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Reassessing the schedule of the sugar season in maple under climate warming

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Daily temperature fluctuations trigger physical and metabolic processes in the xylem, affecting the timing and yield of maple sap production. This study evaluates sap production dynamics, examining the effects of mean monthly temperatures and freeze-thaw cycles before and during the sugar season. We developed a predictive model estimating sap phenology, i.e. the timings of sap season and their climatic drivers, under future warming scenarios in Quebec, Canada. We collected air temperatures and daily sap production at four study sites in 2022 and 2023 using rain gauges for simulating a gravity collection of sap. We estimated sap phenology using a neural network model based on average monthly temperatures. The length of the sugar season was consistent across and within sites, with the highly productive days showing similar occurrence across sites. Sap yields ranged from 9.28 to 23.8 liters in 2022 and 3.8 to 13.6 liters in 2023. Freeze-thaw events occurred on 64% of the days when sap was exuded. Our neural network model predicted that a 2°C increase in mean monthly temperatures would advance the sugar season start by 17 days and end by 13 days. Any mismatch between tapping and favorable weather conditions can significantly reduce sap production. With climate change, producers will be forced to progressively readjust the schedule of their field activities and tapping to match the shifting sugar season.

KEYWORDS

maple syrup, *Acer saccharum*, sap exudation, freeze-thaw cycles, climate change

1 Introduction

Canada has the largest maple syrup industry in the world, representing both an important productive sector and a relevant cultural heritage for the local communities. In 2022, the country reached 78% of the global maple syrup production. The province of Quebec represented the main producer, accounting for 92% of the Canadian production

(Agriculture et Agroalimentaire Canada, 2023). The production chain starts with the sap extraction from the trees. This seasonal activity occurs from late winter to early spring, when temperatures fluctuate above and below the freezing point, freeze-thaw cycles (Tyree and Zimmermann, 2002). These daily environmental changes initiate physical and metabolic processes within the xylem, including the mobilization of sap along the stem. The fluctuation of the temperatures causes the expansion of gas within tissues and generates osmotic pressure through the movement of water in vessels and wood fibers (Graf et al., 2015; Schenk et al., 2021). As temperatures warm up during spring, the frequency of freeze-thaw cycles decreases, resulting in fewer productive days in late April and early May until the complete cessation of sap flow and the reactivation of the xylem functions (Perkins et al., 2022).

The sap production is influenced by several endogenous and environmental factors, such as tree characteristics (e.g., size and vigor), species, site characteristics (e.g., soil type, stand density, and fertility), and management activities (e.g., tapping history, tubing system) (Dey et al., 2017; Perkins et al., 2022; Rademacher et al., 2023). Nevertheless, the variation in the daily temperature is recognized as a main driver of the sugar season and yield. Previous studies established a connection between climatic conditions and sap production, with daily maximum air temperature during the sugar season being identified as a significant contributor (Kim and Leech, 1985). Plamondon (1977) observed that factors such as minimum air temperature and the temperature differential between the minimum and maximum temperatures play crucial roles in shaping the dynamics of sap production. Duchesne et al. (2009) reported that the variation in maple syrup yield between 1985 and 2006 in Quebec was explained by the temperatures from January to April. Furthermore, Duchesne and Houle (2014) suggested that the maple syrup yield is also affected by the daily minimum temperatures in winter and the warmer and drier conditions occurring during the previous summer.

There is evidence of a dramatic increase in the global temperatures. The average annual temperature in Canada has risen by 1.7°C from 1948 to 2012, and projections indicate greater increases for the next future (Vincent et al., 2015; Intergovernmental panel on climate change, 2021). According to the RCP8.5 emissions scenario, and in case of a lack in mitigation measures, the annual average temperature in Quebec is projected to increase by 3.5°C by 2050 (Ouranos, 2015). As temperature plays the leading role in defining sap flow timings and yield, we expect that these anticipated climatic conditions will influence the phenological dynamics of sugar maples (Guo et al., 2020), leading to an advancement of the sugar season in maple (Skinner et al., 2010; Houle et al., 2015).

The impact of the future climate on sap production is becoming a major concern among maple syrup producers. For this reason, the producers have already made or plan to make modifications to their farm management (Kuehn et al., 2017; Legault et al., 2019). However, the lack of knowledge on the impact of climate change on the timings of the sugar season raises questions on the best moment to prepare the trees for the sap extraction (Caughron et al., 2021). Producers also would like to improve the methods of sap extraction to maintain a sustained and homogeneous yield, despite the large inter-annual variability in the optimal climatic conditions for sap flow (Ahmed et al., 2023). To mitigate potential future negative effects on their production, most producers are willing to develop climate change adaptation strategies based on a deeper knowledge of the physiological mechanisms within the trees and innovative technologies of sap extraction that guarantee the long-term health of the maples (Ahmed et al., 2023). However, the adoption of new strategies largely depends on the production scale. Indeed, large-scale producers are more inclined to embrace new strategies and express less concern regarding higher profitability and available capital to invest, compared to small- and mid-scale producers (Caughron et al., 2021). Nowadays, most profitable mid- and large-scale maple farms have implemented technologies, including vacuum tubing systems, while a huge number of producers, generally of small size, still collect sap using the traditional system by gravity.

Some predictions of sap and syrup production for the next decades have been conducted to better understand the effects of climate change on the maple industry. For instance, Duchesne et al. (2009) combined the statistics of annual syrup yields in Quebec with daily climatic records to project future sap yields and the optimal periods of sap production in 2050 and 2090. Skinner et al. (2010) used sap flow days across the Northeastern US and future climate projections using various emissions scenarios to estimate the timings of sap production by 2100. Similarly, Houle et al. (2015) assessed syrup yield across several regions of Quebec and projected future timings of syrup production during the years 2046-2065 and 2081-2100 according to global climatic scenarios. Overall, these studies predicted a higher frequency of years with a short sugar season over the next decades, particularly in southern Quebec.

