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Modelling the effect of climate on maple syrup production in Québec, Canada

Louis Duchesne [a,*], Daniel Houle [a,b], Marc-André Côté [c], Travis Logan [b]

[a] Direction de la recherche forestière, Forêt Québec, Ministère des Ressources naturelles et de la Faune du Québec, 2700, rue Einstein, Québec, Québec, G1P 3W8, Canada
[b] Consortium sur la climatologie régionale et l'adaptation aux changements climatiques (Ouranos), 550, rue Sherbrooke Ouest-Tour Ouest-19e étage, Montréal, Québec, H3A 1B9, Canada
[c] Union des producteurs agricoles du Québec, 555, boul. Roland-Therrien, Longueuil, Québec, J4H 3Y9, Canada

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ABSTRACT

Due to the exceptional sweetness of its sap, sugar maple (*Acer saccharum* Marsh.) is economically exploited at a commercial scale for maple syrup production in northeastern North America. Approximately 80% of world production is realised in the province of Quebec, Canada, where it is economically important for rural communities. Despite important financial investments in industrial infrastructure over recent decades, the maple syrup yield (ml of sap/tap/year) has followed a general declining trend over the last 15 years, presumably because of unfavourable climatic conditions. In this study, the relationship between climate and maple syrup yield by tap for the whole province was investigated.

A multiple regression model using four monthly climatic variables (mean January and April temperature and maximum temperature in February and March) explained 84% of the annual variation in yield between 1985 and 2006. This model was used to predict sugar maple syrup yield using a data set of future climatic scenarios issued from a large number of global climate models driven by different scenarios of CO_2 emissions. The results show that sap yield of sugar maple should decrease by 15 and 22% in 2050 and 2090, respectively, as compared to the 1985–2006 period. The increase in mean April temperature was responsible for most of the reduction in yield. Assuming that the variables included in the prediction model are expressing a pattern of successive climatic conditions that could be displaced in time, i.e., that may happen sooner in the season, the maple syrup yield could be maintained at its current level if the period of sap production can shift in time to occur 12 days and 19 days sooner in 2050 and 2090, respectively. Other potential effects of climate change on sugar maple range and health that could also affect the yield of maple syrup production in the future were not addressed in this study.

1. Introduction

Acer saccharum Marsh. (sugar maple) has a broad distribution in North America, spreading throughout the northeastern United States and southeastern regions of Canada. The bioclimatic domain of sugar maple-dominated stands covers approximately 17% of the commercial forested area of Québec, Canada (Robitaille and Saucier, 1998). Given the exceptional sweetness of its sap (Morse, 1895; Jones and Alli, 1987), this species has been exploited for maple syrup production since a long time from native people to the development of the contemporary industry. Because of the particular climatic conditions prevailing in southern Quebec, e.g. temperature fluctuations around 0 °C between days and nights for a few weeks each spring, the province has become the most important producer of maple syrup accounting to approximately 80% of the world production (Gouvernement du Québec, 2009). In 2007, it brought a cash flow of $223 million to maple syrup producers (Gouvernement du Québec, 2009).

This industry has increased in importance over the last three decades under the influence of several technological developments which allow a single farm to significantly increase the number of taps in its maple stands. In fact, both the number of taps and maple syrup production have doubled between 1980 and 2008 (FPAQ, 2008). However, the amount of taps in operation only slightly influenced annual variations in syrup production. Indeed, maple syrup yield is not only related to industrial infrastructures but also to environmental factors which affect sap flow and/or sap sugar concentration and consequently maples syrup yield (Cool, 1957). Producers of maple syrup are often facing low-yield years during which benefit–cost ratio is reduced. This may also lead to difficulties in market development due to the unstable supply over time.

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[*] Corresponding author. Tel.: +1 418 643 7994x6537; fax: +1 418 643 2165.
E-mail address: louis.duchesne@mrnf.gouv.qc.ca (L. Duchesne).

