped in ice cores from Siple Station, Antarctica, has increased by $31 \pm 4\%$ (IPPC, 1990). Continued increases are expected to cause climate shifts that may lead to more frequent winter thaw–freeze cycles with longer thaw durations (Wigley, 1985). The rates of these climatic changes may exceed the adaptive limits of some northern hardwood species.

Evidence suggests that mean global surface temperatures have increased by 0.6 °C (0.4–0.8 °C) during the last century, with a greater increase in winter than in summer (McElroy, 1994; IPCC, 2001). It already appears that the average number and severity of thaw–freeze events have increased since 1930: Fig. 1 illustrates yearly averages for historical climate data for stations in eastern Canada and the northeastern United States with a weather record >30 years. Although caution is required here, as the number of reporting weather stations has doubled from 1930 to the present; nevertheless, the number of defined thaws lasting longer than 4 days seems to exhibit an increasing trend (Fig. 1a; although not statistically significant, $\chi^2_{\text{calculated}} = 0.72$ with $\chi^2_{0.05,1} = 3.841$, $P > 0.25$ for comparison between the regression slope and the zero slope). Average maximum heat accumulations with GDDs (base temperature of 4 °C) of the most prominent thaw events also show an increase, 0.03 °C each year since 1930 (Fig. 1b; also not statistically significant; $\chi^2_{\text{calculated}} = 1.05$: $P \sim 0.35$). Thaws >4 days were taken as the conservative threshold for biological effects, as below this value negligible dehardening takes place as judged by root CT determination in yellow birch; CT is defined as the highest freezing temperature at which the initial freezing injury was detected in yellow birch (Zhu *et al*., 2002).

Yellow birch

Yellow birch is recognized as one of the most valuable of the native birches (Burns & Honkala, 1990). It is an important source of hardwood lumber and veneer and a good browse plant for deer and moose, and other wildlife feed on the buds and seeds. In the forest, it is easily recognized by its exfoliating bark with its distinct yellowish-bronze color. The inner bark is aromatic and has a flavor of wintergreen. Yellow birch is widespread across northeastern North America. The species grows over a large area with diverse geology, topography, and soil and moisture conditions (Gilbert, 1965; Post *et al*., 1969); its range is represented by the union of the light gray and dark gray shading in Fig. 2. Its northern limit coincides with the 2 °C average annual temperature isotherm, and its southern and western limits coincide with the 30 °C yearly maximum temperature isotherm (Dansereau & Pageau, 1966). Within its distribution, temperature extremes range from −40 °C to 38 °C. The growing season varies from 60 to 150 days, with an average of 120 days. Annual precipitation ranges from about 1270 mm in the east to 640 mm at its western-most limit.

In the south, yellow birch generally grows at high elevations, and is generally restricted to moist gorges above 910 m. The largest concentrations of timber-sized yellow birch are found in Quebec (QC), Ontario (ON), Maine (ME), Upper Michigan (MI), New York (NY), and NB (Quigley & Babcock, 1969). About 50% of the growing stock of yellow birch in North America is found in QC. Yellow birch is present in all stages of forest succession (Marks, 1974) and is seldom found in pure stands associated with hemlock [*Tsuga canadensis* L. (Carr.)], sugar maple (*Acer saccharum* Marsh.), beech (*Fagus grandifolia* Ehrh.), and red spruce (*Picea rubens* Sarg.) (Eyre, 1980). Associations with hemlock and red spruce are considered to be subclimax and climax types, respectively (Kujawski & Lemon, 1969).

The propensity for early phenology in yellow birch is of competitive advantage (Marks, 1975). This early leaf production is likely related to the ability to transport water and nutrients (xylem conductivity) to the developing foliage before producing new wood. Deciduous trees with diffuse-porous xylem, like birch, seem least affected by xylem embolisms caused by winter xylem cavitation, although the reported variation in specific xylem conductivity was large (Wang *et al*., 1992). Winter embolism in yellow birch has been reported as common, reducing xylem conductivity by 80–90% (Zhu *et al*., 2000; Cox & Zhu, 2003). However, the plant's ability to maintain its early foliar phenology rests with its ability