Most of the abovementioned studies focused on chronologies of annual and weekly yields. These statistics contain several potential sources of error, including the evolution of the tapping systems, the new technologies for sap extraction, and the two main species of maple involved in syrup production. Our study investigates the impact of future climate scenarios on the timings of maple sap production in Quebec, Canada, to (1) describe the daily timings of sap production and sap yields; (2) analyze the relationships between the timings of sap production and the temperatures; and (3) build and apply a model to predict the timing and length of the sugar season in a context of climate warming. We raise the hypothesis that warming conditions advance the reactivation of maple in spring, thus affecting the timings of sap production.

2 Material and methods

2.1 Location and characteristics of the study sites

Four study sites were selected in L'Anse-Saint-Jean (ASJ), Laterrière (LAT), Rivière-à-Pierre (RAP), and the Parc national des Monts-Valin (PMV) to cover a wide variability in the climate occurring at the northern limit of sap production in Quebec, Canada (Figure 1). RAP (46.91°N, 72.03°W, 185 m a.s.l.) is the southernmost site, located in the hardwood forest subzone, belonging to the sugar maple-basswood bioclimatic domain. ASJ

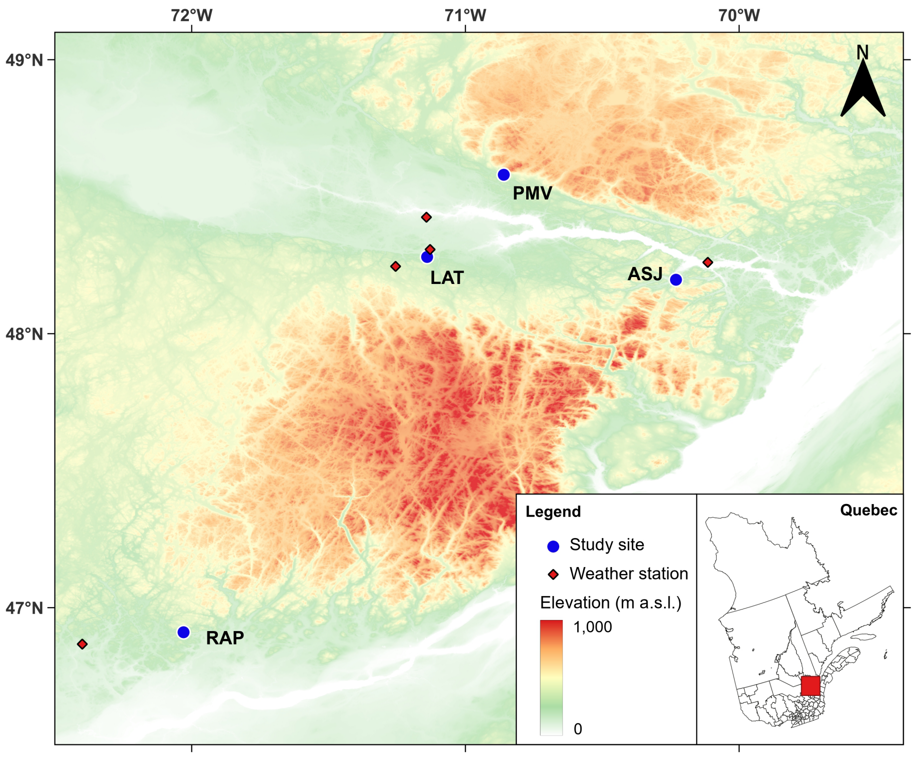

FIGURE 1
Location of the four study sites (blue dot) and weather stations (red triangle) at the northern distribution of sugar maple in Quebec, Canada.

(48.23°N, 70.13°W, 35 m a.s.l.), LAT (48.28°N, 71.14°W, 231 m a.s.l.), and PMV (48.58°N, 70.86°W, 230 m a.s.l.) are in the mixed forest subzone. They belong to the balsam fir-yellow birch bioclimatic domain, with a typical cool continental climate, long, cold winters, and mild, wet summers. Our sites are characterized by Humo-Ferric Podzols, a soil type typically found near the southern edge of the Canadian Shield (Sanborn et al., 2011).

2.2 Data collection

In 2022 and 2023, we randomly installed rain gauges (HOBO Data Logging Rain Gauge RG3-M, Bourne, MA) on two healthy adult sugar maples (*Acer saccharum* Marsh.) per site (Supplementary Table S1). The equipment was installed in early February before the freeze-thaw cycles and the sap production season. The equipment was removed in mid-May when the sugar season was complete. One rain gauge in 2023 at ASJ had some technical issues and was unable to collect data, thus this maple was not included in the successive analyses.

To tap the tree, we made one notch on the stem (ca. 5 cm deep) using a sanitized drill and inserted a new spout connected to a plastic tubing and simulating a traditional gravity tapping. In 2023, the trees were tapped on the opposite side to prevent injuries caused by the previous tapping and potential interference in sap production. The upper part of the rain gauges was protected with a sealed cap to avoid obstruction from snow, leaves, or animals. The sap water moved through the tube into the rain gauge, working as a funnel-shaped collector. Inside the equipment, the water was drained into a small bucket (2.83 ml), which tipped over when filled with sap water, spilling the content out of the rain gauge, and resetting itself for the next measurement. The sap volume was measured by counting the number of times the bucket tips over during a given period, set in this study at an hourly scale and summed up on a daily scale. The measurements were sent to a data logger that recorded the exact time of the tip, the amount of collected sap water, and the air temperature. To maintain the accuracy of the measurements, each equipment was calibrated and disinfected before every maple season.