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Yield of maple syrup may vary according to numerous factors including physical tree parameters (Blum, 1973), genetic characteristics (Kriebel, 1989), foliar chemistry (Leaf and Watterston, 1964), soil fertility (Watterston et al., 1963), sap extraction and conversion methods (Morrow and Gibbs, 1969), and management of the production. For example, modernization of collection systems including the use of plastic tubing and vacuum pumping has gained in popularity over the last decades with an expected positive effect on maple syrup yield (Blum and Koelling, 1968; Koelling et al., 1968). Another potential factor that can affect syrup production is the sugar maple decline that has been reported at various locations in the deciduous forests of Quebec and northeastern US since the late 1970s (Duchesne et al., 2002, 2003). Poor sugar maple health could reduce maple syrup yields.

Although all the factors mentioned above could explain variations in maple syrup yield between trees or between sites, or predispose some stands in affected area to long time trends in syrup yield, none of them could explain the annual variability in maple syrup yield for a large geographical area. Climate is the most probable cause at the origin of yearly fluctuations. Some studies have attempted with success to relate the maple syrup yield to weather variables at the tree or the stand level (Cool, 1957; Plamondon and Bernier, 1980; Kim and Leech, 1985; Pothier, 1995; Robitaille et al., 1995). Most of the few existing studies focused on relationships between daily sap flow variations and daily climatic variables for specific sites with temperature having the most significant influence. To our knowledge, only one study has reported on annual sap yield variations and relationships with climate over a 14-year period (Pothier, 1995). At a site in southern Quebec, sap yield was positively correlated with the number of days characterized by temperature fluctuations around 0 °C during spring time, and with winter precipitation. Although this type of study may provide insights into the factors influencing sap production for specific sites, the results are not necessarily applicable to the vast area of the sugar maple biome comprised within the Quebec forest. Given the previously established link between maple syrup yield and climate, it is important to develop quantitative models that could be used to evaluate the impact of climate change on the maple syrup industry. This paper describes the effects of climate on maple syrup yield for a large geographical area in the province of Québec, Canada. The objectives were to (1) build a model based on climatic variables that can explain annual maple syrup yield variations for the whole area studied and (2) to provide a first evaluation of the impact of climate change on the future maple syrup yield in Quebec. We hypothesized that annual variations in maple syrup yield at the provincial scale may be predicted from temperature data. Results of this study will be particularly relevant to policy makers and governmental or industrial stakeholders involved in the maple industry in several Canadian provinces and American states in northeastern North America.

2. Materials and methods

2.1. Maple syrup production and yields

Every year, an annual survey is conducted on a sample of maple syrup farms in Quebec by an independent consultant group in order to determine the number of taps and annual production (FPAQ, 2008). Although this assessment has been done for many decades following different methodologies, recent surveys are suspected to be statistically more reliable. Moreover, nowadays maple syrup production numbers obtained through surveys are compared to a strict grading classification in order to avoid possible bias. Consequently, we limit our analysis to the 1985–2006 period (22 years). The annual yield was determined by the ratio of the annual production to the number of taps in operation. Annual production statistics reported in pounds per tap were converted to millilitre per tap using a conversion factor of 2.91 pounds per litre.

2.2. Meteorological data

Average climate data were computed from daily observations at 132 meteorological stations scattered throughout the sugar maple bioclimatic domain in Québec (Fig. 1). The stations have been in operation since at least 1980. Available data were minimum and maximum daily temperature, along with total daily precipitation. Sap flow generally occurs from the end of February to the end of April. However, injuries resulting from freezing during winter have been related to maple sap flow during the following spring (Robitaille et al., 1995). Consequently, we focused our analysis on climatic conditions occurring during the January–April period. For each year we computed the monthly minimum, maximum and average temperatures, monthly average daily amplitude, number of days with temperature below zero, number of days with freeze–thaw events, and total precipitation.

