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INTRODUCTION

On a global basis, the sugar maple industry is one of the most sensitive to climate. It is an industry that is unique to North America and traces its roots to Canada's native heritage. Changes in the climate system are not linear, either temporally or spatially. It would be unreasonable to assume that an earlier spring, for example, would yield more sap production as there are many climatic factors that influence sap flow, both positively and negatively, during the short three to four week period of sap production.

The maple syrup industry in Canada has grown by 70% in the last 80 years (Statistics Canada data for 1925 - 2003, Statistics Canada, 1974; Chapeskie, 2004; Chapeskie, 2005). Canada is now the largest producer of maple products in the world reaching $155 million in production value in 2002 (Statistics Canada, 2003). Recent decline in sugar maple production (Drohan et al., 2002) and concern over global environmental change highlights the need for a thorough understanding of the impact of climate change on sap flow, quality and quantity of maple syrup production.

A shift in the locus of the sugar maple producing industry from a cluster of states in the U.S. (New York, Vermont, Michigan and Ohio) in 1860 to the Canadian province of Quebec in 2002 is noticeable (see Figure 1 in Whitney and Upmeyer, 2004). Fifty years ago the United States, primarily New England and New York, used to account for 80 percent of the international maple syrup production, with 20 percent in Canada, but today that trend is completely reversed. The production increase in Canada is associated mainly with Quebec where over 93 percent of the national production occurs. Ontario has actually decreased its production from 1860 to 2002 and shifts have also occurred in the United States. For example, tapping for sap from maple trees was carried out in Iowa, Missouri, Tennessee, North Carolina and Virginia in 1860 but none of these areas show tapping in 2002 (Whitney and Upmeyer, 2004).

Climatic parameters that impact maple syrup production include temperature, precipitation (timing, amount and acidity), snow cover and atmospheric carbon dioxide and ozone concentrations (Bernier et al., 2002). These factors in turn alter nutrient profiles of the soil and trees, respiration and photosynthesis rates, pest and disease vulnerabilities, and stress response (subject to the age of the tree).

Bumper production years for sap from maple sugar trees also depend on the growing conditions of the previous summer to store carbohydrates in the form of starch. These stored starch reserves convert to sucrose and are dissolved in the sap. The amount of sugar (sucrose) in the springtime sap depends on many factors including tree genetics, leaf mass, site conditions, amount of sun in the previous growing season, and overall tree health.

Climate scenarios produced by global climate models have been used to project the impact of climate change on tree species distributions. Dramatic northward shifts, up to 2 degrees latitude, in the geographic range of sugar maple in North America are projected by the end of the 21st century. There have been very few models that have examined the impact of climate change on the displacement of the commercial sugar maple forest specifically. In addition, there is also little accumulated data to show how climate thresholds have changed in relation to syrup production in sugar maple. Since tapping of sugar maple trees begins when the trees are 40 or 50 years old, this is an industry that will be exposed increasingly to the anticipated future climate changes in North America. The highlighted box on the following page provides an outlook, based on published sources, on the sugar maple region of North America using scenarios of future climate change.

This paper begins by examining the literature surrounding climate factors that influence the production of sap from maple sugar trees including temperature, precipitation, snow cover, as well as other environmental factors including ice storms, forest fires, chemical precipitation, nitrogen levels, elevated carbon dioxide and ozone, and forest pests and disease. Next, the paper reviews Iverson's model on geographical shifts in sugar maple trees in North Amercia due to climate. This study presents a summary of climate variables, thresholds, sensitivities and impacts that affect maple sugar sap production in North America by examining climate data from 14 stations across the Canadian provinces of Ontario, Quebec and New Brunswick, and the states of New York and Vermont in the USA. The paper concludes with recommendations for future research on the sustainability of the North American maple syrup industry.

21ST CENTURY OUTLOOK FOR THE SUGAR MAPLE REGION OF NORTH AMERICA USING SCENARIOS OF FUTURE CLIMATE CHANGE, BASED ON PEER-REVIEWED LITERATURE SOURCES

- Current sugar maple dieback in Quebec will continue through 2011 but then subside substantially until the latter half of the 21st century (Auclair et al., 1996).
- Recurrence of major dieback episodes in sugar maple in Quebec from 2045 – 2085 (Auclair et al., 1996).
- Extensive cutting and burning of sugar maple in Quebec from 1860 – 1890 provides the current estimate of maturation of forest to 1981 – 2011 (a “window of vulnerability” (Auclair et al., 1996) or “thermal stress periods” (MacIver, 1987); dieback from 1980 -to -date correlates with the maturation of the Quebec sugar maple).
- Sugar maple is expected to remain in the Great Lakes Region and may gain potential habitat in the U.S. West – currently prairie. This is based primarily on a projection of little or no change in soil water stress under two climate models, CGCM1 and HadCM2 (Walker et al., 2002).
- Sugar maple will be able to grow in lower Michigan in some decades and not in others (because of fluctuations in soil water stress). Sugar maple, after disappearing intermittently, are projected to grow in lower Michigan in the final decade of the century (Walker et al., 2002).
- Five global climate models indicate that sugar maple will be mostly extirpated from the U.S. (Iverson and Prasad, 1999).
- Climate change scenarios indicate that the frost free period in northern Michigan could lengthen by as much as 54 days, annual temperature could increase by 3ºC, May to September growing season temperature could increase by 2.5ºC; May to September heat sum (ºC-days, 4.4 ºC basis) could increase from 1750 to 2250; May to September precipitation could decrease by 7%, potential evaporation could increase by 12%, and the ratio of July-August precipitation to potential evaporation could decrease by 14% (Reed and Desanker, 1992).
- Changes in climate are predicted to shift the sugar maple range northward by 2º latitude (i.e. northern Michigan) climate will be like the lower peninsula of Michigan (Reed and Desanker, 1992).
- Snow packs are predicted to develop later and melt earlier (Groffman et al. 2001, Cooley, 1990).