Climate data were extracted from the Government of Canada archive (Government of Canada, 2024) from November to May 2021-2023 to obtain the daily temperatures for the months preceding and following the sugar season, when the equipment was not installed. We selected the weather stations closest to each study site: Lac aux sable (46.86°N, 72.40°W; 29 km from RAP), Laterrière (48.30°N, 71.12°W; 3 km from LAT), Pointe Claveau (48.26°N, 70.11°W; 17 km from ASJ), and Jonquière (48.42°N, 71.14°W; 27 km from PMV).

2.3 Data analysis and statistics

For each site, a quadratic logistic regression was performed to predict the timings of the sap production for each of the two studied years. The sap production was converted into binary values, indicating the presence or absence of daily sap production. Each model, per year and site, included the day of the year (DOY) as the only predictor. Due to the small number of observations, the sap production measurements were separated into a training (80%) and a test set (20%) to evaluate the model performance. We also applied a 5-fold cross-validation as the resampling method for model assessment. Using the test set, we chose as the optimal threshold the one closest to the top-left corner of the receiver operating characteristic (ROC) curve, which represents the relationship between the true positive rate (sensitivity) and the false positive rate. We averaged the optimal thresholds to use the same value for all regressions.

We performed support vector machine regressions to predict site-specific data logger temperatures for the period preceding and following the sugar season when the rain gauge was uninstalled. These models can be effective when dealing with the non-linear relationships of temperatures (see for example Yalavarthi and Shashi, 2009). We used the minimum and the maximum temperatures collected by the weather stations as predictors. We separated the chronologies into a training set (70%) and a test set (30%) to assess how well the model generalizes to new data and evaluating the model performance. We applied 10-fold cross-validation with 5 repetitions as the resampling method due to the small amount of data per site and year (53-87 observations) to ensure more reliable and robust performance metrics. The goodness of fit of the regression models was evaluated using the coefficient of determination (R^2) for the training and test set to determine the capacity of the model to capture the variance in temperature and the root mean squared error (RMSE) to measure the precision of the predictions.

We calculated the average monthly minimum and maximum temperatures across sites and years using the daily temperatures estimated by the vector machine regressions. We then used regressions to test the relationship between monthly temperatures (explanatory variables) and the onset and ending of sap production (response variables). We obtained the coefficient of determination (R^2) to evaluate the fitting of each model, and we compared visually the range of temperatures across months and the influence of minimum and maximum temperatures on the timings of sap productions.

A neural network model was performed to estimate the timings of sap production using the average monthly temperatures as input. We applied the final model to scenarios of monthly temperatures raising from 0 to 2°C to estimate the timings of sap production under a context of warming, being capable of adapting to new data patterns. We separated the observations into training and validation. The learning rate was set to 0.1. Due to the reduced sample size, we used only one observation for validation, which represented a holdback of 0.125. The performance of the model was evaluated using the coefficient of determination (R^2) for the training and the residuals. Most statistical analyses were performed in R (R Core Team, 2022) using the packages caret (Kuhn, 2008) and pROC (Robin et al., 2011). The neural network model was performed using JMP Pro 17.0 (SAS Institute Inc., 2022, Cary, NC).

3 Results

3.1 Phenology of sap production and sugar season

The quadratic logistic regressions estimated the sugar season based on the daily sap flow occurrence for each study site and year (Figure 2). The accuracy of the training set and the Cohen's Kappa coefficient were 0.74-0.90 and 0.24-0.75, respectively. The threshold was established using the test set according to the closest top left threshold in the ROC curve and was averaged and fixed at 35% for all regressions. We observed an earlier onset in 2023 (DOY 72-90) compared to 2022 (DOY 80-93). The estimated durations of the sugar season in 2022 and 2023 were 35-41 and 32-39 days, respectively. Although the high productive days occur at the same time among sites, we observed a difference in the beginning and ending of the sugar season between trees within the same site.

At RAP, the southernmost site, the sap production occurred from late-March to late-April (DOY 80-120, 41 days) in 2022 and from early-March to mid-April (DOY 72-110, 32 days) in 2023. At ASJ, sap production started in early-April in 2022 (DOY 93-127, 35 days) and 14 days earlier in mid-March 2023 (DOY 79-110, 32 days). LAT had the same onset in late March, with a longer duration in 2022 (DOY 90-128, 39 days) compared to 2023 (DOY 90-123, 34 days). At PMV, the northernmost site, sap production onset was in late March 2022 (DOY 85-129, 45 days) and lasted 10 days less in 2023, with onset in mid-March (DOY 79-113, 35 days). On average, the sap production started approximately 7 days earlier and the duration was 7 days shorter in 2023.

3.2 Sap production

Compared to 2022, we observed an increase in sap production of approximately 22% at RAP (from 9.28 to 11.4 liters) and a decrease of 65% at PMV (23.8 to 8.35 liters) in 2023 (Figure 3). There was an increase of less than 1% at LAT (13.5 to 13.6 liters) and a decrease of 75% at ASJ (15.6 to 3.8 liters) from 2022 to 2023 (Supplementary Table S2). The daily pattern of sap production exhibited many days with low sap production and few, very productive days. Across sites and years, the 50th and 75th percentiles of daily sap production were 80-364 ml and 175-923 ml, respectively. Furthermore, days with sap production below 100 ml contribute only to 2-21% of the total sap production. Only occasional and highly productive days recorded a sap flow >2 l. The cumulated sap production confirmed the synchronism in the productive days, although with different amounts of sap yield.

We considered freeze-thaw events to occur when the nighttime (minimum) temperature was <-1°C and the daytime (maximum) temperature was >3°C. On average, freeze-thaw events occurred in 64% of the sap flow days, i.e. when daily sap production was >3.73 ml. For daily productions >100 ml and >1 l, freeze-thaw events occurred in 72 and 94% of the days during the sap season, respectively. When sap flow occurred without freeze-thaw events (36% of the days), the average minimum and maximum temperatures were 0°C and 11°C, respectively.