2.3. Statistical analysis

All possible multiple regression models were tested with RSQUARE procedure (SAS Institute, 2002) to determine the maximum amount of variance in annual variation in maple syrup yield that could be explained as a function of weather variables. The final model was selected based on Mallows's Cp-statistic (Mallows, 1973) and Akaike's information criteria (Akaike, 1973). Multicollinearity among weather variables of the selected model was tested and results indicate that dependencies among variables do not affect the regression estimates (condition indices ≤ 9.5; variance inflection factor ≤ 7.4) (Belsey et al., 1980). We also verified that no autoregressive structure remained in the error terms of the selected model using the AUTOREG procedure (SAS Institute, 2002).

Comparing model predictions with an independent data set (model validation) is a crucial step in ecological modelling (Aber, 1997). The model was calibrated on a period of 17 years (1985–2001) and was subsequently validated using independent data over a five-year period (2002–2006) which corresponds to approximately 20% of the data set. To evaluate the model, the coefficient of correlation and the Nash and Sutcliffe efficiency coefficient (Nash and Sutcliffe, 1970) were used. Observed and

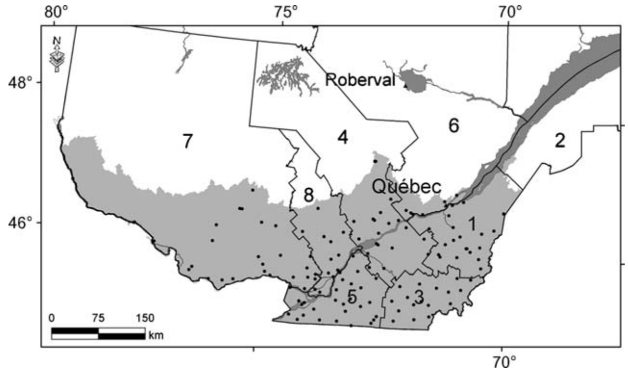

Fig. 1. Location of the 132 meteorological stations (black circles) used to generate climatic conditions for the sugar maple bioclimatic domain. The shaded area corresponds to the bioclimatic domains dominated by sugar maple. The numbers correspond to the grouped administrative regions—1: Chaudière-Appalaches, 2: Bas Saint-Laurent–Gaspésie, 3: Estrie, 4: Centre-du-Québec–Mauricie, 5: Montérégie, 6: Capitale nationale–Saguenay-Lac-St-Jean, 7: Laurentides–Outaouais–Abitibi-Témiscamingue and 8: Lanaudière–Laval–Montréal.

simulated values were compared using the paired *t*-test ($p = 0.05$). The evaluation was made for the calibration and the validation periods and for both periods combined.

2.4. Future maple syrup yield

Future climate projections were obtained from a large ensemble of global climate models (GCMs) made available to researchers by the Program for Climate Model Diagnosis and Intercomparison (PCMDI, Meehl et al., 2007). This provides researchers access to climate simulations produced by a large number of modelling centres around the world. Simulated climate data is available for present day (20th century) atmospheric conditions, as well as projected future climate in response to three projected future greenhouse gas emission scenarios (SRES family A2, A1b and B1 scenarios; Nakicenovic et al., 2000). These simulations have been endorsed by the international panel on climate change (IPCC) and form the basis of their 4th assessment report published in 2007. Gleckler et al. (2008) demonstrated the robustness of using the median or average of a large ensemble of climate simulations versus individual projections for reproducing the observed climate. An ensemble of simulations also has the advantage of providing a more robust indication of uncertainty in the projected future conditions. In total, 68 climate simulations were available for the present period (1961–2000) as well as two future horizons (2046–2065 or horizon 2050; and 2081–2100 or horizon 2090) were selected for the analysis. Climate simulations were produced from 16 individual GCMs (four simulations per model in average). The number of simulations for each SRES emissions scenarios was 25, 21, and 22 for the A1b, A2 and B1 scenarios, respectively. Selection was based on the availability of daily climate variables required in the final syrup yield regression model.