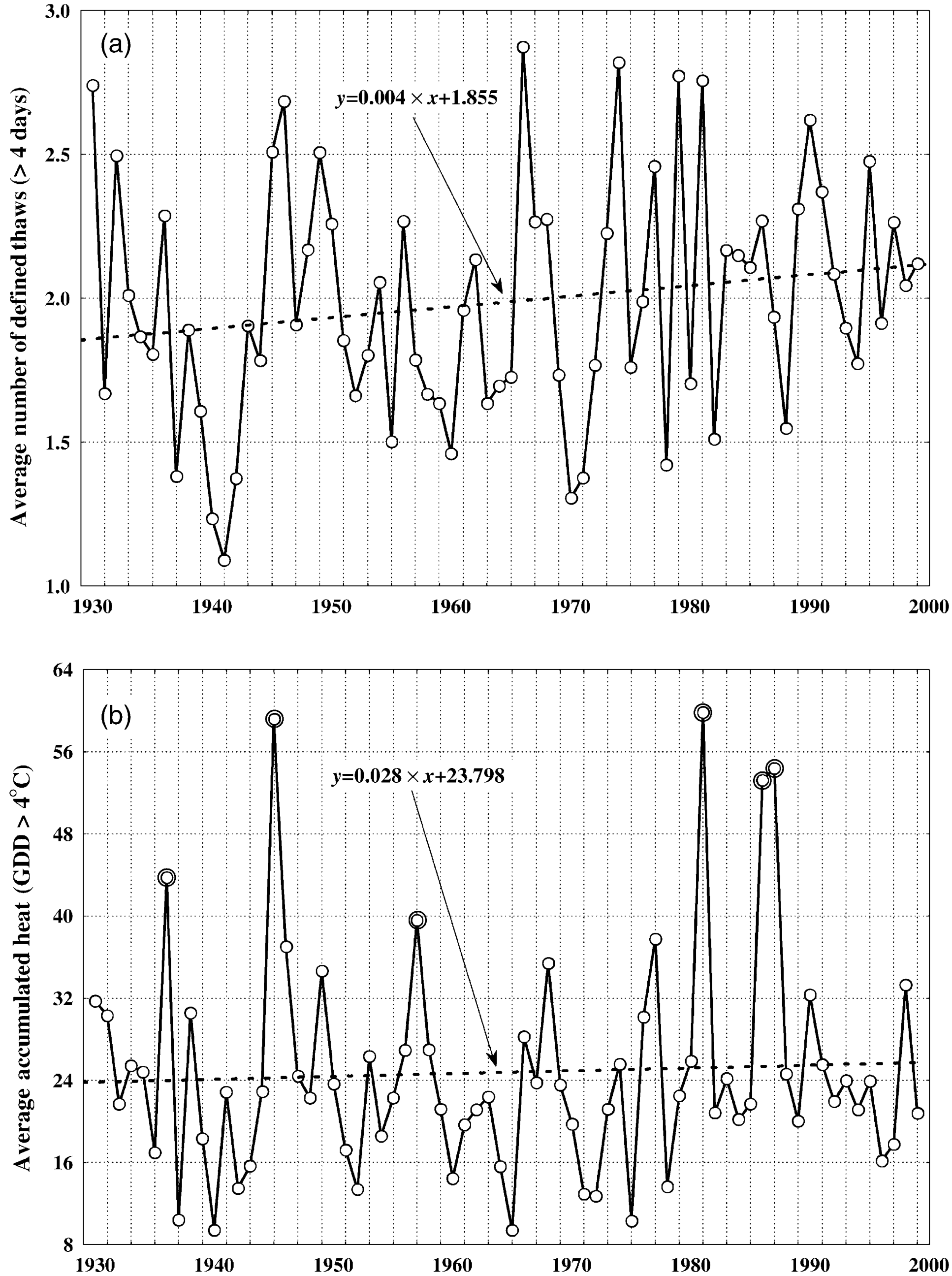

Fig. 1 Shows time series of (a) the average number of thaws >4 days in duration and (b) average maximum heat accumulation (growing degree days, with a base temperature of +4 °C) for the greatest thaw event, recorded at each station in a given year. The number of stations (n) contributing to the average varies per year (1936, $n = 219$ and 1981, $n = 424$). The dashed lines in (a) and (b) are trend lines fitted to the data. A few significant thaw events during 1930–2000 are identified with double-circle symbols in (b).

to refill its 'old' xylem using root pressure before bud break or cambial activity. This places emphasis on early root activity to obtain water as it becomes available from the previously frozen soil, making roots susceptible to freezing damage after their initial dehardening during prolonged winter and spring thaws, where the insolating snow cover has been removed. It is obvious that the success of this species is determined not only by the balance of potential gains from early leafing set against the danger of leaf damage because of late frosts (Lechowicz, 1984), but also by the risk of root damage caused by freezing of dehardened tissues which can occur following a prolonged winter thaw (Cox & Malcolm, 1997; Cox & Zhu, 2003).

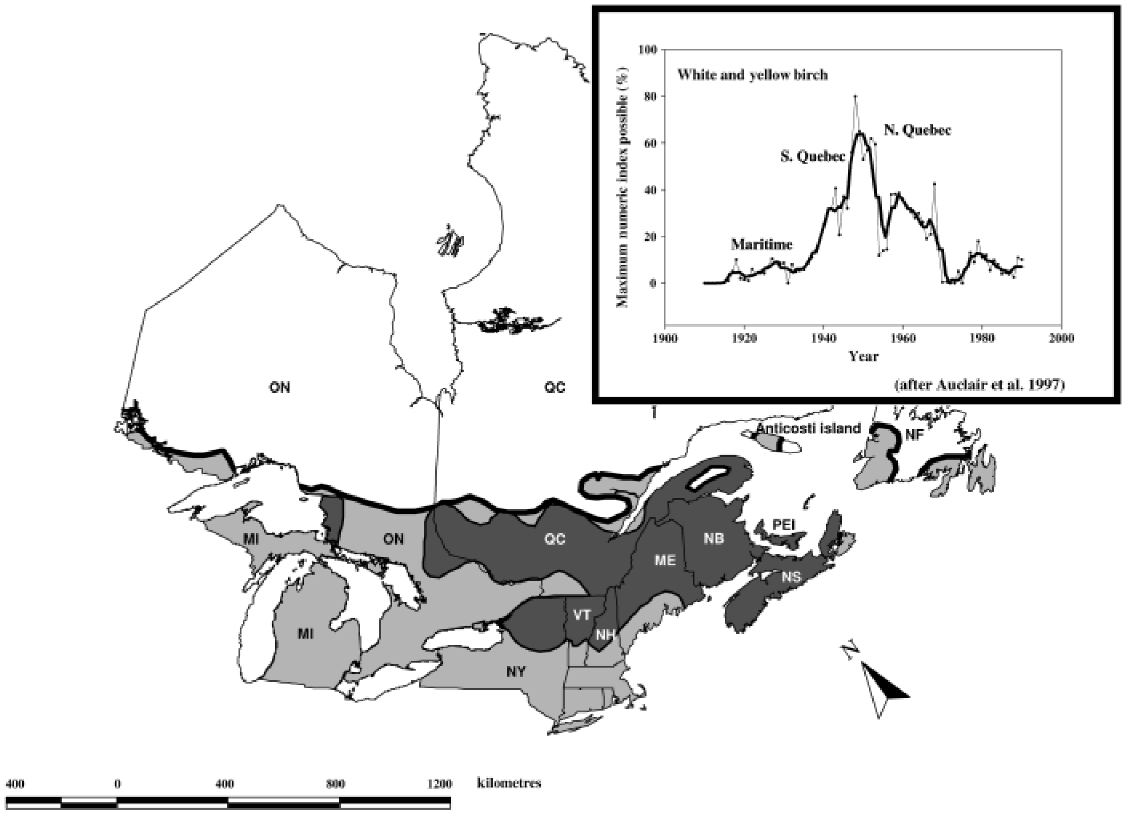

Fig. 2 The extent of the geographic range of yellow birch [light gray area with its northern and elevational limit (Gaspé Peninsula, QC, USA) represented by the heavy bold line], and the extent of documented accumulated birch dieback for the period 1930–1960 [overlay, dark gray area; after Braathe, 1995] in eastern Canada and northeastern United States. The inset provides a 'Numerical Index' of birch dieback as a % of maximum potential level for white and yellow birch in the Maritime Provinces and Quebec (after Auclair *et al.*, 1997); the solid line is a 5-year running mean of annual value. Province and State name abbreviations from east to west are: NF, Newfoundland; PEI, Prince Edward Island; NS, Nova Scotia; NB, New Brunswick; ME, Maine; NH, New Hampshire; VT, Vermont; QC, Quebec; NY, New York; ON, Ontario; MI, Michigan.

Historical birch dieback

Dieback on yellow birch in the 1930s and 1940s was impressive for its rapidity and severity when compared with that of any other eastern hardwood species (Sinclair *et al.*, 1987). The inset to Fig. 2 illustrates a generalized summary of a 'numerical index' of dieback (% of maximum potential level) in white and yellow birches in eastern Canada (Auclair *et al.*, 1997). This numerical index was derived as an aggregate of three attributes commonly reported in the literature and in forest-pathology survey reports (i.e., symptom code, intensity code, and cover-type code). Historical observations although hugely anecdotal, the work of Auclair *et al.* (1997) and others, provide valuable summary information on birch dieback intensity and occurrence.

Dieback in yellow birch was first observed between 1932 and 1935 in central and southern NB, and for brevity can be used as an example summary of the decline in the Maritime Provinces. There had been a greater than expected reduction in radial increment since 1925 (Hawboldt & Skolko, 1948; Balch, 1953). Ten percent of birches were reported dead or dying in 1938 and, by 1940, 25% mortality was reported in central and southern NB. At this time, no important damage was found in the northern part of the province (Balch, 1953). Fifty to 90% of birches were reported dead or dying in southern NB by 1943 and dieback had increased in northern NB (Balch & Hawboldt, 1943). The following year, 75% of birches were reported dead or dying in northern NB. The dieback was widespread in Cumberland and Colchester counties, and noticeable in Pictou County, NS (Balch, 1944, 1946).