INFLUENCE OF CLIMATIC AND OTHER ENVIRONMENTAL FACTORS ON SAP PRODUCTION

There are many climate and other environmental factors that influence the quality and quantity of sugar maple tree sap production including temperature, precipitation, snow cover, ice storms and forest fires, chemical precipitation, nitrogen levels, elevated carbon dioxide and ozone, and forest pests and disease.

Temperature

Temperature affects sap flow directly. For sap flow in sugar maple trees, air temperatures are required to be below freezing at night (<0 degrees Celsius) and above freezing during the day. The ideal daily temperature range during the late winter and early spring is between -5 degrees Celsius to +5 degrees Celsius. If this cycle is interrupted by periods of temperatures above or below this optimum range, then the flow of sap will also be affected. As days and nights warm, the sap quality and quantity begins to decrease.

The cumulative effect of 10 to 15 days with highs above 10 degrees Celsius and/or 10 to 15 nights without a frost, after February 1st of each year, is sufficient to bring the sugar maple trees out of dormancy. In areas where average winter temperatures are above 0 degrees Celsius there is no sap flow and this helps define the southern limits of the commercial range of the sugar maple producing industry. If temperatures are below the optimum then the sap doesn't flow or the flow is delayed until sufficient warming. On the other hand, if temperatures are above the optimum the tree begins to bud and then the sap is bitter and produces poor quality maple syrup products.

Reports from Vermont indicate that some sugar maple trees are budding 19 days earlier than normal. For example, on average, sugar maple bud break have occurred on May 11 but in 2002 it occurred on April 22 (http://www.uvm.edu/~empact/climate/climate.html). Other reports (see Crop Production, 2004) across the eastern United States and Ontario are also suggesting that sap flow is starting earlier during the past decade, compared to historical records, with earlier shifts of 4 to 6 days and up to one month. According to Dr. Tim Perkins, Proctor Maple Research Center, Vermont, it appears that the season open/season close dates in New England/New York are as much as 7 to 10 days earlier than 40 years ago, and the duration of the season is decreasing (Perkins, pers. comm., 2005).

Preliminary data (Sajan, 2005) for Ontario shows that in 1960 the first date of maple syrup production, known as the boil date, was March 24, but by 2002 this date had advanced to March 7. If the data from 1960 to 2005 is broken into two periods, before and after 1980, then, after 1980, 75 percent of the first boil dates are before March 21 with 17 percent before March 11. In comparison, prior to 1980, 80 percent of the first boil dates occurred after March 21.

Precipitation - temporal and spatial changes

Sugar maple is extremely susceptible to high winds, mid-winter thaws and summer droughts. Summer droughts have been identified as factors negatively impacting sap flow and quality. If climate change is expected to increase severe droughts in August to the extent where the foliage is affected and the leaves drop prematurely, this will reduce the storage of starch needed for the following spring's sap production. If climate change results in stronger and more frequent storms or wetter, milder winters, this could lead to a reduction in sap flow (Foster et al., 1992).

Snow Cover

Snow is a critical regulator of soil processes. Acting as an insulator, a snow pack of 30 centimeters prevents soil freezing and provides sufficient root moisture in mature sugar maples (Bertrand et al., 1994; Decker et al., 2003). Snow packs respond very dynamically to climate change. One of the most significant consequences of global climate change on northern forests may be a reduction in snow cover (Groffman et al., 2001).

Warmer winters result in less snow cover to insulate the soil from freezing. Lack of accumulated snow or a meltdown of the snow pack in winter can result in deep soil frost and root kill (Groffman et al., 1999). The injuries to the tree include irreversible tracheid and vessel cavitation. When a continuous snow pack develops in December, it appears that the soil stays above the freezing point even at shallow depths. However, when the snowpack develops later, significant freezing and damage occurs to the roots (Waite and Scherbatskoy, 1994) along with a reduction in both the quality and quantity of sap (Robitaille et al., 1995).

Thaw-freeze stress between December and March is defined by daily maximum air temperature greater than or equal to 10 degrees Celsius for at least 3 consecutive days, followed by a freeze (daily minimum air temperature less than or equal to minus 10 degrees Celsius) for at least one day within the succeeding 7 days since the last day of thaw (Auclair et al., 1996). Root-freeze stress during this same period is defined as the number of days when snow depth is less than or equal to 5 centimeters, and the daily minimum air temperature was less than or equal to minus 10 degrees Celsius (Auclair et al., 1996).

Ice storm Damage and Forest Fires

Climate change may be characterized by an increased number of ice storms or drought-induced forest fires (Dale et al., 2001). Both of these would be detrimental to sugar maple forests. Sugar maple is extremely fire sensitive owing to its thin bark.

