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PROJECTING SPATIAL CHANGES IN SUGAR MAPLE SAP FLOW REGIMES IN A CHANGING CLIMATE

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by

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Abstract

Anthropogenic climate change presents a potential threat to maple syrup production in Canada. To mitigate risks associated with climate change, information about the biological changes that may occur in a warming climate are necessary. This project studied one component- sap flow- that in part determines the economic viability of maple syrup production. A temperature-based sap flow model was used to project the start of the sap flow season in southern Ontario, and GIS applications were used to aggregate the results. The start of the sap flow season was projected for early, mid, and late-century periods under two climate change scenarios, RCP4.5 and RCP 8.5, using data from the Canadian Regional Climate Model (CRCM) CORDEX experiments. In both scenarios, a majority of the study area experienced an earlier start to sap flow; the northernmost extent of the sugar maple range saw the greatest shift to earlier sap flow dates, particularly in the RCP8.5 scenario. Some areas around the Great Lakes did not meet the criteria for sap flow to begin for the mid-century and late-century periods in both scenarios. For the mid-century period, the RCP4.5 scenario showed sap flow beginning earlier for most of the province- excluding the northernmost areas- than RCP8.5. For the late-century period, RCP8.5 showed a greater shift in sap flow dates than RCP4.5. The results suggest that maple syrup producers will need to take adaptive measures to respond to shifts in the sap flow season.

Acknowledgements

I would like to sincerely thank my advisor, Dr. Colin Robertson, and my reader, Dr. Robert McLeman, for their guidance– this research would not have been possible without their expertise. I would also like to thank my family: my parents for their encouragement, my sister for keeping me positive, and my partner for the immense support he provided throughout this degree. I lovingly dedicate this work to my late grandfather, Lloyd Gosse, whose belief in education inspired all of his grandchildren to pursue postgraduate studies.

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1.0 Introduction

Anthropogenic climate change is expected to significantly impact Ontario's forests (Colombo et al. 2007). Changes in temperature, precipitation, and disturbances (e.g. pathogens and forest fires) may alter both the health and distribution of species (Dale et al., 2001). The economic value of forests, in both timber and non-timber products, is expected to be affected by climate change. Ochuodho et al. (2012) found that in most economic and climate change scenarios, the forestry sector in most of Canada will experience a significant economic loss - in a worst case scenario, climate change impacts on forests could result in Ontario losing over $200 billion in GDP by the end of the century.

The geographical range of 130 tree species in North America is estimated to move an average of 700km northward over the course of the century due to climate change (McKenney et al., 2007). Studies of both flora and fauna around the world suggest that the geographic distribution of species will shift; for species adapted to narrow climatic conditions, ranges will contract in some cases.

Maple syrup, produced primarily by sugar maple (Acer saccharum) trees, is one product whose production will likely be impacted by a changing climate (Murphy et al., 2012). In the short term, changing temperatures will affect sap flow in maples, and in the longer term, a changing climate could result in a shift in the geographical range of maples (Brown et al., 2015). The current range of sugar maples is shown in Figure 1.

Canada accounts for 71% of the world's maple syrup production, mostly in Québec; Ontario produces 5% of Canada's maple syrup products (Agriculture and Agri-food Canada, 2019). In 2018, Ontario produced 465,000 gallons of syrup, valued at slightly under $24 million

CAD (Agriculture and Agri-Food Canada, 2019). In addition to its economic value, maple syrup also holds historical and cultural significance to Canadians (Murphy et al. 2012).

While there is considerable research examining the impact of climate change on forest ecosystems (e.g. Dale et al., 2001; Aitken et al., 2008; Matthews et al., 2013), there are few studies looking at sugar maples specifically, and even fewer that discuss biological and phenological responses of sugar maples to climate change. Among these studies, nearly all are focused on Québec or the northeastern United States, and only Brown et al. (2015) studies Ontario specifically. Existing literature has found that producers have already begun to tap sugar maples earlier in the season (Houle, 2019), and that adaptive measures will become increasingly important to ensure the continued economic viability of maple syrup production (MacIver et al., 2006; Skinner et al., 2010). The timing of sap flow is critical to producers, as tapping too early or too late results in reduced volumes of sap collected (MacIver et al., 2006).