In 1946, although 48–91% of birches were dead or dying throughout NB, there was some indication that the rate of dieback was decreasing. In NS, however, dieback on birch was heavy to severe in Colchester and Cumberland counties and negligible to moderate elsewhere (Balch, 1946). Dieback on yellow birch was common in 1944. By 1946, many stands reached an

Table 1 Original references to birch decline in Canada

Maritimes		Quebec		Ontario	
Years reported	Reference	Years reported	Reference	Years reported	Reference
1932–35	Hawboldt & Skolko (1948)				
		1936	Pomerleau (1953)		
1938–40	Balch (1953)				
		1939–44	Davidault (1953)	1944	Balch (1944)
1944–46	Balch (1944, 1946)	1946	Balch (1946)		
1947	Barter (1947)	1947	Davidault (1948)	1947–51	Sinclair & Hill (1953)
1948	Reeks (1948)	1948–51	Martineau (1953)	1948–52	Sinclair (1952)
1949–52	Barter & Balch (1950)	1950			
	Hawboldt & Greenidge (1952)				
	Nordin (1951)		Barter & Balch (1950)	1950–52	Bier (1953)
		1951–52	Stillwell (1954)		
		1953	Redmond (1955)		
		1954	Redmond (1957)		
		1956	Redmond (1958)		

advanced stage of dieback, becoming severe by 1947 (Balch, 1944, 1946; Barter, 1947). Light dieback was reported on Cape Breton Island, NS in 1947 (Barter, 1947). This dieback of yellow birch became progressively more severe in 1949 and 1950, but was less evident by 1952 (Barter & Balch, 1950; Hawboldt & Greenidge, 1952). Stands of white and yellow birch in Prince Edward Island also showed various stages of dieback by 1948 (Reeks, 1948). Lightly injured trees continued to show signs of improvement in NB, but injury was still moderate to severe in NS in 1947 (Barter, 1947). This recovery of birch continued from 1949 through 1952 (Barter & Balch, 1950; Nordin, 1951; Hawboldt & Greenidge, 1952). By 1950, an improvement of less severely injured trees was also reported in NS, continuing until 1952 (Barter & Balch, 1950; Nordin, 1951; Hawboldt & Greenidge, 1952). Trees in some localities in the Maritime Provinces were still reported suffering in 1954. There were no reports of yellow birch dieback in the Maritime Provinces from 1954 to 1960.

Similar information on the history of birch decline is available for QC and ON. The years of decline were reported and their references for the Maritime Provinces, QC, and ON are provided in Table 1. A recent and well-documented decline in 1981 in southern QC and part of Atlantic Canada was also included in this study.

The main diagram in Fig. 2 shows an overlay map of yellow birch distribution adapted from Auclair (1987) in Braathe (1995) and summarized by Braathe (1995), Auclair *et al*. (1997), and Allen (2003). The inset shows the observed accumulated dieback (maximum numerical index possible) for the 1930–1960 period for selected areas of northeastern North America (shown in dark gray). The details for the calculation of the numerical index are provided in Auclair *et al*. (1997).

Potential causal factors

Both biotic and abiotic factors have been suggested as causes for the decline of yellow birch. The bronze birch borer (*Agrilus anxius* Gory) was found to be associated with yellow birch dieback, but researchers concluded that the borers were not the primary cause, but only a factor contributing to the decline (Balch, 1938, 1940, 1944; Balch & Hawboldt, 1943; Hawboldt, 1947; Pomerleau, 1953). Organisms such as fungi, bacteria, and insects were found to be of insufficient virulence to initiate birch dieback (Bier, 1953). Therefore, like the bronze birch borer, they also require pre-existing weakness to invade yellow birch effectively, and to produce mortality in twigs and branches (Hawboldt, 1947; Hawboldt, 1952; Hansborough, 1953; Hill & Sinclair, 1954; Redmond, 1957). A direct causal relationship between a virus and birch dieback symptoms was never found (Hansborough, 1953). Climatic analysis showed no evidence of spatial or temporal pattern in the occurrence of water deficiencies to account for the geographic distribution of the observed dieback (Clark & Hare, 1953). Dieback symptoms were found in the crown when large proportions of the rootlets were killed (Pomerleau, 1953). Braathe (1957, 1995) suggested a correlation between birch dieback, the thaw of March 1936, and the late spring frosts in 1944 and 1945. Similarly, Benoit *et al*. (1982) suggested that an 'unusual' thaw in February and periods of severe cold in March 1981 following seasonal temperatures (Fig. 3) provoked a decline of yellow birch in southern QC.

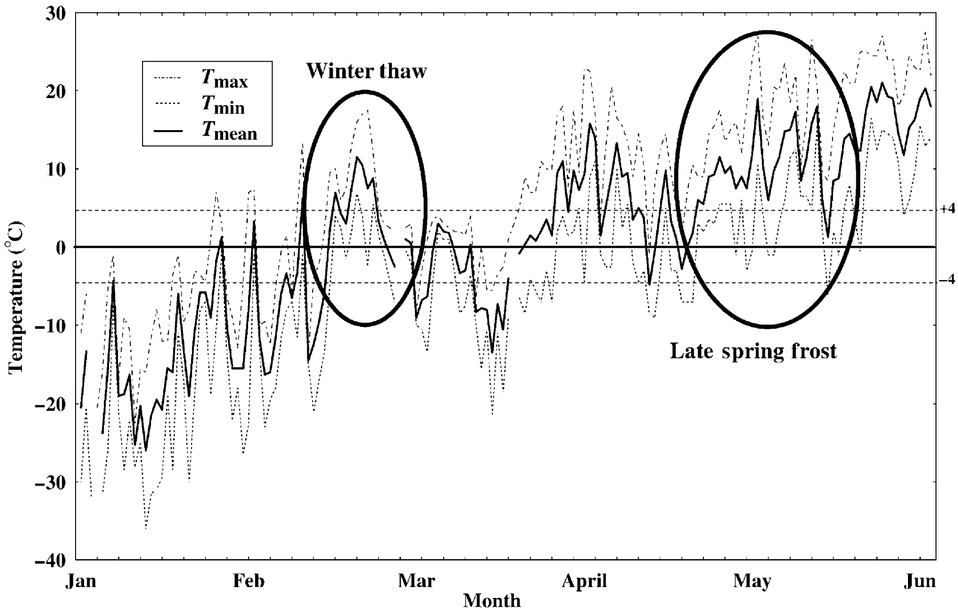

Fig. 3 Air temperature time series for Lennoxville, QC showing daily maximum (dashed line), mean (solid line), and minimum (dotted line) air temperatures for the winter and spring of 1981. A winter thaw and late spring frost event are identified. Thresholds of +4 °C and −4 °C were used to define biologically significant thaws, as winter temperatures <4 °C followed by refreezes >−4 °C have marginal effect on dehardening plant tissue (Cox & Malcolm, 1997; Zhu *et al*., 2002; Cox & Zhu, 2003).