In 1998, a severe ice storm ravaged much of the commercial sugar maple area for sap production. In ice storm damaged 200-year sugar maple trees, autumn starch concentrations declined to winter low levels 2 weeks earlier than undamaged trees. Starch re-synthesis, the production of spring starch, occurred in early March about 2 weeks later than in undamaged trees (Wong et al., 2005).

Chemical Precipitation

The health of sugar maple stands in Ontario and Quebec are being adversely affected through continuous exposure to acid rain. Acidic precipitation, found in excessively high levels throughout eastern Canada, damages the sugar maple trees directly or influences the ecological processes in such a way that the development of a healthy sugar maple forest is impeded. Both managed and unmanaged sugar maple stands are affected. Acid rain impacts the sugar maple trees by: damaging the leaf surfaces; reducing cold tolerance; decreasing vitality and regenerative capacity; increasing susceptibility to drought, insects and disease; increasing vulnerability to climatic perturbations; and accelerating the rate of soil nutrient decline (Hall et al., 1997).

Acid rain has caused acceleration in the loss of base cations from maple dominated hardwood forests in Ontario (Hall et al., 1997). As the soil acidification increases, the soil base saturation decreases and the nutrient status of sugar maple seedlings decline (Hall et al., 1997). If projected into the future this is expected to result in long term declines in forest productivity and health over the life-time of the stand and increases in dieback and mortality. The dieback of sugar maple in eastern Ontario is more prevalent in areas of high excessive levels of soil acidification. As dieback of sugar maple exceeds certain thresholds, the viability of sugar maples in the commercial maple producing zone is considerably reduced. For example, sugar maple trees with greater than 50 percent dieback in southern Quebec in the early 1980s had a mean sap flow rate 12 percent lower than trees showing little or no dieback (Robitaille et al., 1995).

Liming has been shown to reduce the impacts of acid rain. Sugar maple stands subjected to liming treatments show noticeably less dieback symptoms than stands with no liming treatment. The application of fertilization and liming techniques both reduce symptoms of decline (Brydges, 2005). Fertilization restores leached nutrients and liming controls soil and water pH (Bell et al., 1998). Both of these treatments increase tree vigor and hence have a positive impact on sugar maple syrup production. In a sugar maple stand at the Lake Clair Watershed in Quebec, similar to stands in Ontario, improvements in N, P, Ca and Mg were noted four years after the lime application. Over the four year period, liming increased the radial growth of sugar maple by 45 percent for rates from 1 to 10 $t.ha^{-1}$ and by 90 percent for rates of 20 $t.ha^{-1}$, compared to the control trees (Moore et al., 2000).

Foliar Nitrogen and Leaf Colouration

The percent peak red colouration in sugar maple is negatively correlated with foliar nitrogen concentrations and positively correlated with foliar starch concentrations. Foliar nitrogen deficiencies have been shown to enhance foliar starch accumulation (Schaberg et al., 2003).

An increase in foliar starch may result in increased sap yield. Consequently, the degree of red colour expression shows promise as a predictor of starch and sugar concentrations and sap yield (Schaberg et al., 2003). Tree colour is related to the amount of sap in the tree. Anthocyanin, a pigment contributing to the red colour in sugar maples during the fall season, is formed in the sap when the sugar concentration gets quite high. Bright sunshine and temperatures that are just above the freezing mark during the day promote the development of anthocyanins within the sweet sap. Temperatures that drop below 0 degrees Celsius during the day will reduce the amount of anthocyanin produced and will cause the leaf to appear yellow.

Elevated CO_2 and O_3

The responses of sugar maple trees to atmospheric ground-level ozone (O_3) and atmospheric carbon dioxide (CO_2) are consistent with the responses of other tree species, although sugar maple is relatively ozone tolerant. The responses are also consistent from the leaf to ecosystem level with the two gases acting in opposing ways even at very low concentrations (Karnosky et al., 2003).

Elevated carbon dioxide (CO_2) concentrations generally:

- increase photosynthesis (Noormets et al., 2001)
- decrease fine root respiration (Burton et al., 1996)
- increase plant carbon allocation to below ground processes, including root growth, respiration, and exudation (Lynch and St. Clair, 2004; Edwards and Norby, 1999)
- delay autumnal foliar senescence (J.G. Isebrands, unpublished results; Karnosky et al., 2003)
- alter concentrations of defense compounds (Lindroth et al., 1997), antioxidants and secondary metabolites (Wustman et al., 2001)
- have lower foliar nitrogen concentrations (Cotrufo et al., 1998)

Elevated ozone (O_3) concentrations generally:

- decrease photosynthesis (Coleman et al., 1995a)
- alter carbon allocation (Coleman et al., 1995b)
- decrease growth (Karnosky et al., 1996)
- accelerate leaf senescence (Karnosky et al., 1996)
- increase foliar injury (Karnosky, 1976)
- predispose trees to pests and disease (Karnosky et al., 2002)

Stomatal sensitivity appears to be unique to the sugar maple, rendering it more resistant to environmental change than, for example, the red maple (Karnosky et al., 2003). The combined increase of carbon dioxide and ozone results in greater reductions in stomatal conductance. This suggests that it is the sugar maple stomatal sensitivity to environmental change that may mitigate the detrimental effects of these changes. A significant decrease in photosynthesis was not observed in sugar maple growing under experimental atmospheric carbon dioxide and ozone treatments (Karnosky et al., 2003).