GCM climate data were extracted for each simulation for those model grid cells that intersect the study area (Fig. 1 shaded area). Because each GCM has a unique grid and resolution, individual GCM grid cells intersecting the area of interest were combined using a weighted average technique where grid cells are weighted by their proportional areal coverage of the entire study region. Simulated data were then used to predict syrup yield for the present period, and was validated versus the observed syrup production values for the region. Potential effects of climate change on syrup yield were then examined by calculating yearly anomalies in syrup yield for current and future periods for each simulation. Anomalies were calculated by subtracting the individual simulation's 40-year mean syrup yield for the present period (1961–2000) from the yearly projected values. Anomalies had the advantage of removing biases in "raw" GCM projections, as some models were shown to have tendencies to consistently over-or under-predict syrup yield due to inherent warm or cold biases in each individual GCM.

Potential adaptation capacity of sugar maple to changing climate was assessed by determining the required advancement in the timing of climate variables to reproduce, as closely as possible, current climate conditions in the two future periods. For example, an advance of one week would mean that a variable of monthly mean temperature for April in the final regression model is recalculated as the mean temperature from March 25 to April 23.

3. Results

Maple syrup production increased from 9.2 Ml in 1985 to 23.6 Ml in 2006 (Fig. 2). However, large fluctuations were observed over years despite a smooth and progressive increase in the

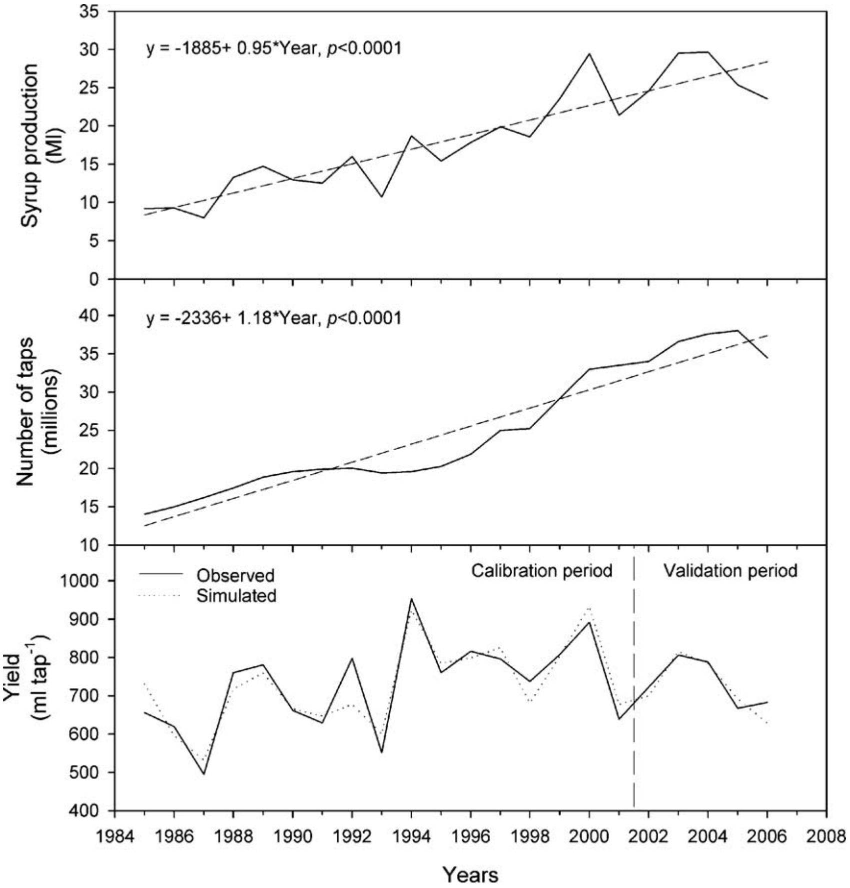

Fig. 2. Evolution of the maple syrup production, the number of taps in operation, and the annual yield per tap during the 1985–2006 period.

Table 1
Results of the multivariate regression analysis of the annual yield of sugar maple syrup in relation to monthly weather data ($n = 17$).