Frost and drought have also been put forth as possible factors initiating dieback (Bier, 1953; Redmond, 1955; Magasi, 1984).

Objectives

The objective of this paper is to determine to what extent past birch decline events and specifically those of yellow birch, are related to extreme thaw–freeze events in northeastern North America. This will be done by comparing actual historical birch decline events, that include decline of yellow birch and paper birch (*Betula papyrifera*) (Braathe, 1995), with the extent of thaws predicted and mapped using known physiological-biophysical thresholds and past weather records. This was achieved by (1) summarizing historical records of birch dieback in eastern North America, and (2) using concurrent historical weather data to develop past patterns of damaging extreme thaw–freeze events since 1930. Several techniques to define, quantify, and spatially and temporally track biologically significant thaw events during the 1930–1960 birch decline period were developed. These techniques included (1) using historical weather records from 2100+ weather stations in northeastern North America and (2) using a geographic information system (in particular ArcView™ GIS) and geo-statistics (Kriging) to display the spatial extent of historical thaws and spring frost events. Thaw–freeze mapping was also applied to examine two significant events observed in 1981.

Methods

The daily weather data used in this study included daily minimum and maximum air temperatures (°C), all obtained from Environment Canada (Atlantic Climate Centre), and from the online National Climatic Data Center (USA). The daily mean temperature ($\bar{T}$) is obtained by taking the average of the minimum and maximum temperatures.

A definition of a thaw–freeze was developed and expressed as accumulated degree days during the thaw prior to a refreeze. A thaw that is considered to be biologically significant to yellow birch has certain attributes: snow removal (Braathe, 1957) and an estimated minimum growing degree day accumulation prior to a refreeze as recorded in the climate record prior to the decline (Braathe, 1995). A critical thaw was later refined through experimentation in terms of thaw duration (Cox & Malcolm, 1997) and temperature thresholds for various effects on physiological and biophysical processes (Zhu *et al*., 2000, 2001, 2002; Cox & Zhu, 2003). This biologically significant thaw may now be defined to start when the daily maximum temperature reaches +4 °C after being below freezing for their cold requirement. This threshold temperature (+4 °C)

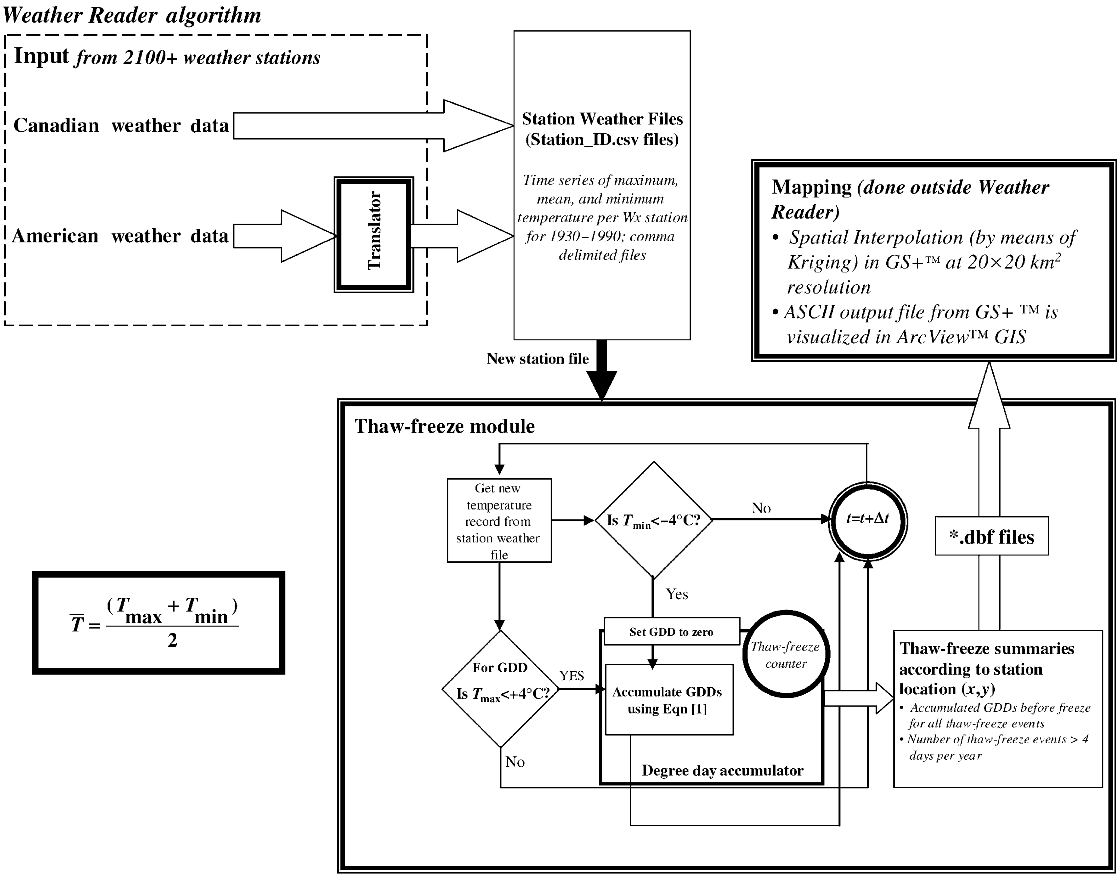

Fig. 4 Information flow, decision controls, thaw–freeze calculations (growing degree day), and summarizing functions in the Weather Reader algorithm. Variable 't' represents time and 'Δt' the daily time-step between weather records. '*.csv' files are comma delimited and '*.dbf' files are database files. Although more than 2100 stations are read in, only the stations with more than 30 years of weather records are retained in the thaw–freeze analysis. The translator shown in the diagram is used to convert the American data formats into Canadian formats. T_{max}, daily maximum temperature; T_{min}, daily minimum temperature; $\bar{T}$, daily mean temperature (all in °C); x, longitudinal position; y, latitudinal position; GS + ™, spatial interpolation software; ArcView™ GIS, geographic information system.

represents the point at which biological activity in yellow birch begins. Cumulative GDDs are calculated based on the daily mean temperature values above 4 °C (i.e.,

$$\text{GDDs} = \sum_{i=1}^{n} \left[(T^i_{\max} + T^i_{\min})/2 - 4 \right], \qquad (1)$$

where T_{max} and T_{min} are the maximum and minimum temperature for the ith day of the thaw, and n represents the number of days during the thaw with a $\bar{T} > 4°$ C). The thaw event ends when the daily minimum temperature reaches a value of -4 °C. This is the point at which the roots and/or shoots are likely to incur injury.