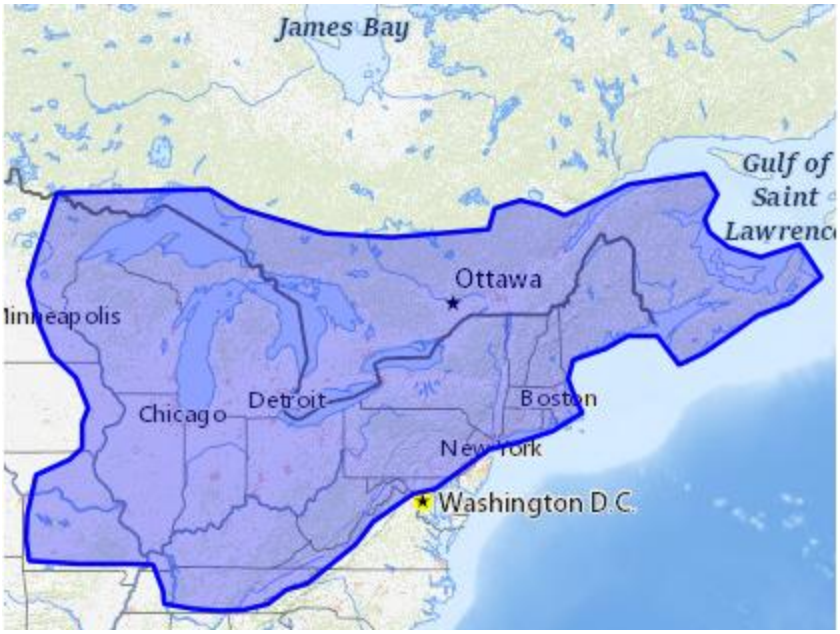

Figure 1: Current sugar maple range. USGS, 2020.

This project seeks to fill some of this knowledge gap by examining the impact of climate change on the spring sap flow regimes of sugar maples, upon which maple syrup production relies. This research focuses exclusively on Ontario. This will provide an assessment to the industry about the spatial patterns of changes in sap flow regimes resulting from climate change.

1.1 Research Goal

The purpose of this research is to forecast the potential impacts of climate change on sap flow regimes in maple syrup-producing trees in Ontario.

1.1.1 Research Objectives

1. Synthesize current literature on climate and climate change impacts on sugar maples to identify optimum maple sap flow conditions.
2. Acquire, edit and transform regional climate data for two representative concentration pathways (RCP4.5 and RCP 8.5) into a format suitable for input into a Geographic Information System (GIS).
3. Using a temperature-based optimum sap flow conditions model the start of sap flow seasons based on forecasted spring temperatures
4. Produce maps showing the spatiotemporal patterns of changes in sap flow regimes for Ontario
5. Assess and evaluate the sap flow model and its projections.

2.0 Literature review

2.1 Climate change

Climate change is arguably the most pressing modern environmental issue; shifts in the global climate system have the potential to alter or damage both human and natural systems. Though public discourse often centres on the change in the mean global surface temperature, the tangible impacts of climate change are more complex than global averages. In addition to shifts in temperatures and precipitation, changes in winds, tropical storms, atmospheric circulation, and the cryosphere are expected (Stocker et al., 2013). Changes are expected to be highly heterogeneous, with the greatest temperature changes occurring in the Arctic (Fyfe et al., 2013; Stocker et al., 2013).

Canada is expected to see considerable changes in climate. In Ontario, projections suggest that even under a very low forcing scenario, the province could be warmer by an average of 1.7°C by the end of the century; in a high forcing scenario, the average change is 6.3°C (Zhang et al., 2019). The province as a whole is expected to have more precipitation, particularly in the Great Lakes region (McDermid et al., 2015; Zhang et al., 2019; Zhang et al., 2020). The projections in both the McDermid et al.(2015) and Zhang et al. (2019) studies were based on findings from the Intergovernmental Panel on Climate Change (IPCC).