Variable	Coefficient	Std. error	T-statistic	Partial R^2	p-Value
Constant	570	113	5.0		≤ 0.001
Mean January	−11.4	5.9	−1.9	12.3	=0.078
Maximum February	22.7	4.6	4.9	33.6	≤ 0.001
Maximum March	13.7	6.3	2.2	2.1	=0.049
Mean April	−60.8	11.5	−5.3	36.4	≤ 0.001
Total				84.4	≤ 0.001

Table 2
Linear correlation coefficients and results of the paired t-test between measured (x) and simulated (y) values for the daily stem diameter variations (mm).

	Periods		
	Calibration (1985–2001)	Validation (2002–2006)	Overall (1985–2006)
n	17	5	22
r	0.92	0.92	0.92
P for paired t-test	0.999	0.527	0.821
RMSE	46	29	43
Efficiency[a]	0.85	0.78	0.94
x (ml)	727	734	728
$(y-x)/x$ (%)	<0.001	−1.3	−0.3

[a] Model efficiency = 1 − $(\text{RMSE})^2$/variance of observed values.

number of taps over time (14.0 million in 1985 to 34.5 million in 2006). For example, in 2001, total maple syrup production dropped by 27% as compared to the previous years despite a slight increase (2%) in the number of taps used for sap collection. Annual yield ranged from 495 ml tap^{-1} in 1987 to 953 ml tap^{-1} in 1994 and averaged 728 ml tap^{-1} over the study period. In fact, the significant increasing linear trends observed in the total production ($p < 0.001$) and the number of taps ($p < 0.001$) was not reflected in the annual yield (Fig. 2, $p = 0.164$). A multiple regression model using monthly weather values explained 84% of the variance in the maple syrup yield variation over the calibration period (Fig. 2 and Table 1). Mean temperatures of January and April were negatively related to the annual yield, while maximum temperatures of February and March were positively related (Table 1). Simulated values of annual yield variations were generally in good agreement with observed values in terms of temporal synchronicity and magnitude (Fig. 2 and Table 2). During calibration, validation and the whole periods, predicted and observed values did not differ significantly ($p \geq 0.527$). Correlation coefficients between observed and simulated values were 0.92 for all periods, and efficiency coefficients range from 0.78 to 0.94. The bias was lower than 1.3% in all periods considered. The unexplained variance in the regression models can be attributable to many sources, including the distribution of sugar bushes and climate variability over the studied area, surveys for production and yield estimation, and ecological processes that could not be defined from the selected weather parameters.

In order to explore the capability of the selected model to predict future maple syrup yields at the provincial scale, we analysed more closely the regional variability associated with the annual yield. Regional data, however, were only available for the 2003–2008 period (FPAQ, 2008, Fig. 3). Although some regions presented higher yields than others, annual syrup yield variations were similar among regions with the exception of the very low yield of the Bas-Saint-Laurent–Gaspésie (Lower St. Lawrence-Gaspé) region recorded in 2007. These observations suggest that the yield–climate relationship is relatively stable over the studied area.

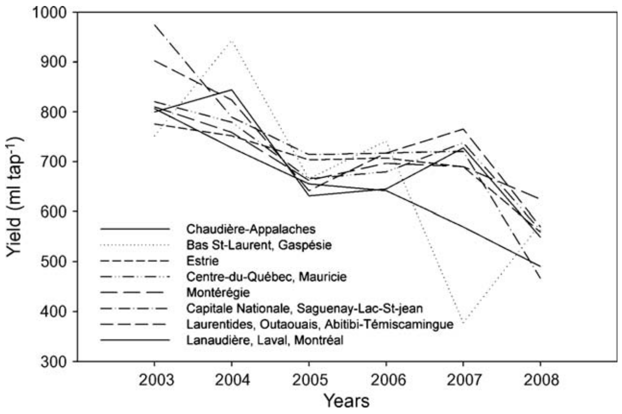

Fig. 3. Evolution of the maple syrup yields per tap during the 1985–2006 period in each administrative regions of Quebec used for yields statistics computations.