On average, the sap flow days occurred with minimum and maximum daily temperatures of -3.0 and 11.8°C, respectively. Based on the 10 most productive days across sites and years, the minimum daily temperatures ranged from -13 to 6.8°C and the maximum daily temperature ranged from 0 to 24°C. The days of the sugar season with no sap flow occurred with a minimum temperature of -4.6°C (range between -18 and 5°C) and a maximum temperature of 4.9°C (range between -8 and 23°C).

3.3 Temperature estimations

The vector machine models estimating the daily temperatures in the sites from the weather stations produced R^2 of 0.86–0.97 (training) and 0.78–0.97 (validation) for the maximum temperatures. For the minimum temperatures, the R^2 was 0.88–0.96 (training) and 0.85–0.97 (validation) (Supplementary Table S3). The estimations indicated that the weather stations could estimate reliable temperatures for the periods before and after the sap production in the study sites, when no data logger was installed in the field.

The first nighttime frosts occurred in October in both study years (Figure 4). Maximum temperatures fell under 0°C in late November and mid-November in 2021 and 2022, respectively. The temperatures of December were colder in 2021 (from -15 to -3°C) compared with 2022 (from -8 to 0°C). Similarly, January 2022 experienced lower temperatures (from -26 to -13°C) than January 2023 (from -14 to -3°C). For both years, February temperatures were mostly negative. March and April were characterized by negative minimum but positive maximum temperatures. May had mild temperatures, generally above the freezing point. In each year, most daily maximum temperatures remained above the freezing point throughout the sugar seasons. In contrast, daily minimum temperature was generally <0°C, exceeding the freezing point at the final days of the sap production (late April to early May).

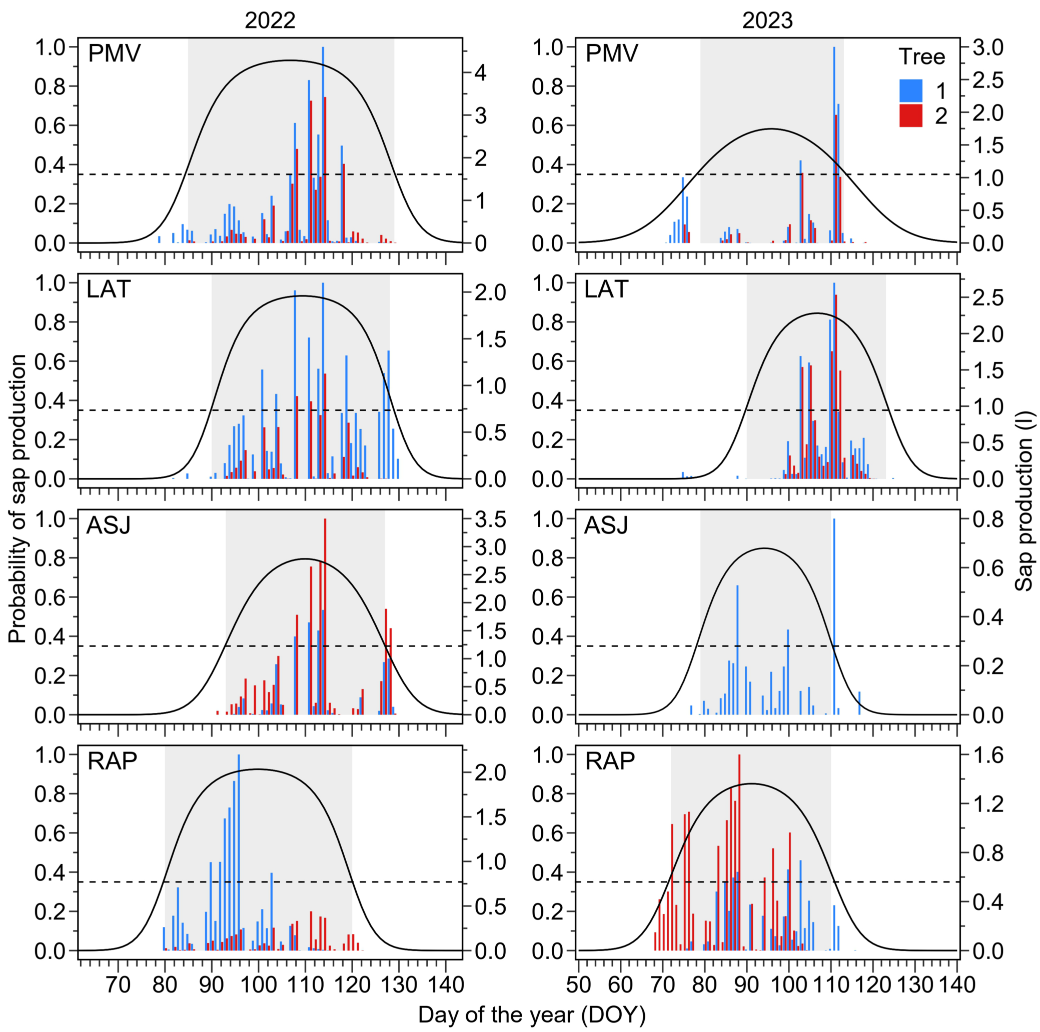

FIGURE 2
Sap production (l/day) in maple trees and the probability of sap flow occurrence during spring 2022 and 2023 at four sites in Quebec, Canada. The dashed line and the grey area represent the chosen threshold and the predicted timings of the sap production, respectively.