A Weather Reader algorithm (Fig. 4) was developed to convert American daily weather records to conform to Canadian data formats, to join the Canadian and American data sets, and to calculate: (1) daily accumulated GDDs (using from start to end of each thaw–freeze event until the end for each weather station with at least 30 years of weather data); (2) an annual summary of the number of thaw–freeze events lasting longer than 4 days (annual frequency); and (3) maximum accumulation GDDs for the greatest single thaw–freeze event per station for each year.

The algorithm output for each station, for each year, was imported as a geo-referenced spreadsheet into ArcView™ GIS (version 3.3). Maps of the greatest GDD accumulation in a single thaw in each year and the number of thaw events per station per year were generated. From these maps, years that contained biologically significant thaw–freeze events over wide geographic areas were selected for further analysis.

Quality control of daily weather records was performed by checking for gaps in the weather records. A method was developed to determine if a thaw was uncharacteristic. This was done by comparing daily mean temperature values with the 30-year mean temperature, $T_{30\text{-year}}$, (for that year) for each of the

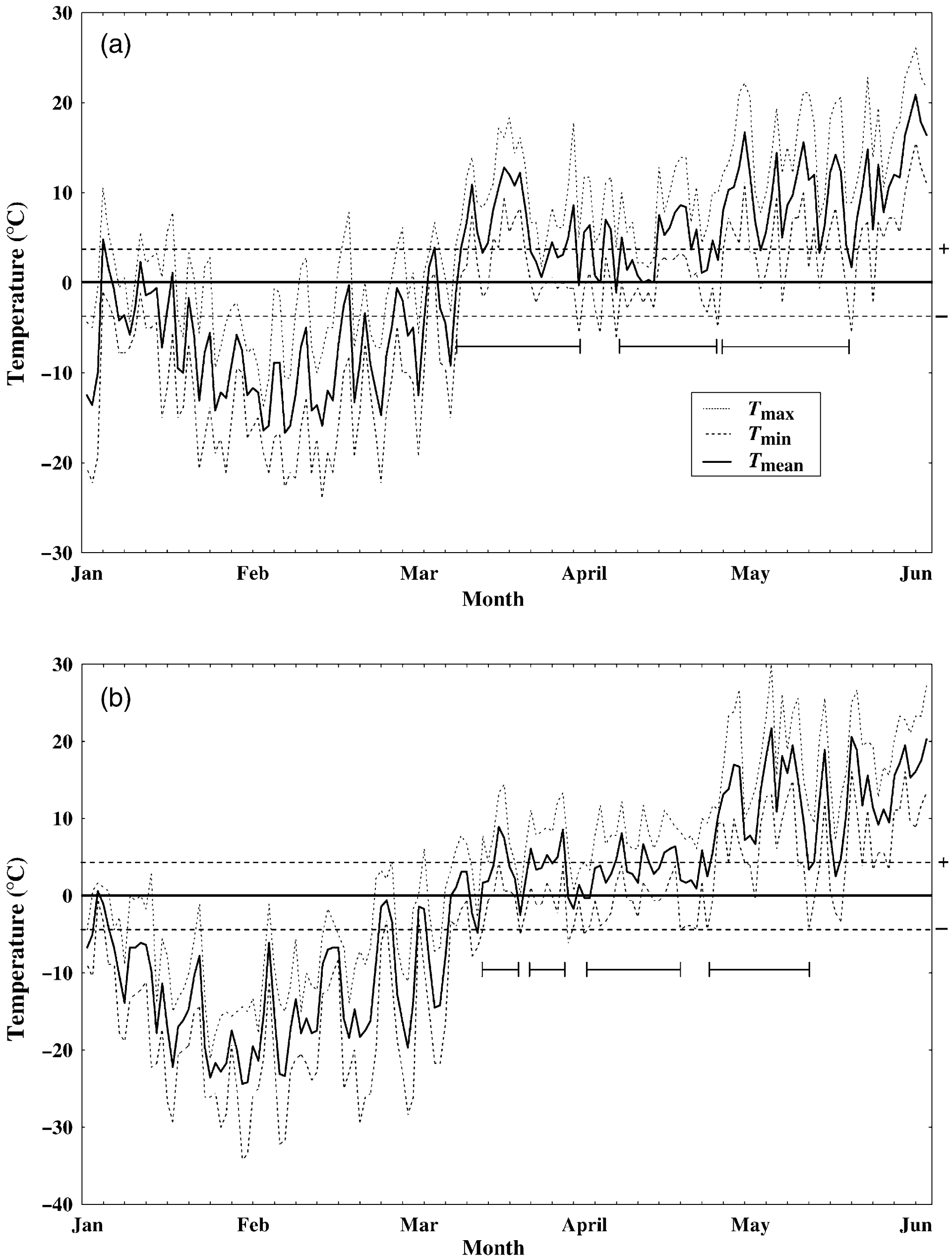

Fig. 5 Air temperature time series for a typical station in eastern NS (Truro) (a) and in southern QC (St Hyacinthe) (b) from January 1 to May 31, 1936. The thaw events >4 days in duration are marked with horizontal bars. Thresholds of +4 °C and −4 °C were used to define biologically significant thaws.

selected weather stations, i.e.,

$$\Delta T_{\mathrm{normal}} = \overline{T} - T_{30\text{-year}}. \qquad (2)$$

Once the extreme thaw events were identified, files for the daily accumulation of GDDs per thaw event for each station were exported from ArcView™ as database files (*.dbf) into GS+™ for Windows™ for spatial interpolation (Kriging) of a continuous surface based on a weighted moving average of the known station values. Kriging allows flexibility in defining the spatial interpolation model, and takes into account the model of the spatial process (i.e. the variogram) (Babish, 2000).

Kriging of daily GDD was done in two steps: (1) the sample variance was used to estimate the shape of the variogram – a curve that represents the variance as a function of distance (i.e. the variogram describes the spatial relationship between the daily weather