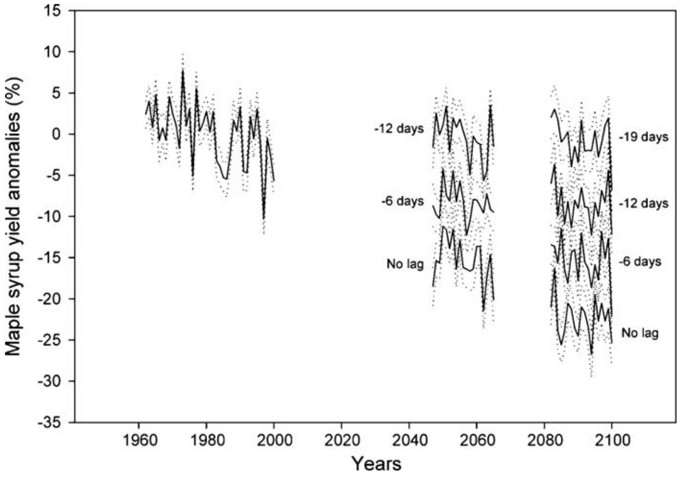

Fig. 4. Future maple syrup yield anomalies predicted from climate change scenarios. The effect of the progressive displacement in time of the sugar maple syrup season (lag in days) in order to adapt to the changing climate is also shown. A production similar to the reference period could be maintained if sugar maple is able to shift its sap flow season by 12 and 19 days, in the -2050- and the -2090- periods, respectively.

3.1. Maple syrup yield projections

Validation of GCM data indicates that ensemble climate simulations perform reasonably well in reproducing observed values of syrup yield. Observed data have mean annual syrup yields of 724 ml tap^{-1} whereas the ensemble median of 68 simulations is 744 ml tap^{-1} for the present period.

Simulations of the future maple syrup yield for the periods -2050- and -2090- using the predictive model obtained from the actual period of time (1984–2006) show average decreases of 15 and 22%, respectively. Assuming that the variables included in the model represent a timely succession of climatic conditions that could be displaced in time, i.e., that may happen sooner in the season, the maple syrup yield could be maintained at its current level if the period of sap production can shift in time to occur 12 days and 19 days sooner in the periods -2050- and -2090-, respectively (Fig. 4).

4. Discussion

4.1. Maple syrup yield versus climate

Little is known about relationships between sap flow (and maple syrup yield) and climate on an annual basis for large geographical regions. Most of the few existing studies focused on relationships between daily sap flow variations and daily climatic variables for specific sites. For example, at a site located in southern Quebec, Plamondon (1977) reported that the daily minimum and the difference between the minimum and maximum temperatures were correlated with daily sap flow variations over 40 days of observations in March–April 1975. Daily sap flow variations over two years have also been accurately predicted from an efficiency function determined from weather data (Plamondon and Bernier, 1980). In a four-year period of observations in central Michigan, Cool (1957) observed that daily maximum temperature correlated significantly with daily sap flow. Daily maximum temperature has been shown to be the most important climatic factor to increase daily sugar maple sap flow over a five-year study in southern Ontario (Kim and Leech, 1985).

To our knowledge, only one study has reported on annual sap yield variations over a 14-year period and relationships with climate (Pothier, 1995). Sap yield was highly positively correlated with the number of days characterised by temperature fluctuations around 0 °C during spring time, and with winter precipitation at a specific site in southern Quebec.

In the present study, a major innovation is that a large part of the variation in the annual yield of maple syrup over a relatively long period of time for a large portion of the sugar maple domain may be explained from a simple model using four monthly temperature variables (mean January and April and maximum February and March). In this model, the links with February, March and April temperature was somehow expected, since sugar sap flow may occur from the end of February to April, depending on the climate of a given year and stand location (see discussion below). However, the inclusion of January (mean January temperature was negatively related to the annual yield and explained 12.3% of its variance, Table 1) was somehow surprising. Two possible explanations may arise from links with snow pack depth and sap flow and/or sugar content.