2.2 Climate modelling

The IPCC is an international group of scientists and policy makers who produce Assessment Reports (AR) that synthesize the literature discussing the physical science of climate change, vulnerability and adaptation to climate change, and mitigation options. The most recent reports are AR4 (2007) and AR5 (2013). The World Climate Research Programme brings modelling groups from around the world together to participate in the Coupled Model Intercomparison Project (CMIP); simulations from CMIP models are the basis for the Assessment Reports. Each modelling group participating in CMIP develops their own climate model(s) to contribute to the project. The CMIP models vary in complexity from basic energy-balance models to more sophisticated Earth system Models (ESMs) (Flato et al., 2013). CMIP phase 3 (CMIP3) was the group of models used in AR4. AR5 used both CMIP3 and CMIP5 models. A total of 25 and 51 models were included in CMIP3 and CMIP5, respectively.

Climate models are simplifications of the global climate system. In the past decade, our understanding of the complexities of the global climate system has improved significantly, and this improvement in understanding has resulted in better climate models. CMIP3 used coupled Atmosphere-Ocean General Circulation Models (AO-GCMs), which model the dynamics of interactions of land, ocean, atmosphere and sea ice (Flato et al., 2013). Earth System Models (ESMs) are currently the most detailed and sophisticated models available; these models include biogeochemical feedbacks, such as the carbon cycle, in addition to the dynamics in AO-GCMs. Some ESMs are of "intermediate complexity", which may not include all of the biogeochemical components of full ESMs, but may include other smaller-scale features such as ice sheets to answer specific questions (Flato et al., 2013). Most of the models in CMIP5 are ESMs.

Climate models run at very large scales, typically with a resolution of 1-2° (~110-225 km) over land and 1° over the ocean (Flato et al., 2013). In some cases, AO-GCMs or ESMs cannot answer local and regional scale questions, so climate models must be downscaled (see section 2.2.2).

2.2.1 Climate change scenarios

The IPCC has developed multiple climate change scenarios for both AR4 and AR5. The AR4 emissions scenarios were developed in the Special Report on Emissions Scenarios (SRES) (Nakicenovic et al., 2000). Four model "families" were developed, representing varying levels of development, investment in technology, population, and wealth distribution: A1, A2, B1, and B2. SRES A2 represents a high emissions scenario, SRES A1 represents a moderate emissions scenario, and B2 represents a low emissions scenario. The B2 scenario is also moderate emissions, but the A1 family is more commonly used in the literature. The A1 family was based on rapid development, significant investment and advancement in technology, high international mobility, and a population that peaks at 9 billion in 2050 and declines to 7 billion by 2100. The A2 family was based on heterogeneous economic growth across regions, continual population growth that reaches 15 billion by 2100, and a lack of improvement in equitable income distribution on a global scale. The B1 family was based on similar assumptions as the A1 family, but assumes more investment in environmental and social protection instead of in economic growth.

While the SRES scenarios represented a number of different narratives about global social and political possibilities, they did not explicitly include climate change mitigation strategies (van Vuuren et al., 2011a). For AR5, new scenarios were developed- Representative Concentration Pathways (RCPs) that included different levels of mitigation, and were based on the amount of radiative forcing (W/m2) in their scenarios. As in SRES, 4 scenarios were developed: RCP8.5, RCP6, RCP4.5, and RCP2.6. RCP 2.6 is based on very strong mitigation policy and a decline in GHG emissions before 2100 (van Vuuren et al., 2011b). RCP4.5 assumes some mitigation policy- GHG emissions pricing- to stabilize forcing at 4.5 W/m2 (Thomson et al., 2011). RCP 8.5 is a modified A2 scenario which assumes no climate policy (Riahi et al., 2011). RCP6, like RCP4.5, is a moderate scenario, though RCP 4.5 is more commonly used in the literature. Because RCP scenarios are based on the level at which radiative forcing stabilizes, they are not purely based on GHG emissions; for example, RCP6 can be seen as either having medium baseline emissions, or as having high mitigation.

2.2.2 Downscaling techniques and Regional Climate Models

Current climate models, coupled Atmosphere-Ocean General Circulation Models (AO-GCMs), have grid scales of several hundred kilometres (Meehl et al., 2007). They do not capture meso- and local-scale phenomena, such as orographical controls on local climate patterns. Regional climate models seek to capture more local-scale processes. Climate models are inherently uncertain, and the level of uncertainty tends to increase at finer scales (Giorgi et al., 2009). As such, techniques for creating regional climate projections has been and continues to be an area of considerable research (Flato et al., 2013; Giorgi et al., 2009). In order to create regional climate models, observations or numerical simulations need to be downscaled; Rummukainen (2010) likens regional climate models to a magnifying glass for GCMs.