Increasing levels of ozone and carbon dioxide appear to have relatively lower immediate effects on sap flow compared to the impacts of temperature or precipitation. If the atmospheric concentrations of both gases continue to increase in the future climate, this might cause decreases in stomatal conductance and ultimately reduce ultimately reduce sap flow.

Pests and Disease

Elevated concentrations of atmospheric carbon dioxide have been shown to increase disease susceptibility. Temporal changes in temperature may also alter disease susceptibility of the sugar maple. For example, synchronicity between pear thrips (a forest insect primarily of fruit trees) emergence and sugar maple budburst correlates with damage levels. Cool temperatures that slow bud burst promote damage. Pear thrips damage correlates with lower root starch concentration in the fall following the attack. Heavy pear thrips damage was found to be detrimental to syrup production of sugar maples for over two years following the outbreak (Kolb et al., 1992).

In addition, invasive pests, such as the Asian Long-horned beetle, continue to be a major threat to the maple sugar bush. This is becoming an area of increasing interest since effects are dramatic and immediate.

CLIMATE-INDUCED GEOGRAPHICAL SHIFTS IN SUGAR MAPLE

Climate change is expected to affect all forest species, their productivity and geographical distributions.

A statistical modeling approach to estimate distributional changes in sugar maple that could occur under a globally changed climate was developed by Iverson et al. (1999), using five global climate model (GCM) scenarios. Iverson et al. (1999) used monthly means (averaged from 1948-1987) of precipitation, temperature, and potential evapotranspiration to model the current climate in the eastern United States. From these data, annual means were calculated for each of the above variables, and two attributes were derived, based on their physiological importance to tree growth for the sugar maple region: July/August ratio of precipitation to potential evapotranspiration (PET) (the time trees are most prone to drought stress in the eastern United States), and May/September (i.e., growing season) mean temperature. The data were then transformed to county averages via weighted averaging, based on county area.

Five scenarios of future monthly temperature and precipitation under an equilibrium state of 2 X CO_2 were used for predictions of potential future species distributions: the Geophysical Fluid Dynamics Laboratory (GFDL) (Wetherald and Manabe, 1988), Goddard Institute of Space Studies (GISS) (Hansen et al., 1988), Hadley Centre for Climate Prediction and Research (UK) (Hadley) (Johns et al., 1997), United Kingdom Meteorological Office (UKMO) (Cullen, 1993), Canadian Climatic Centre (CCC) models (McFarlane, 1992). Iverson et al. (1999) generated importance values (IV) for each species as follows:

$$IV(x) = [100BA(x)/BA(\text{all species})] + [100NS(x)/NS(\text{all species})]$$

where x is a particular species on a plot, BA is basal area, and NS is number of stems (summed for overstory and understory trees). In monotypic stands, the IV would reach the maximum of 200.

All five global climate models indicate that sugar maple trees will be mostly extirpated from the United States by the next century (Iverson et al., 1999; Iverson and Prasad, 2002). This is consistent with some of the other models which suggest a northward movement of the sugar maple range by 2 degrees latitude over the next 100 years.

CLIMATE TRENDS AND MAPLE SYRUP PRODUCTION

Climate data from 14 stations were used to examine climate variables, thresholds, sensitivities and impacts that affect sap production across northeastern North America.

Climate Stations and Data Sources

The climate stations used in this preliminary study are located in Ontario (2 stations), New York State (1 station), Vermont (2 stations), New Brunswick (1 station for temperature, 1 station for precipitation), and Quebec (7 stations). The Quebec climate stations are more predominant in this study (see Figure 1) due to the high volume of syrup production from this province.

Daily and monthly temperature and precipitation data for 10 of the 11 Canadian locations was obtained from Environment Canada's long-term Adjusted Historical Canadian Climate datasets (http://www.cccma.bc.ec.gc.ca/hccd/). These homogenized temperature and rehabilitated precipitation datasets incorporate a number of statistical adjustments to the data and are used for climate research, including the detection of climatic trends. Quality controlled historical daily and monthly temperature and precipitation data for the remaining Canadian location, Madawaska, ON was retrieved from Environment Canada's National Climate Data Archive. This station has a long record of continuous observations. All Canadian snow cover data was obtained from the Environment Canada CRYosphere SYStem (EC CRYSYS) project: (http://www.msc-smc.ec.gc.ca/crysys/crysys_freecd_e.cfm). The Canadian snow cover data has been quality checked and assembled by staff of the CRYSYS project.

United States daily temperature and precipitation data was obtained via on-line ftp access to the Global Historical Climatology Network: ftp.ncdc.noaa.gov/pub/data/ghcn/daily/. Historical daily data available from this source has been quality control checked. However, no statistical adjustment or homogenization of the data has been done. The stations were selected to correspond with coverage of the major maple sugar producing area of the northeastern U.S. These are long term stations with a 24-hour observation program. Snow cover data was not available on-line and this information was extracted from a NOAA data CD (National Climatic Data Centre, 1995) (Daily Summary) which included information up to 1993, with a minimum data record of 40 years.

Climate Variables, Thresholds, Sensitivities, Trends and Impacts

The following table provides a summary of the climate variables, thresholds, sensitivities, trends and impacts that affect sap production as applied to climate data from 14 stations across northeastern North America.