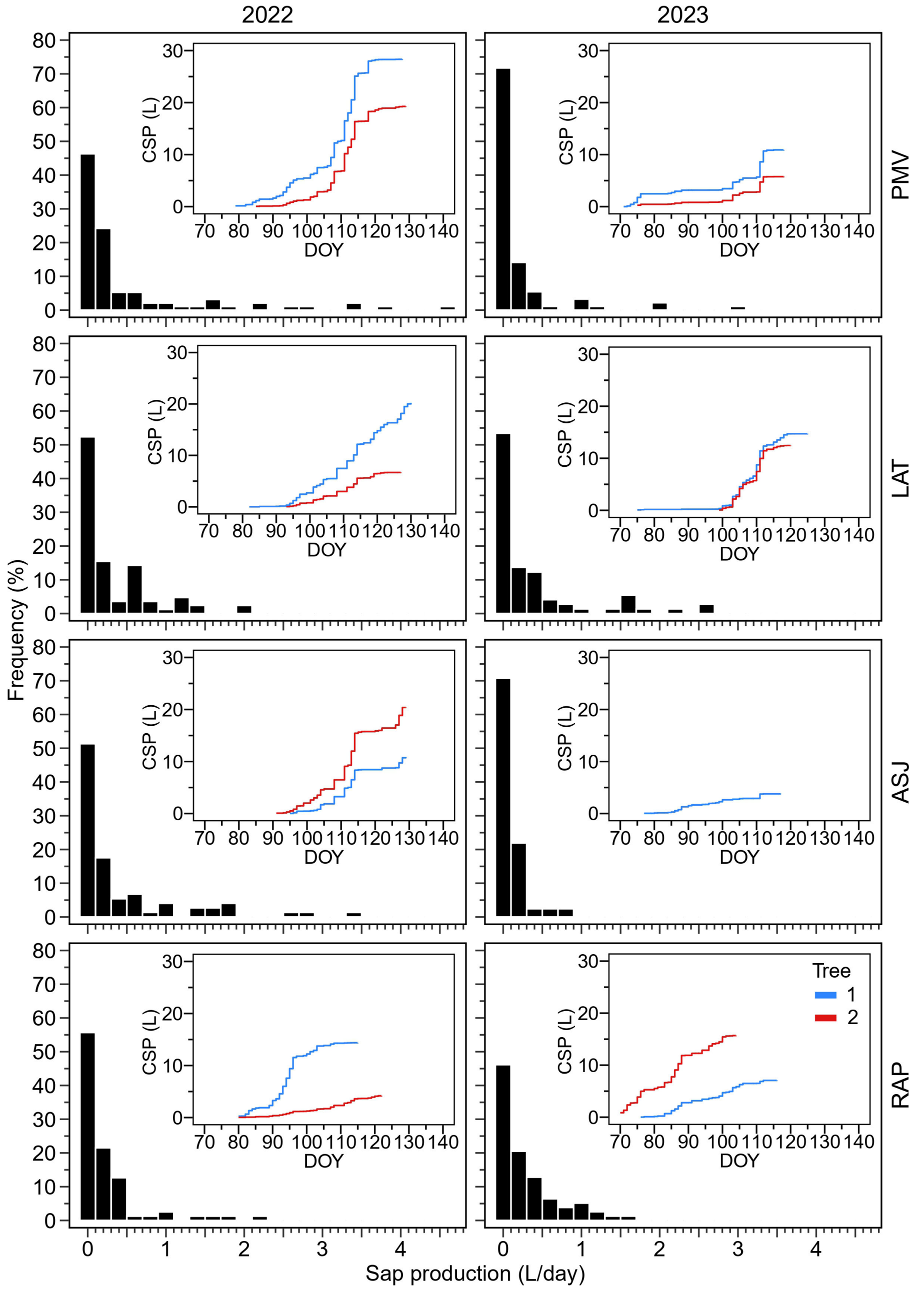

FIGURE 3
Distribution of the daily and cumulated sap production (CSP) during the sugar seasons 2022 and 2023 at four sites in Quebec, Canada.

3.4 Linear regressions and neural network

Linear regressions demonstrated that warmer monthly minimum and maximum temperatures before and during the sugar season advance the timings of sap production (Figure 5). We observed significant relationships on most maximum temperatures ($p<0.05$) and in January and March for minimum temperatures. Mean temperatures differed across years in January, with colder conditions and late sugar seasons observed in 2022. In April, the models were significant only for maximum temperature.

Neural network analysis produced a global R^2 of 0.94 (training), with separate R^2 of 0.85, and 0.82 for the onset and the ending, respectively (Supplementary Figure S1). No overfitting was detected, even with the limited data volume, and the temperature increases did not compromise the calibration range. For the monthly average temperatures across all sites and years, our model estimated a sugar season spanning from late-March to early-May (DOY 87-123), lasting 37 days (Figure 6). By incrementing the temperature up to 2°C, our model of sap phenology estimated an advancement of the onset by 2-17 days, and an advancement of ending by 2-13 days. The sugar season, i.e. the duration of sap production, increased up to 4 days under warming temperatures, more specifically 37 days at the first warming (0.1-0.2°C), and then rising to 41 days with warming of