There are two broad categories of downscaling techniques for regional models: dynamical downscaling and statistical downscaling. Dynamical downscaling is physics-based, and is modeled at higher resolutions than GCMs. Statistical downscaling requires statistical relationships between large-scale predictors and meso- to local-scale predictands to be established, and these relationships are applied to output from GCMs (Giorgi et al., 2009). While statistical downscaling has many benefits (Fowler et al., 2007), only dynamical downscaling will be discussed here, as this technique used to create regional climate models (RCMs).

Dynamical downscaling uses lateral boundary conditions from a GCM to produce a regional climate model or limited-area model (LAM). Some approaches "nest" a finer-resolution climate model within a GCM over a region of interest, while LAMs are exclusively for a given region, though boundary conditions are still taken from global GCMs (Rockel, 2015), and are still "nested" within a GCM (Environment and Climate Change Canada, 2015). Dynamical downscaling has also been an area of considerable research in the past decade, and this has resulted in several improvements (Flato et al., 2013). The primary development in the field has been the coupling of regional climate models with oceans, and in some cases sea ice and biogeochemistry (Artale et al., 2010; Smith et al., 2011). Coupled RCMs offer significant improvement in quality for many processes, such as precipitation and lake effects (Flato et al., 2013).

There have been significant improvements in RCMs in recent years, in part because of integrating RCMs with earth systems models, not just atmospheric climate models (Rockel, 2015). This follows the development of Coupled Earth-Atmosphere GCMs in the past decade that incorporate processes such as land surface and vegetation. However, evaluating the value of regional downscaling as a whole is challenging because most studies are not replicated, and so each have their own methods, observational datasets, variables being studied, and region(s) being studied (Flato et al., 2013).

The Canadian Regional Climate Model (CRCM) is a LAM that is designed to work over any specified domain on the globe (Environment and Climate Change Canada, 2015). The CRCM uses boundary conditions from a GCM (in this case the Coupled General Circulation Model (CGCM) developed by the Canadian Centre for Climate Modelling and Analysis (CCCMA)). Experiments run using the RCP4.5 and RCP8.5 scenarios are available at resolutions of ~45 km2 and ~25 km2. Data from the CRCM with a ~25 km2 resolution was used for this study.

2.2.3 GIS as a tool for analyzing climate change impacts

GIS has been an invaluable tool in environmental studies for many years. Nearly two decades ago, Mackey (1996) stated that "GIS and environmental modelling provide new capabilities for analysing the space/time distribution of ecological phenomena." The role of GIS in environmental analysis has continued to grow, and has been adopted as a tool in many disciplines, including conservation (van der Wel et al., 2004), natural hazards (Pradhan, 2010; Raj and Sasipraba, 2010), and meteorology (Dyras et al., 2005).

GIS has already proven to be an important tool for understanding climate change. In a 2009 study, Mearns et al. developed a framework for assessing climate change impacts, and identified GIS as a critical tool. Aside from the scientific value GIS tools offer, another principle benefit of using GIS is that it is an exceptionally useful way to communicate climate change to policy makers and the public. O'Neill and Hulme (2009) found that GIS-based visualization tools were effective in engaging the public with climate change. Shaw et al. (2009) found that GIS (along with other visualization tools) were highly effective in fostering participatory approaches to climate change.

GIS tools are beneficial not just in their analytical capacity, but also in the flexibility of their end use. GIS tools do not necessarily have to produce maps or other visuals, but their ability to do so (and usually fairly easily with proper data availability) makes it an attractive tool for researchers whose work is based in informing public policy, industry, or the general public. In the case of climate change impacts, this is a particularly important feature in an analysis tool since it allows complex climate science to be presented in a clear and accessible way.

GIS is a useful tool in this study because it allows for assessment of changes at local scales instead of broadly defined regions. Studies that aggregate data based on regional definitions often obscure intra regional variation and transitions between regions. Mapping results is also an important way to make results helpful to a non-academic audience: maps can be interpreted more easily than tabular visualizations.