Climate Variables	Climate Thresholds and Sensitivities	Climate Trends and Impacts
Maximum and Minimum Temperatures	Days with maximum temperature <= 5°C AND Days with minimum temperature >=-5°C from February 1 – March 31. **Sensitivity:** Optimum sap flow if daytime and nighttime temperatures are in this range.	The results of a combined optimal minimum and maximum temperature analyses are presented in Figure 1. The number of days with minimum and maximum temperatures in the optimal range has significantly increased by approximately 2 to 4 days over a 90 to 109 year period at three Quebec stations (La Tuque, La Pocatiere, Les Cedres). Non-significant increasing trends are found at the remaining Quebec and Ontario stations, while the two stations in Vermont show a non-significant decrease in the indicator. As any statistically significant increasing trend in this indicator would be beneficial to syrup production, the trend results suggest that conditions for this indicator are improving at sites in Quebec.
Maximum Temperature	Number of days with daily maximum temperature >10°C, from February 1 – March 31. **Sensitivity:** Warmer daytime temperatures have a negative effect on sap production.	There are statistically significant increases in the number of days with a maximum temperature greater than 10°C at nine of the study locations (1 to 4 days over varying periods of record). Non-significant increasing trends are found at the remaining four stations. This indicator supports an increasingly negative effect on syrup production, since the optimum temperature for sap production is being exceeded.
Minimum Temperature	Number of days with daily minimum temperature >0°C, from February 1 – March 31. **Sensitivity:** Warmer nighttime temperatures have a negative effect.	Statistically significant increases in the number of warm nights with minimum temperatures >0°C are found at eight stations (1 to 4 days over varying periods of record). There are non-significant increases in this indicator at four other locations, and only one non-significant decrease at Ottawa, Canada. As for the previous indicator, the trends in this indicator would support an increasingly negative effect on syrup production.

Climate Variables	Climate Thresholds and Sensitivities	Climate Trends and Impacts
Maximum Temperature (3-day period)	Number of 3-day periods with maximum temperature >=10°C, during the period December 1 – March 31. **Sensitivity:** Prolonged winter thaws followed by sudden freeze leads to major maple dieback, negative effect on sap flow.	Due to the low annual occurrences of these periods at most stations during any given year, the linear regression trends in this indicator were not calculated. However, the average number of annual occurrences is less than 1 occurrence per year at all locations.
Mean Temperature	Winter (December-January-February) mean temperature >0°C. **Sensitivity:** Maximum tolerated mean temperature is 0°C.	Winter (December-January-February) mean temperatures have significantly increased by approximately 1.5°C to 2.5°C at eight stations over the 89 to 109 year period of record, and increased non-significantly at four other locations. Only a very small non-significant negative trend was found at Montpelier, Vermont. An analysis of the historical annual winter mean temperatures at each of the stations indicated that no stations have yet reached the maximum tolerated syrup production threshold level of a mean winter temperature >0°C.
Effective Growing Degree Days	Effective Growing Degree Days (EGDD) (from April 1) where EGDD is defined as days with mean daily temperatures >5°C after "budburst". For the purposes of this analysis, April 1 was selected as the first date in every year for calculating these EGDD; the Ontario Ministry of Agriculture, Food and Rural Affairs (OMAFRA) also uses April 1 as the start date. **Sensitivity:** Higher EGDD promotes tree growth and a positive effect on the following spring's sap production, with the minimum EGDD being 1150 for sugar maple.	Significant increases in EGDD (100 to 500 over varying periods of record) were observed at eight stations. Non-significant increasing trends in this indicator are found at four other sites, and there is only one non-significant decreasing trend at Watertown. Values of this parameter are for the most part greater than the threshold of 1150, and this parameter would therefore not represent a limitation to future production if the increasing trend is continued forward in time.
Coldest Month Temperature	Coldest month mean temperature <-18°C or >1°C. **Sensitivity:** Maple optimum temperature range for the coldest month is between -18°C and 1°C.	The coldest month (either January or February) mean temperature trend is increasing significantly at four Quebec locations: 1.5°C to 2.2°C increase over a 90 to 91 year period. Non-significant increasing trends are observed at seven other locations, while there are non-

Climate Variables	Climate Thresholds and Sensitivities	Climate Trends and Impacts
		significant decreases in this indicator at the most southerly U.S. stations of Watertown and Montpelier. The analyses also showed that the maximum threshold of this indicator for maple growth, 1°C, has not occurred at the study stations during their periods of record - all stations have observed mean coldest monthly temperatures less than this upper threshold. The minimum temperature threshold for maple growth, -18°C, varies in occurrence from north to south in the study area. Northerly locations in Quebec, such as La Tuque and Bagotville, have often experienced this condition in the historical record, while the more southerly study locations have never met this condition. More importantly, the same stations which have experienced this condition the most frequently are generally also the locations which show an increasing trend in the mean temperature of the coldest month. If this trend continues, the frequency of occurrence of this minimum temperature threshold would be decreased, a benefit to the syrup industry.
Precipitation (August Departure)	Departure of August precipitation from normal. **Sensitivity:** A dry August leads to low quality/quantity sap production in the following year.	Significant increases in August precipitation of approximately 35 mm over an 81 to 100 year period are found at four locations (Madawaska, Ontario; Lennoxville, Quebec; Watertown, New York; and Burlington, Vermont), while non-significant increasing trends of various magnitudes are observed at eight other locations. Only one station, Bagotville, Quebec, shows a non-significant negative trend in this indicator. The analysis indicates that August precipitation is increasing either significantly or non-significantly at all but one of the stations.
Precipitation (May departure)	Departure of May precipitation from normal.	There are significant increases in May precipitation of varying amounts at two locations (Les Cedres and Causapscal).