The winters preceding a sugar maple dieback in 1932 (Pomerleau, 1991) and in 1981 (Payette et al., 1996) were characterized by periods of unusually thin snow cover that enhanced soil vulnerability to low air temperatures, which probably resulted in freezing and frost damage to the roots (Bertrand et al., 1994). In another experimental study, the removal of snow around sugar maple trees led to serious damage to roots and high nutrient export in soil water in spring and summer (Boutin and Robitaille, 1995). Soil freezing resulted in lower sap volumes and total sap sugar released during the season (Robitaille et al., 1995). It is possible that high air temperature during January may reduce snow cover depth, which reduces its insulation capacity, explaining the positive effect of low mean January temperature on sap yield.

The accumulation of soluble sugar in roots coincides with period of lowest soil temperature, suggesting that temperature during winter plays a decisive role in the sugar–starch–sugar cycle (Bertrand et al., 1999). Another biochemical change observed during cold acclimation of many tree species is a marked increase in soluble sugar concentration (Sauter and Van Cleve, 1991; Bertrand et al., 1999). Soluble sugar is thought to be a membrane and protein stabilizer during winter desiccation. It has been suggested by Sauter (1980) that passive leakage of sucrose into the vessels seems more probable during cold winter periods when enzyme activity is limited. Moreover, it has been suggested that severity and duration of freezing is among the main factors that determine the volume of water pulled into the sapwood during the conditioning period (dormant season), the latter determining the amount of water available for exudation (O'Malley, 1979). Consequently, low temperatures during winter may stimulate both sugar formation within the stem and sap flow during spring time.

It is important to mention that high maple syrup yields may be the result of a high amount of sap collected and/or the result of a high sugar content of the sap. Our data set does not permit to distinguish between both sources of variation. Nevertheless, following daily measurements of sugar concentration and sap volume from 29 trees over 18 years, Marvin et al. (1967) demonstrated a highly significant relationship between sugar concentration and volume of sap yield for individual trees. Johnson et al. (1987) also suggested that sap exudation was related to sucrose concentration, which appears to be independent of water uptake processes. Consequently, higher sap flow was generally related to a higher sugar maple concentration. Moreover, sugar content and sap flow has been related mainly to the same climate variables over a 14-year period (Pothier, 1995). These observations suggest that high yield years were the result of the combined effects of high sap flow and high sugar concentration.

Apart from the inclusion of January in the model, most of the variance in annual yield is explained by the mean April temperature followed by the maximum temperature of February and March. Although the effect of temperature on sap yield is well known, physiologically, the process is not fully understood. Temperature-dependant mechanisms have been proposed to explain sap and sucrose exudation during the dormant season (Sauter et al., 1973; Tyree, 1983; Cortes and Sinclair, 1985; Johnson et al., 1987; Cirelli et al., 2008). Occasionally, sap flow may begin in late February, but is most frequently observed in March when temperature is high enough to initiate sap flow (Kim and Leech, 1985). Consequently, higher maximum temperature in February and March favoured the initiation of sap flow. High daily sap flow is also observed during April until high air temperatures induce stoppage of sweet sap flow, with the result that high April temperatures reduce the total annual yield. Apart from the effect on physical and chemical mechanisms that produce sap flow, high April temperatures also accelerate the physical plugging of the tap, which is caused by the combined effects of a bacteria invasion and vessel blockage by microorganisms and/or gummy substances (Ching and Mericle, 1960).