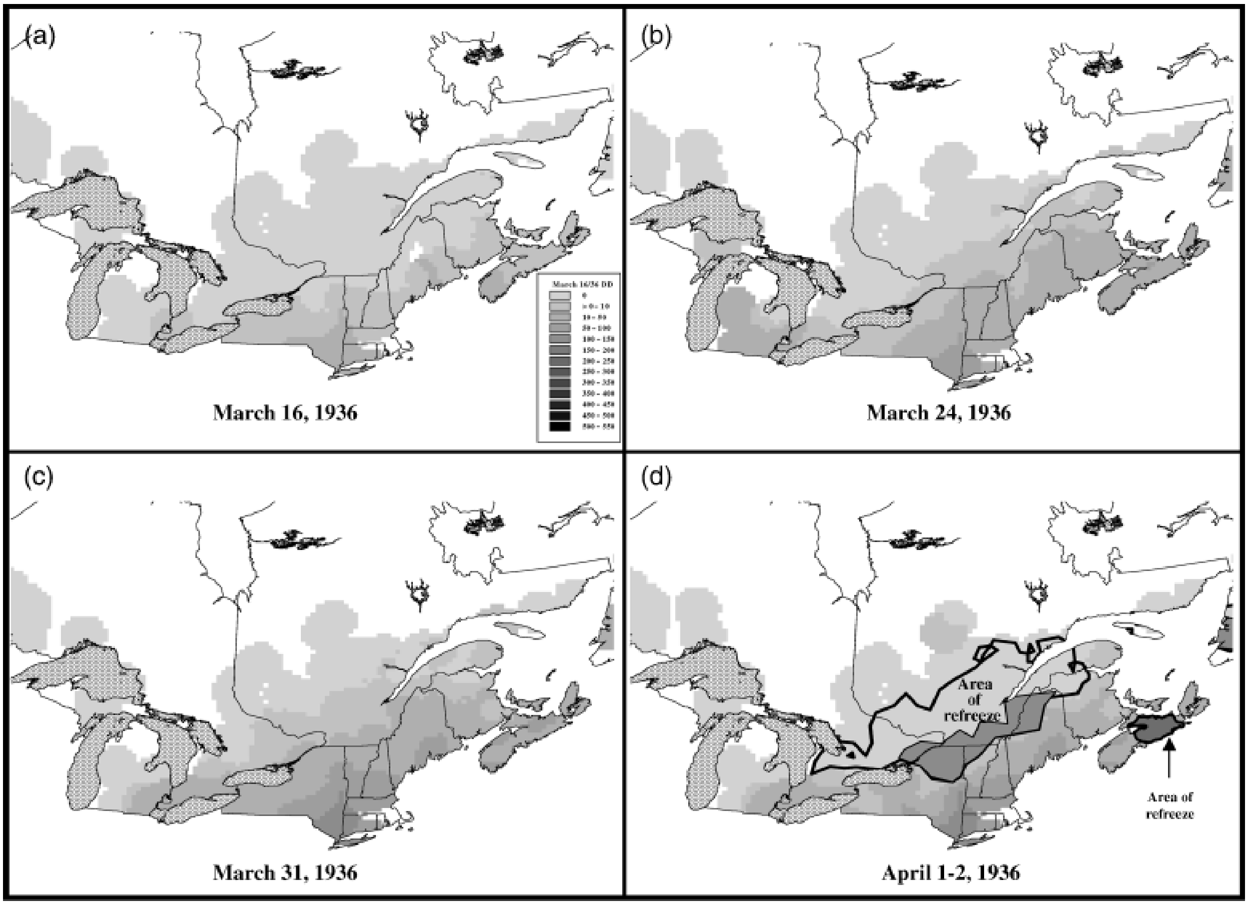

Fig. 6 Accumulated growing degree days (GDD; range light gray = 0; darkest gray = 50–150) (base temperature of 4 °C) during thaw at different times in 1936: (a) at commencement of thaw, (b) in the middle of thaw, (c) at height of thaw, and (d) total area affected by the last frost. The area of refreeze significant to yellow birch dehardening (with sufficient GDD accumulation; ~40–50 GDD) and refreeze injury is restricted to the southern portion of the refreeze zone (shown in dark gray) and the refreeze zone in eastern NS. The refreeze event in NS occurred on April 2, whereas the main refreeze event in southern QC, southern ON, the northern portion of the New England states, and northern NB occurred on April 1.

parameters); (2) the estimated variance function was used to determine the weights needed to define the contribution of each climate station value to the interpolation between two known station values. Climate stations close to the point for which an estimated value was to be generated, contributed the greatest to the interpolation.

For geo-spatial interpolation and tracking of individual thaw–freeze events through time, spatial resolution of the maps was set at $20 \times 20\,km^2$ per grid cell. The mapping projection used for our spatial illustrations was the Lambert Conformal Conic (WGS 84). Decimal degrees were converted to meters with a Central Meridian of −75. Accumulated GDDs for each day of the winter season (i.e. January 1–May 31) or in terms of day of year, 1–152, and year were then exported from GS+™ for Windows™ as an ASCII grid (152 rows × 78 columns) into ArcView™ for postprocessing and visualization.

Results and discussion

A summary of 1930–2000 average annual maximum thaw GDD calculations for the greatest single thaw–freeze event per year for all stations in the study area is shown in Fig. 1b. The years 1936, 1945, 1957, 1981, 1986, and 1987 have significant 'peaks' compared with other years. Suspect years for the period of birch decline (1930–1960) include 1936, 1944, and 1945.

1936 Thaw event

The 1936 thaw events for a station in eastern NS in Colchester County are shown in Fig. 5a. This particular station experienced three major events: a March thaw, a mid- to late-April thaw, and a late frost in May (Fig. 5a) following seasonal spring temperatures. This pattern occurred throughout the region. Some stations did not experience this last frost of at least −4 °C, however,

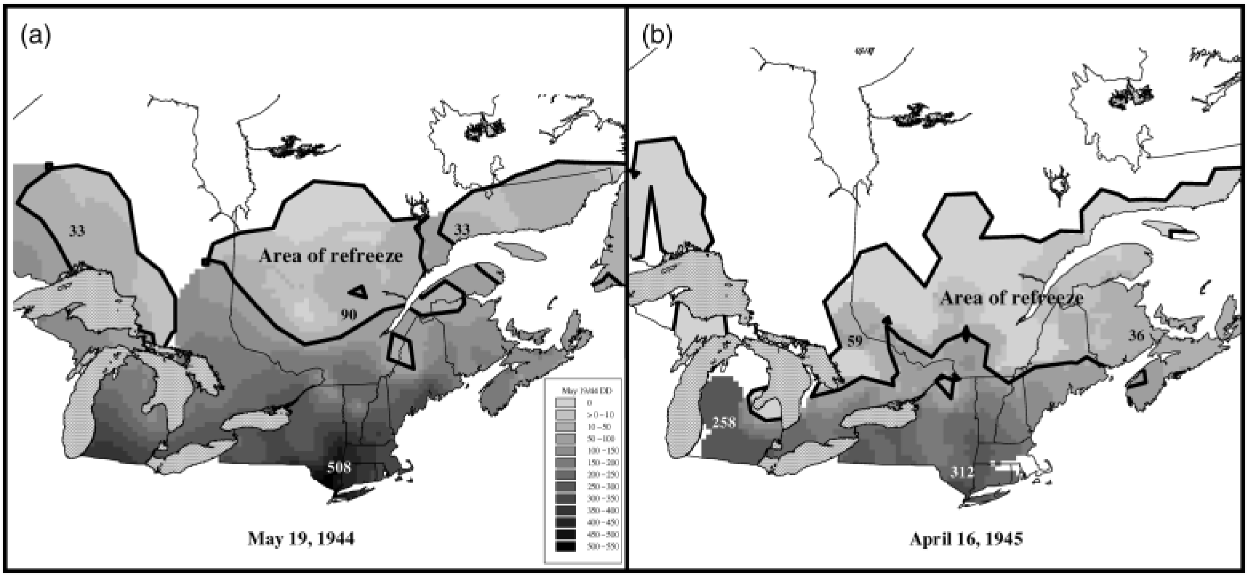

Fig. 7 Accumulated growing degree days (GDD; range light gray = 0; black = 500–550) (base temperature of $+4\,^{\circ}$C) during 1944 (a) and 1945 (b) thaws (April 25–May 19 and March 12–April 16, respectively) and the total area affected by refreeze. Observed GDDs at some locations are presented on the thaw–freeze maps; darker gray shading signify locations with the greatest GDD accumulation.

many of these stations experienced temperatures just slightly above $-4\,^{\circ}$C. Southern NB had much the same pattern, but not as pronounced. Most of northern NB and the Gaspé Peninsula (QC) had a less pronounced March thaw than NS, and had accumulated GDD levels just below 50 before the late spring frost in May. In southern QC, the March thaw was even less pronounced than in the Maritimes, but the region did undergo a significant late frost event in May, as illustrated in Fig. 5b.