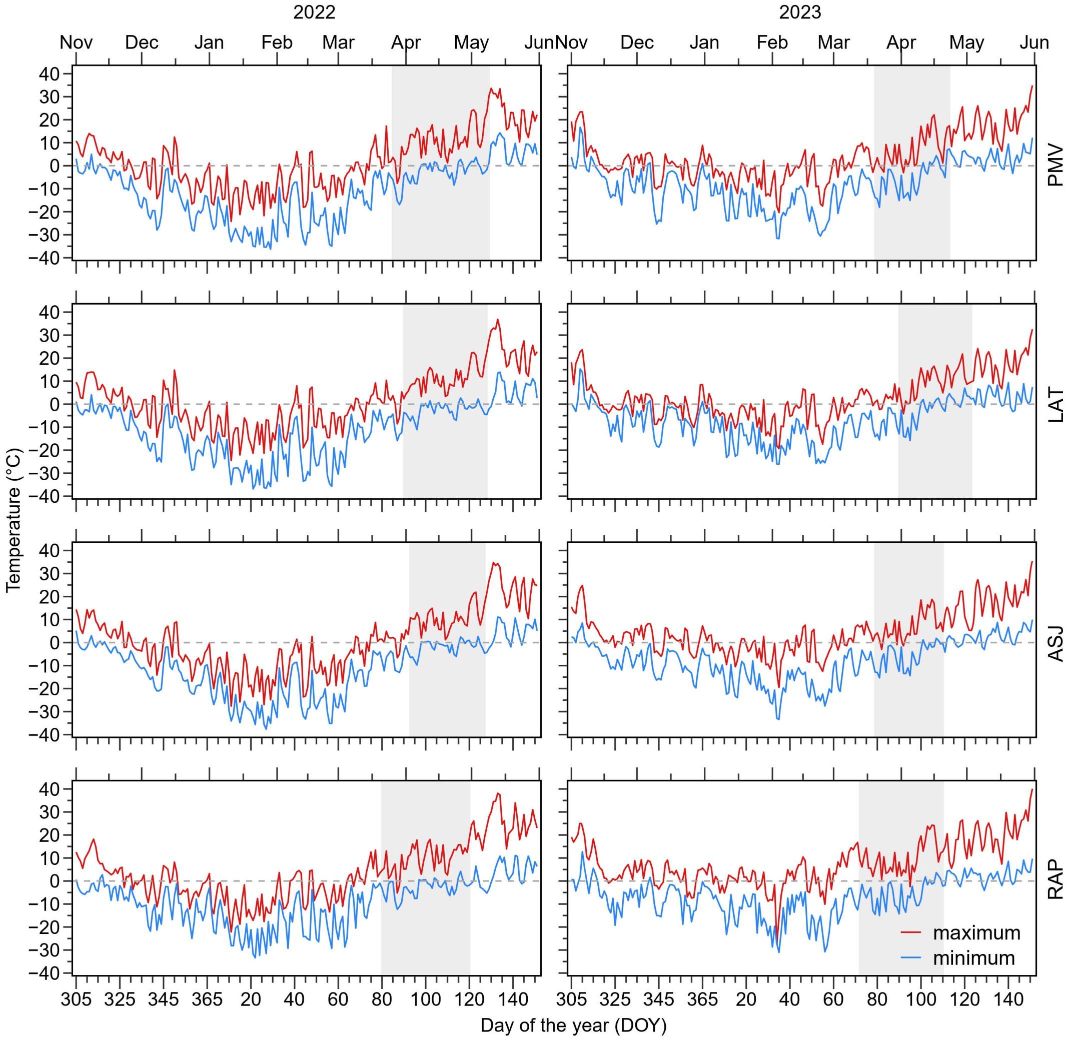

FIGURE 4
Predicted minimum and maximum air temperature before and during the sugar seasons 2022 and 2023 at four sites in Quebec, Canada. The grey area represents the estimated timings of the sap production.

1.9-2.0°C. The first warmings (0 -0.5°C) produced faster advancements in the sugar season, while advancements slowed down under higher temperature increments.

4 Discussion

In this study, we investigated the relationships between winter and spring temperatures on the timings of sap production in Quebec. We built a model to predict sap phenology under warming conditions, which estimated advancements in both the onset and the ending of sap production under warmer January to April conditions. We estimated an advancement of 17 and 13 days on the onset and ending of the sugar season, respectively, based on an increase in the average monthly temperatures of up to 2°C. These results confirmed our hypothesis that warming temperatures advance the growth reactivation of maples, the rehydration of the xylem, and, consequently, the timings of sap production.

4.1 Comparing sugar season and yield between years

Compared with 2022, sap production in 2023 began and ended 7 and 12 days earlier, respectively, resulting in a shorter sugar season. This advancement of sap phenology can be associated to the higher temperatures occurred in spring 2023. The southernmost study site, RAP, also exhibited the earliest sap production during both years, probably related to the earlier spring warming (Duchesne and Houle, 2014). In contrast, the latest onset of sap production was recorded at ASJ in 2022, likely due to its colder temperature compared to the other study sites.

Compared to 2022, sap yield in 2023 increased marginally at RAP (+22%) and LAT (+1%) but decreased substantially at PMV (-65%) and ASJ (-75%). This marked reduction is in agreement with the statistics provided by the producers. Indeed, Canada experienced a productive season in 2022, which was followed by a drop in production (-40%) in 2023, the lowest production since 2018