Climate Variables	Climate Thresholds and Sensitivities	Climate Trends and Impacts
	Sensitivity: A wet May leads to low quality/quantity sap production in the following year.	All other stations show non-significant increases of various magnitudes in this indicator. No sites show a decrease in the indicator. Increasing May precipitation trends, if projected into the future, could have a negative impact on syrup production.
Precipitation (Summer Departure)	Departure of Summer (June-July-August) precipitation from normal. **Sensitivity:** A summer drought can reduce quality/quantity of sap in the following year.	There are statistically significant increases in summer precipitation at two Quebec stations, Causapscal and Les Cedres. A random pattern of non-significant increasing and non-significant decreasing trends is observed at the remaining stations. These results would suggest that summer droughts are presently not a limiting factor to syrup production.
Precipitation (Winter Departure)	Departure of Winter (December-January-February) precipitation from normal. **Sensitivity:** A winter drought can reduce quality/quantity of sap in spring.	A significant decrease in winter precipitation occurs at only one station, Les Cedres, Quebec: 90 mm over the station's 90 year data period. As with the previous indicator, there is a random pattern of non-significant increasing and non-significant decreasing trends at the remaining stations. These results would suggest that winter droughts are presently not a limiting factor across most of the study region.
Snow cover	Day in December of first continuous snow cover (> 2 cm). **Sensitivity:** Earlier snow cover is beneficial for root freeze protection.	All trends in this indicator were found to be non-significant and varied randomly across the region from increasing to decreasing.
Snow cover and Minimum Temperature	Number of days with <5 cm of snow cover AND daily minimum temperature <= -10°C from December 1 – March 31. **Sensitivity:** Root freeze stress, if no insulating snow layer.	There is a significant decrease in this indicator at La Pocatiere, Quebec (7.6 days over 83 years). Non-significant decreases are found at the remaining locations, except non-significant increasing trends occur at the two Vermont locations, (see Figure 2). Significantly increasing trends in this indicator would not be beneficial to syrup production.

Given the analysis presented above, the most significant atmospheric influence on sap production is temperature, especially the optimum thermal window. This finding provides a significant opportunity to develop environmental prediction capabilities, as well as monitor the migratory changes in sap production under climate change.

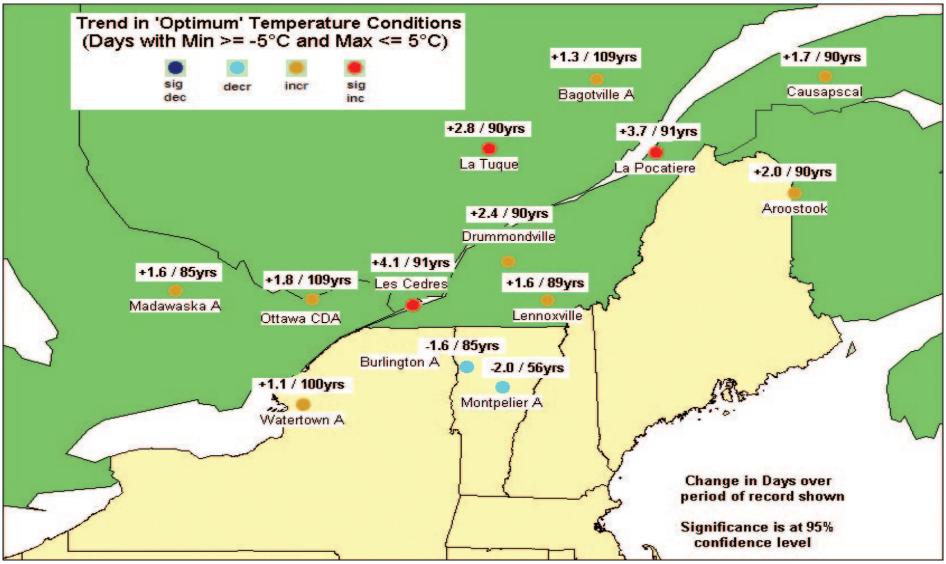

FIGURE 1. Best fit linear regression trend in number of days between February 1 and March 31 with minimum temperature >=-5°C and maximum temperature <=5°C. (The optimum temperature range preferred for sugar maple sap production is –5°C to +5°C, so an increasing trend in this indicator is beneficial for maple syrup production).