Calculations for this year (1936) involved weather records from 198 stations with at least 30 years of data. All but one station in NS recorded at least one thaw, with a maximum number of five thaw events >4 days in duration. Maximum heat accumulation per station shows that some stations in eastern NS accumulated $100<$ GDDs<200. These high accumulations occurred before the late frost event, or during the March thaw–freeze event. Accumulations for NB stations are representative of the March thaw as well, except for a few stations along the ME–NB border, where GDD values were highest before the last frost in May. Stations in southern QC and along the St Lawrence River, also reached the highest levels of accumulated GDDs, before the late frost in May. Accumulated values at other stations can be attributed to the second thaw–freeze event in April.

Figures 6a–d give the spatial evolution of the March thaw, with Fig. 6d giving the extent of the refreeze area following GDD accumulation during the thaw; refreeze occurred mostly on April 1 whereas localized refreeze in NS occurred on April 2. The darker gray portion of the refreeze area (south-central QC, north New England states, and NS) experienced a deeper thaw, where >10–50 GDDs were estimated to have been accumulated. The remaining refreeze area underwent a weaker thaw, accumulating no more than 10 GDDs.

1944 Thaw event

Temperature records in 1944 exhibited a 'normal' progression into spring, with a late frost occurring on May 17. The area that experienced the late frost was mostly in QC, including the Gaspé Peninsula and some areas of northern NB. Thaw counts for eastern Canada were limited to one or two events, with most affected areas having experienced >50–200 GDDs before the onset of the last frost in May. For the same period, accumulated heat units were negligible in the rest of NB, PEI, and NS (<10 GDDs).

Figure 7a provides accumulated GDDs from the last temperature drop to $-4\,^{\circ}$C (April 25), through to May 18, the start of the frost, to May 19, the end of the frost. The total area affected by the refreeze is also outlined. The rest of eastern Canada continued with a normal progression into summer.

1945 Thaw event

The year 1945 had an extraordinarily warm spring (record spring temperatures), with a subsequent freeze to $-7\,^{\circ}$C in the middle of April. The 1945 event covered nearly all the same areas affected by the 1936 and 1944 thaw events, as well as additional areas. The early

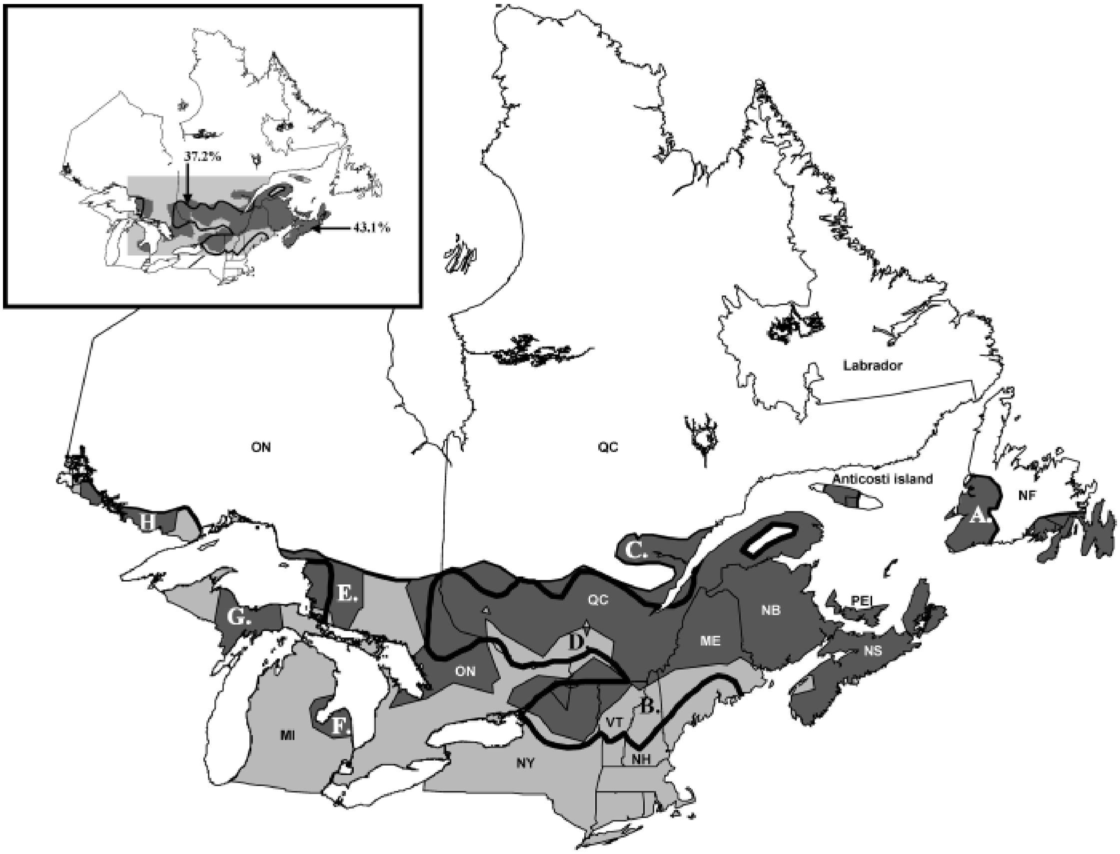

Fig. 8 Overlay of projected biologically significant refreeze areas and documented birch dieback (after Braathe, 1995) for 1930–1960. Inset provides a calculation (within the limits of the light gray box) of the proportion of the area covered by the calculated refreeze area (43.1%) and the documented birch dieback area (37.2%). The calculated refreeze area is ~1.2 times larger than the documented birch dieback area. The single capitalized letters on the map (A–H, from east to west) represent the areas in the calculated and documented distributions where differences exist. These differences are discussed in the text. For Province and State name abbreviations, refer to the caption of Fig. 2.

spring thaw was widespread across eastern Canada, with high GDD values before recurring frosts of −4 °C. Figure 7b illustrates the refreeze area after a significant thaw that extended from March 12 through to April 16. This freeze event was particularly widespread, with variable amounts of accumulated degree days of 10–200 (depending on location) before the last freeze.