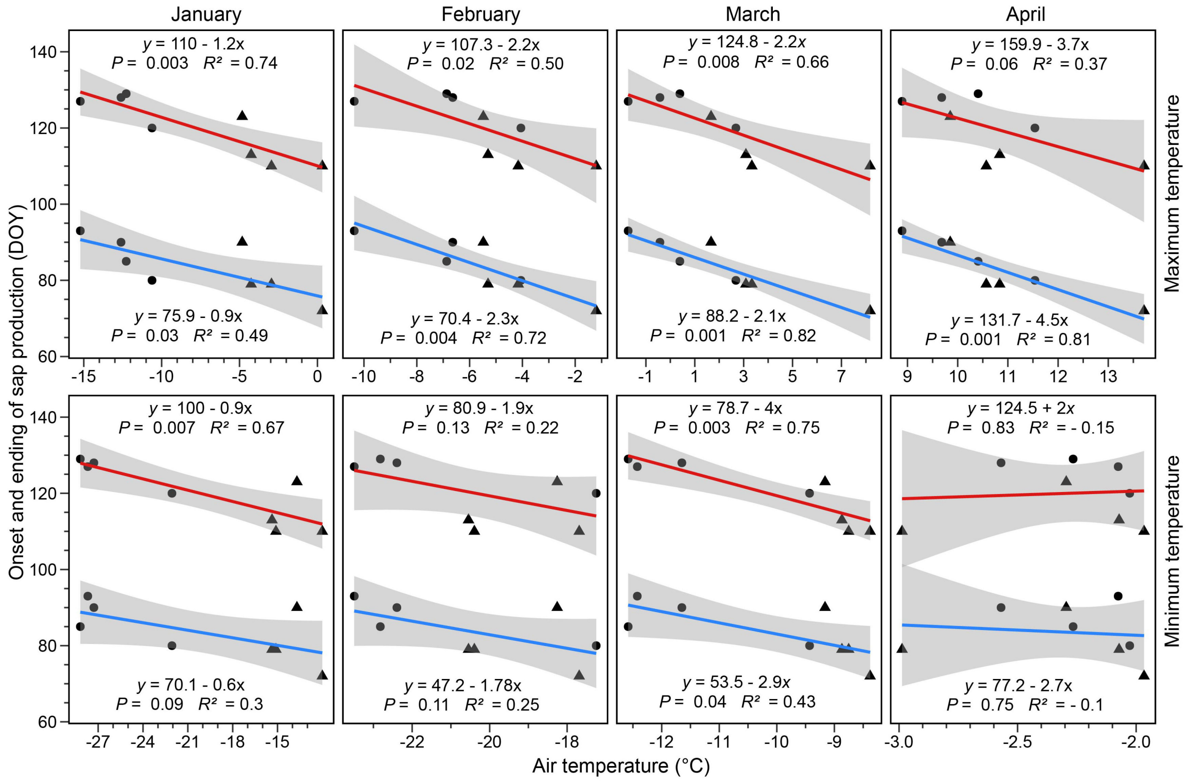

FIGURE 5
Linear regressions between average monthly minimum and maximum air temperature and the timings of sap flow season (onset in blue and ending in red) in 2022 (round symbol) and 2023 (triangle symbol). The grey area represents the 95% confidence interval.

(Agriculture et Agroalimentaire Canada, 2023). The year 2022 was characterized by low winter temperatures, specifically in January. On average, the mean monthly minimum and maximum temperatures in January 2022 were 12.3 and 9.7°C lower than in January 2023, respectively. Duchesne et al. (2009) found that mean January temperatures accounted for 12% of the variation in annual syrup yields. Additionally, Duchesne and Houle (2014) reported that winter cold hardiness influenced the spatial variability in yield. The soluble sugars that accumulate in the stem during winter enhance the frost hardiness of tissues by lowering the freezing point, thus reducing the vulnerability to frost and damage from cold temperatures (Wong et al., 2003). Hence, cold temperatures may affect positively the sugar accumulation during winter and the quality of sap during the sugar season.

Our findings demonstrate the impact of winter temperature on sap phenology and sap yield. These results are crucial for maple syrup producers, which raise questions on the evolution of this production under climate change. The observed trend in the sugar season under warming conditions suggest the need for investigating more in depth the potential changes in the sap yield. To effectively address this issue, the research should develop tailored, site-specific designs that test local climatic and environmental conditions. In terms of adapting tapping practices to climate change, adjusting tapping dates and employing technologies like vacuum tubing systems, could help to maintain an elevated yield under changing conditions (Skinner et al., 2010; Rapp et al., 2019).

4.2 Sap production and freeze-thaw events

The daily freeze-thaw events occurred during 65% of the productive days. If we consider exclusively days with high productions, i.e. >100 ml and >1 l), the frequency of daily freeze-thaw events increases to 72 and 94%, respectively. These results demonstrated the close relationship between the daily freeze-thaw events and the higher sap productions, and confirmed the previous findings by Duchesne and Houle (2014), where sap flow measurements occurred in 80% of the days with freeze-thaw events. The potential changes in the occurrence or frequency of freeze-thaw events driven by the warmer climate predicted for the next decades could negatively affect the number of productive days and, consequently, the sap yield (Ho and Gough, 2006; Skinner et al., 2010). However, contrasting predictions are proposed in the literature on this issue. Ho and Gough (2006) predicted no substantial modification in the number of freeze-thaw events under future warming. Accordingly, Skinner et al. (2010) estimated no difference in the number of sap flow days by 2100 across the Northern-Eastern US. In our study, the days with sap flow and without freeze-thaw events may be related to productive periods when sap flow continues at nights and extends until the next day (Perkins et al., 2022). As a result, maple producers can benefit from these extended and unexpected sap flows occurring at night and keep the vacuum system running also during nighttime to profit from an extended period of sap flow.

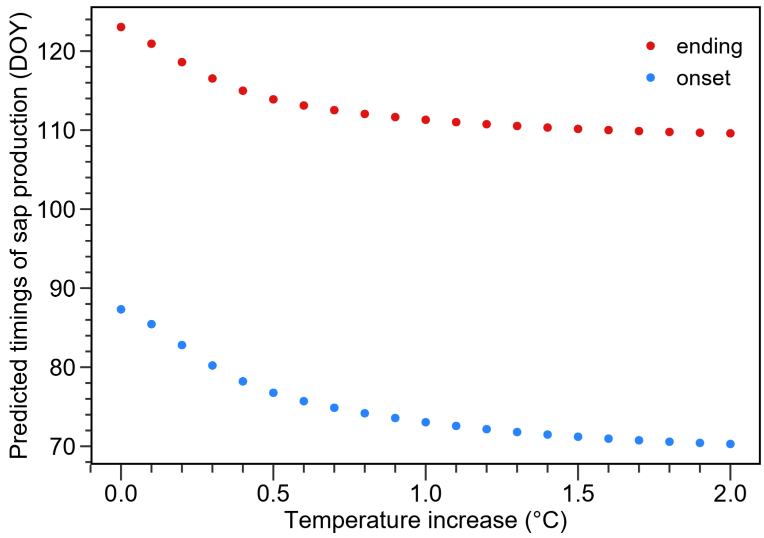

FIGURE 6
Predicted timings of onset and ending of sap production obtained by neural network model according to temperature increases based on average monthly minimum and maximum air temperatures.