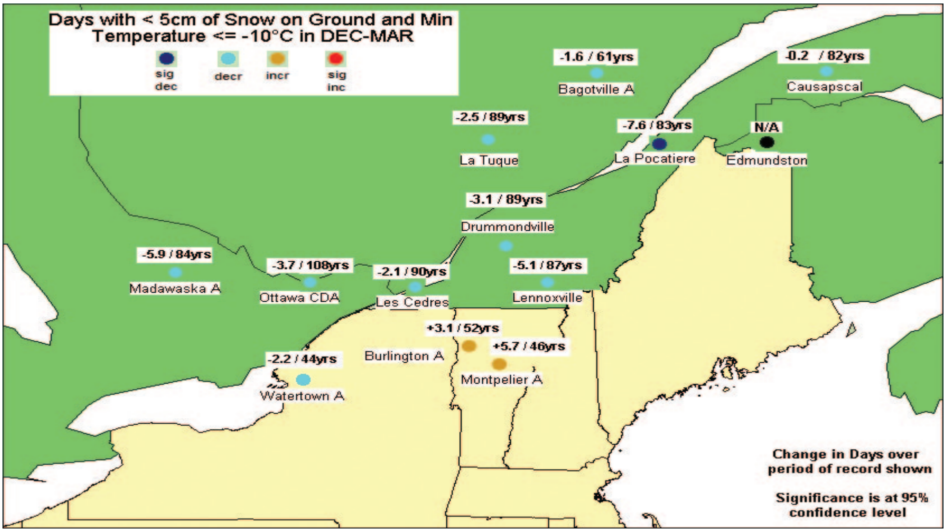

FIGURE 2. Best fit linear regression trend in number of days between December 1 and March 31 with < 5 cm of snow cover and minimum temperature <= -10°C. (An increasing trend in this indicator is not beneficial for maple syrup production).

CONCLUSIONS ON THE SUSTAINABILITY OF THE NORTH AMERICAN MAPLE SYRUP INDUSTRY

Sustainability of a climate sensitive industry of this type depends on its adaptive capacity and, in particular, the ability to increase resilience to the changing climate. For example, good forest management practices, efficient technologies for sap collection, remedial actions, such as fertilization and liming, are sound investment strategies to reduce the cumulative stresses on established and aging sugar maple stands. Environmental prediction models need to be developed to help producers understand and cope with the variability of the climate.

With this in mind, the current paper has profiled our current understanding of climate influences on the sugar maple industry in North America. The analysis section, although limited, has provided some insight into the changing nature of the climate and, in doing so, has highlighted the importance of the optimum thermal window for sap production. The preliminary analysis of a few climate stations throughout northeastern North America indicates the increasing fragility of the southern regions of the commercial sugar maple forest in the United States and the sustainability of the industry in the Quebec region for at least the next 20 years, depending on the rates of future climate change. The periods of optimum temperatures are illustrated in Figures 3 and 4 for a Quebec and Vermont climate station, respectively. The increasing trend towards warmer temperatures in Vermont and the more infrequent periods of optimum temperatures are clearly evident in recent decades in Vermont, once more echoing the fragility of the United States sugar maple industry compared to Quebec. More detailed analysis, using additional climate stations, throughout North America and Ontario is clearly warranted.

The seasonal shifts in production towards an earlier spring onset of optimum conditions does not always translate into more sap production, given the fragility of the sap season to extreme weather events. In addition, sap production is clearly site specific and governed by many interacting stresses, including the health of the forest, industry technologies and exposure to extreme weather events. The most appropriate adaptation actions will involve forest management practices to improve the health of sugar maple and enhance resilience to pests and severe weather events. In this latter case, greater monitoring of climate conditions within each woodlot along with production indicators would be a worthwhile investment by individual producers. For example:

1. When considering the impact of climate change on sugar maple it is extremely important to examine all of the main climatic variables and influences and how they interact (Aber et al., 2001; Bassow and Bazzaz, 1998; Bragg et al., 2004).
2. Map the geographic range where temperatures during the late winter and early spring are between -5 degrees Celsius at night and +5 degrees Celsius during the day. Identify seasonal periods when this cycle has been interrupted by periods of above or below 0 degrees Celsius temperatures.
3. Identify years with periods of 10 to 15 days with high temperatures above 10 degrees Celsius and/or 10 to 15 nights without a frost, after February 1st.

4. Identify areas within the commercial tapping regions where average winter temperatures are currently above 0 degrees Celsius.
5. Gather data and models on budding dates of sugar maple trees (Raulier and Bernier, 2000). Examine phenology data to see if an earlier budding trend is appearing in sugar maple in Ontario as well as in other species. (Refer to Canada's plantwatch program (www.plantwatch.ca) as well as publications by Beaubien and Hall-Beyer (2003) and Schartz and Reiter (2000) on Lilac and Honeysuckle phenological observations (http://plantwatch.sunsite.ualberta.ca/)).
6. Gather data on tapping start dates, first boil dates, last boil dates and production per tap for Quebec and Ontario. Compare to eastern U.S. data, currently being gathered by Tim Perkins, Proctor Maple Research Center, Vermont. Evaluate whether an earlier trend is occurring in tapping start dates and first boil dates.
7. Include the tropical El Niño-Southern Oscillation (ENSO) and global atmospheric-oceanic mechanisms such as the SOI (Southern Oscillation Index) in the prediction models to help explain episodic decadal surges in temperatures and also changes in winter snow pack accumulation and summer precipitation.
8. Identify years with warmer temperatures in February and March, followed by sudden severe freezing. Gather daytime and nighttime temperature profiles for February and March.
9. Identify years with an unseasonably dry August and/or an unseasonably wet May, which may be detrimental to sugar maple growth and sap production (Tardiff et al., 2001; Richardson, 2004). Identify changes in precipitation patterns, especially at the more southern sites, where precipitation increases in importance as a determinant of sugar maple growth (Lane et al., 1993).
10. Identify periods of thaw-freeze stress between December and March (defined by daily maximum air temperature greater than or equal to 10 degrees Celsius for at least 3 consecutive days), followed by a freeze (daily minimum air temperature less than or equal to -10 degrees Celsius) for at least one day within the succeeding 7 days since last day of thaw (Auclair et al., 1996). Identify periods of root-freeze stress during this same period (defined as number of days between December and March when snow depth was less than or equal to 5 cm, and the daily minimum air temperature was less than or equal to -10 degrees Celsius) (Auclair et al., 1996).
11. Gather remote sensing data that have quantified annual changes in fall colours. The degree of red colour expression shows promise as a predictor of starch and sugar concentrations and sap yield.
12. Identify early spring weather characterized by high winds (i.e. winds after a storm), mid-winter thaws. Identify years of high summer droughts.
13. Correlate the climate change parameters with the 'window of vulnerability' time periods, based on maturation of the sugar maple forests in eastern Quebec; i.e. 1956 – 1968; 1981 – 1993 and 2045 – 2085 (Auclair et al., 1996).