Comparison of observed dieback extent and projected thaw–freeze areas

Figure 8 provides an overlay of the documented accumulated birch decline from 1930 to 1960 (after Braathe, 1995) and the projected thaw–freeze areas based on a composite of the intersections of refreeze areas from Figs 6d, 7a, and b with the geographic range of yellow birch. In general, the two distributions coincide very well. The accumulated thaw–freeze projection for 1930–1960 overlaps with 82.6% of the documented distribution of birch decline and 54.6% with the geographic range of yellow birch in eastern North America. The projected extent of thaw–freeze is about 1.2 times larger than the documented extent of dieback (inset to Fig. 8). Areas that are projected to have experienced some level of dieback (i.e. regions A, C, E, F, G, H, and Anticosti Island in Fig. 8), although not specifically shown in Braathe's map, have appeared to have undergone some dieback according to Auclair *et al.* (1997, Fig. 1, p. 180). The thaw–freeze mapping in regions B and D (Fig. 8) indicates that the level of GDD accumulation (<50 GDD) and refreezing may not have been as severe as predicted by Braathe (1995) and others.

Application of thaw–freeze mapping to two 1981 thaw events

Lachance (1988) described snow cover for the winters of 1981 and 1982 as noticeably low, but temperatures

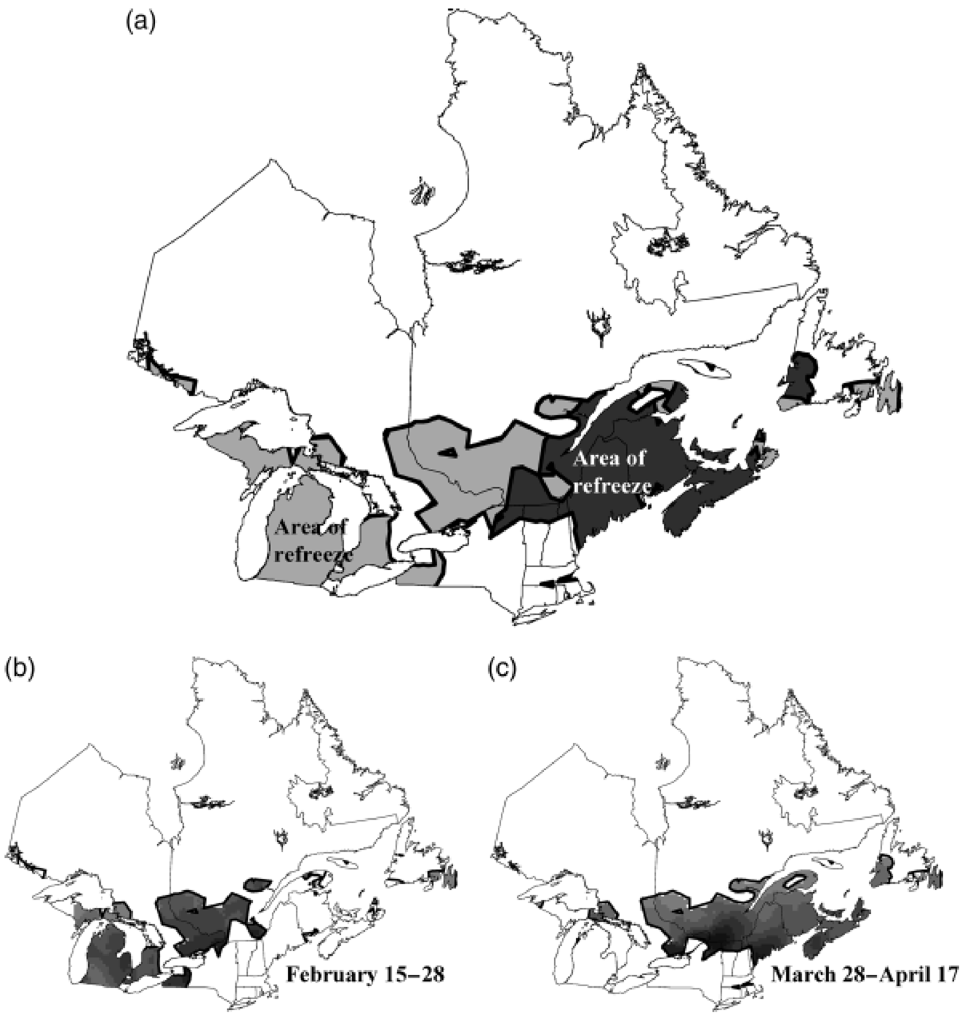

Fig. 9 Thaw–freeze mapping applied to two biologically significant thaw events in 1981 – February 15–28 and March 28–April 17. (a) Gives the total area affected, and (b) and (c) give the geographic extent of the February and March–April thaws with the degree of GDDs accumulated just prior to refreeze; darker gray shading signifies locations with the greatest GDD accumulation.

in December 1980 and January 1981 were the coldest ever recorded in southern QC. In addition, this region sustained the warmest and longest winter thaw recorded since 1900: all snow covering the ground melted from February 14 to February 28, 1981. The winter thaw was followed by a cold spell in mid-March. There was also a late spring frost throughout most of southern QC, the Gaspé Peninsula, and northern NB. Stations in central and southern NB and NS underwent an early spring thaw, but did not experience the February thaw or the late spring frost event that occurred in the northern regions of the study area (Fig. 9).

Most of eastern NS experienced a thaw event of 50–100 GDDs during March and April. Stations in southern QC and the Lac St Jean region (northwest of the Saguenay River; embedded in region C of Fig. 8) experienced a late frost in the middle of May, and had much higher accumulations of GDDs before the last frost (50–200 GDDs).

The first winter thaw from February 15 to 28 is illustrated in Fig. 9b (Fig. 9a gives the accumulated area of refreeze for 1981). A second early spring thaw–freeze event from March 28 to April 17 in 1981 is illustrated in Fig. 9b. The greatest GDD accumulation before refreeze (>50 GDDs) occurred mostly in the southern limits of the refreeze area generated by both events (darker gray colors; Figs 9b and c).

Concluding remarks

Mapping techniques developed in this paper enable us to track and spatially display temporally anomalous winter and early spring thaw–freeze events. The analysis of winter and early spring thaw–freeze events revealed that biologically significant events (GDDs > 50) encompassing huge areas of eastern Canada and the northeastern United States did occur in 1936, 1944, 1945, and also in 1981. Other years had more localized thaw–freeze events that overlapped with some of the larger events. Some of the years described had several thaw–freeze events. It was concluded that (1) the areas affected by several of these thaw–freeze events corresponded well with the timing and locations of accumulated yellow birch dieback and decline, and (2) widespread anomalous weather patterns occurred at least four times during the 1930–1990 period.

As considerable efforts are invested in modeling future weather based on varying climate-change scenarios, the newly developed Weather Reader algorithm could become an important tool to assess the future of yellow birch as well as other hardwoods under various climate-change scenarios, over time and spatially across North America and hardwood regions of the world prone to thaw–freeze effects (e.g. Norway, Scotland).

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