In most cases, we recorded a low sap production at the beginning of the sugar season. During this period, there are intervals of a few days with colder temperatures, resulting in no freeze-thaw events and, consequently, no sap production. A positive pressure initiates with several freeze-thaw cycles (Tyree and Zimmermann, 2002). On average 28% (11 days) of the days during the sugar season showed no sap exudation. Freeze-thaw events also occurred during some of these unproductive days. In fact, 17% of the days with no sap flow occurred after freeze-thaw events, corresponding to only 1 to 4 days per site and year. This result suggests that the occurrence of one or few freeze-thaw events is not sufficient to induce sap exudation, but several events eventually foster sap exudation, which is likely associated with previous consecutive unproductive days, particularly at the start of the season. During this early and unproductive time, the stems and the soil are still partially frozen, thus slowing down sap exudation (Perkins et al., 2022). As the sugar season advanced, the results indicated an increase in daily sap production, which may be related to the higher frequency of freeze-thaw events. We also observed that without the occurrence of freeze-thaw events, sap exudation may continue, as a possible result of a carry-over effect of previous freeze-thaw cycles. However, such a hypothesis needs to be tested. Further study would be needed to determine the number of consecutive days with or without these cycles required to continue or cease the sap exudation.

4.3 Projections of sap phenology

We estimated an advancement of up to 17 and 13 days in the onset and the ending of sap production, respectively, under warming scenarios. These results are based on the timings of sap production and average monthly temperatures from January to April. We applied uniform temperature increases of up to 2°C in these monthly averages, representing a moderate warming scenario compared to the projected rise of up to 3.5°C in the annual average temperature by 2050 for Quebec (Ouranos, 2015). Our estimations are in agreement with previous studies that predicted both an earlier onset and ending of the sugar season (Duchesne et al., 2009; Houle et al. (2015); Skinner et al., 2010). Specifically, Duchesne et al. (2009) estimated advancements in the sugar season of 12 days and 19 days in 2050 and 2090, respectively. Another study considered a moderate and an extreme carbon emission scenario, with advancements in the period of sap production of 15 and 30 days in 2100, respectively (Skinner et al., 2010). Similarly, Houle et al. (2015) suggested that the sugar season could advance, on average, by 9-13 days for 2046-2065, and by 15-19 days for 2081-2100, and found no significant variation in the length of the sugar season during the simulated periods.

Previous modeling efforts were based on monthly or yearly temperature projections derived from gas emission scenarios and historical syrup yield records (Skinner et al., 2010; Houle et al., 2015). Contrarily, our model is based on a uniform temperature increase and continuous daily sap production measurements over the sugar season. Despite the difference in the data source and model structure, our results converge with previous findings (Skinner et al., 2010; Houle et al., 2015). Moreover, mathematical models have been developed to explain the advancement of the sugar season under warmer conditions from an eco-physiological perspective (Graf et al., 2015; Schenk et al., 2021). Graf et al. (2015) reported that root water uptake and freezing point depression are the main factors driving sap exudation, despite the need of additional experimental evidences.

Freeze-thaw events drive the timings of sap production. During the sugar season, ice crystals form in the air-filled fiber cells when the air temperature drops below 0°C. This process draws water into the fibers, compressing the air bubbles. As negative pressure spreads within the tree (where stem pressure is lower than atmospheric pressure), water is pulled up through the roots and stem until the sap freezes (Kozlowski and Pallardy, 1996). As the temperature rises above the freezing point during the day, the branches and the stem thaw, pushing the sap back into the vessels. This shift in temperature stimulates the conversion of stored starch to sucrose, which is loaded into the sap. When ice crystals in the fibers thaw, osmotic pressure from sucrose draws water out, leading to sap exudation from the taphole due to positive pressure (Pickard, 2003; Perkins et al., 2022). For these reasons, predicted warming conditions advance the fluctuations in air temperature above and below the freezing point, which consequently lead to earlier freeze-thaw cycles, fluctuations in the temperature of the wood, and the exudation of sap from the tap holes (Kurokawa et al., 2022).

Our model agrees with the scientific literature. However, the robustness and precision of the results could benefit by longer chronologies of sap phenology. Further research is needed to investigate the effects of climatic drivers different than the temperature and the uncertainties associated with the variability in sap yield within a maple stand. Explanations on the complex interactions between tree physiology, and the timings and dynamics of sap production could help the producers to sustain the production in the context of climate change.

5 Conclusion

Our study estimates advancements of 17 and 13 days for the onset and the ending of the sugar season under warmer scenarios. The variations in winter and spring temperatures influence sap production (Duchesne et al., 2009). Our results also indicate that the daily freeze-thaw cycles occur during 65% of the sap flow days, thus demonstrating the relationships with an abundant sap exudation. Overall, our study provides evidence that climate change, and particularly the warmer temperatures in winter and spring, can affect sap phenology and the sap yield for the sugar maple industry. Technological advances have greatly enhanced the production system over the recent decades by enabling highly automated systems that maximize the yield. However, with the shifting timing of the sugar season, there is an urgent need for further investigation to assess the ecophysiological processes underlying sap exudation in maple. Such studies will enable a more rational determination of the optimal window for tapping the trees, a critical and yet largely unexplored aspect of the production chain. Gaining new insights into tapping timings and potentially improving tapping methods could mitigate the uncertainties and the pressures that producers face under the ongoing climate change. Small-scale producers should adapt to climate change by strategically adjusting tapping times based on the predicted onset and ending of sap production. Such adaptation strategies are vital for ensuring the economic sustainability of the maple syrup industry and the long-term health of maple stands in the following decades.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

GdLS: Formal analysis, Investigation, Methodology, Software, Visualization, Writing – original draft. RS: Methodology, Supervision, Writing – review & editing. SK: Investigation, Resources, Writing – original draft, Writing – review & editing. GdL: Writing – review & editing. SR: Conceptualization, Funding acquisition, Methodology, Project administration, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fagro.2024.1496255/full#supplementary-material

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