4.2. Time trend in maple syrup yield

Total production of maple syrup increased during the study period, following the overall trend in the number of taps in operation (Fig. 2). However, despite the efforts invested by producers over recent decades to improve existing industrial infrastructures, there was no long trend in the annual maple syrup yield (ml/tap, Fig. 2). Efficient collection systems, including the use of plastic tubing (Koelling et al., 1968) and vacuum pumping (Blum and Koelling, 1968) are well known to increase total yield. These systems have gained in popularity over recent decades, with an expected positive effect on maple syrup yield, which was not the case. It is possible that the development of new and improved collection equipment was not synchronized among producers and regions; while some producers began to use new equipment, the equipment of others became obsolete, with an overall negligible effect on the syrup yield for the area studied. The absence of an increased yield over time despite the considerable investment in collection infrastructure need to be analysed in much more details.

In Québec, sugar maple decline (lower crown vigour, slower growth, and less abundant regeneration) was observed over a large area (Duchesne et al., 2002, 2005; Duchesne and Ouimet, 2008). The negative effect of decline and crown dieback on sap volume has been previously documented (Wilmot and Brett, 1995). Thus, sugar maple decline may have reduced maple sap yield over time, possibly countering the potential positive effect of equipment improvement.

The Québec maple industry overproduced syrup for many years in the late-1990s and early-2000s, leading to the establishment of a quota system in 2004 in order to control the production at the provincial scale. A quota was determined for each maple syrup producer according to the two best years of its historical production. However, this legislation was strictly implemented for the year 2005 and producers were allowed to produce over their quota limit in 2004. For 2005 and 2006, a large number of maple syrup producers were unable to produce their quotas because it was based on their best years of production rather than their average one.

Thus, the quota system appeared to have minor impacts on maple yield in terms of ml/tap during the period of study. The major impact was rather to stop the implementation of new taps in existing sugar bushes (Figs. 3 and 4). Moreover the yield–climate model explains 84% of the variance associated to maple syrup yield during the calibration (1985–2001) and the validation period (2002–2006). A significant effect of the quota policies on sugar maple yield would have resulted in a reduction of the model efficiency during the calibration period.

Overall, the high determination coefficient of the climate–yield model (84%) shows that climate was the main factor involved in the annual variation of syrup yield over the period studied, and that other sources of variation were actually negligible, at least for the large area where the study was conducted.

4.3. Future yield prediction

Simulations of the future maple syrup yield for the periods -2050- and -2090- show average decreases of 15 and 22%, respectively. The negative effect on future yield results mainly from the effect of the projected increase in the mean April temperature (average increase of 2.6 and 3.9 °C as compared to the period 1985–2005 in -2050- and -2090-, respectively), since high temperatures in April induce stoppage of sweet sap flow. It suggests that the major effect of climate change in the future will be from the premature ending of the sap flow season. Assuming that the variables included in the model are expressing a timely succession of climatic conditions that could be displaced in time, i.e., that may happen sooner in the season to adapt to the changing climate, the expected reduction in maple syrup yield could possibly be avoided. The maple syrup yield could be maintained at its current level if the period of sap production can shift in time to occur 12 days and 19 days sooner in the periods -2050- and -2090-, respectively (Fig. 4). Informal knowledge of the current temporal variability suggests that sugar maple may somehow adapt sap flow timing to the future climatic conditions predicted by the set of global climate models used in this exercise. It implies that the producers and the industry as a whole must also potentially adapt to the new timing of sap flow in the future.

All the above considerations, however, do not take into account the other potential effects of climate change on the range of sugar maple and its health that could potentially affect the yield of maple syrup production in the future.

5. Conclusion

A simple multiple regression model using monthly climatic variables explained 84% of the variance in the annual sugar maple syrup yield (ml/tap/year) for a large area of the sugar maple forest of northeastern North America that produces 80% of the world's syrup. This model was used to predict sugar maple syrup yield based on a set of climatic scenarios produced from a large number of global climate models. The results show that median global production should decrease in the future. A best-case scenario would be that production will be maintained if the duration of sap flow can shift in time to occur two to three weeks earlier in the season. More research is needed to document the temporal variability of sap flow within years and how it could vary among regions. Also, the absence of increasing yield trends over time, despite the considerable investment in collection infrastructures need to be analysed more fully.

Acknowledgments

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