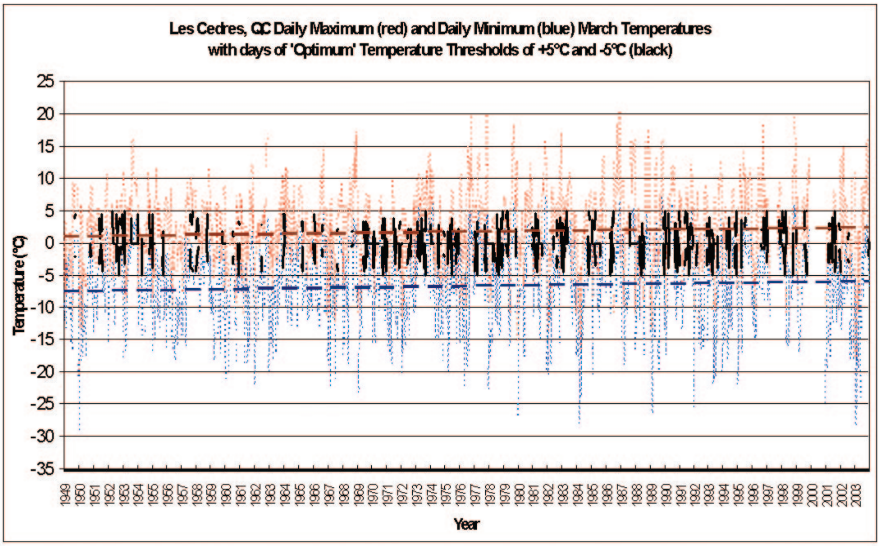

FIGURE 3: Optimum Temperature occurrences, maximum (red) and minimum (blue) temperature trends for Les Cedres, Quebec. Black shaded areas indicate the optimum thermal window for sap production.

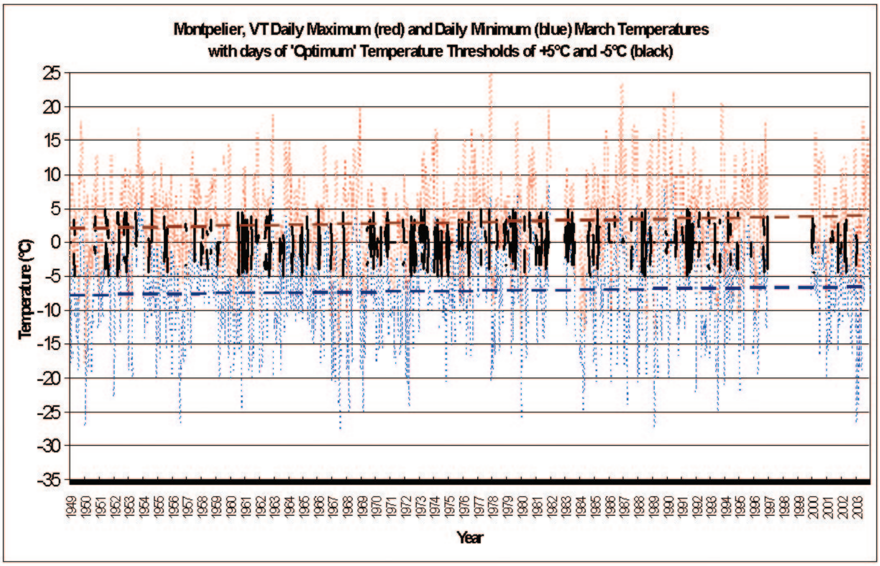

FIGURE 4: Optimum Temperature occurrences, maximum (red) and minimum (blue) temperature trends for Montpelier, Vermont. Black shaded areas indicate theoptimum thermal window for sap production.

14. Examine changes in average winter temperatures and average snow accumulation within the commercial range for maple syrup production.
15. As well as late winter and early spring temperatures, also include other factors in the model relating climate change to sugar maple production such as snow pack accumulation, freeze-thaw patterns, and the previous year's growing season temperatures and drought conditions.
16. Determine whether any combination of climate parameters and tree age can explain relatively low and high production years. Can future good or poor production years be predicted?

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