2.3 Climatic influences on sugar maple health and syrup production

Maple syrup yields vary widely from year to year; fluctuations in temperature and moisture result in variation in sap volume, sap sugar content, and the length of the sap flow season (Bauce & Allen, 1991; Bertrand et al., 1994; Duchesne et al., 2009; Duchesne & Houle, 2014). Sap flow occurs in sugar maples when there are below freezing nighttime temperatures and above freezing daytime ones, with the optimum range being -5° and +5°C (MacIver et al., 2006). To be commercially viable, the sugar sap concentration needs to be high (2-3%); if the sugar concentration is lower, it takes more sap (and consequently more energy) to produce a given volume of maple syrup (Wilmont et al., 1995). For commercial production, the volume of sap flow is also important, and this is affected by climatic conditions and tree health (Duchesne et al., 2009; Wilmont et al., 1995).

Duchesne et al. (2009) found that mean January and April temperatures, along with maximum February and March temperatures accounted for 84% of the annual variation in yield from 1985-2006 period, which was marked by an overall decline in maple syrup yield (mL of sap/tap/year). While winter conditions are a key determinant of maple product yields, summer droughts and low autumn soil water recharge are also detrimental to sugar maple health (Bauce & Allen, 1991). As such, an understanding of the past and current climatic influences on tree health is a necessary prerequisite to diagnosing the impacts of climate change on maple syrup (and other maple product) production.

2.3.1 Freeze stress

Robitaille et al. (1995) found that trees that were subjected to deep soil freezing had significantly lower sap flow rates, lower sap volume, and lower total sugar per tree for at least two years after their experiment; they posited that this was related to poor health, including branch dieback (and consequent thinning of the canopy). Several past sugar maple diebacks, as well as other northern hardwood diebacks, have been the result of climatic variability, particularly freeze stress on root systems (Bertrand et al., 1994; Auclair et al., 1996; Cleavitt et al., 2008). Soil freezing events are associated not with just low temperatures, but a lack of snow cover (Bauce & Allen, 1991; Bertrand et al., 1994). Thus, wintertime snowmelt and thaw events can actually increase the risk freeze damage. Other research suggested that snow depth was as important a factor as snow cover, as shallow snow kept soil warmer, but close to 0ºC, making it more susceptible to freeze-thaw events (Decker et al., 2003).

Root freezing and thaw-freeze events have been found to be a precursor to sugar maple decline and dieback, though not necessarily a cause. Rather, freeze stress events have a deleterious effect on tree health, weakening and predisposing them to diebacks as a result of other stressors, such as drought (Auclair et al., 1996). However, Bertrand et al. (1994) found that a lack of snow cover in a forest stand resulted in lowered soil water content, so freeze stress itself can result in moisture stress. Further, Boutin and Robitaille (1993) found that root-level freezing stress is followed by a rapid acidification of the soil, which in itself can lead to tree decline. Other research has suggested that much of the damage done by soil freeze events stems from direct cellular damage to roots as opposed to physical damage from frost heaving (Cleavitt et al., 2008).

2.4 Climate change impacts on hardwood forests

Climate change will have (and has already had) a greater impact in winter than in summer in temperate zones (Kreyling, 2010; Zhang et al., 2019). Given the critical role that wintertime climatic conditions have on sugar maple health, such climatic shifts could have significant impacts on tree health and sap production.

A general northward migration of sugar maples (and most other species) is expected, though Aitken et al. (2008) note that the migratory response to climate change is unlikely to occur quickly enough because of the rapidity of anthropogenic climate change. Brown et al. (2015) used a GIS-based approach to determine suitable maple habitat in Ontario, in current maple syrup-producing regions. They suggest that in the south and west, habitat changes from mostly suitable for maples to mostly unsuitable for maples over the 21st century, though some portions in the northernmost syrup-producing regions have more suitable maple habitat towards the end of the century. However, the results are based on physical characteristics, and do not take into account local adaptation strategies or improvements in technology.

2.4.1 Phenological changes

Phenology refers to the timing of natural events, such as when flowers bloom or when leaves begin to turn. Changes in phenology have the potential not just to change the timing of bud break (which marks the end of the sap flow season in sugar maples), but also the health and distribution of trees (Chiune and Beaubien, 2001; Chiune, 2010). Though phenology can be complex to forecast (Ibáñez et al., 2010), changes in it can have significant effects on both individual species as well as entire ecosystems (Groffman et al., 2012).

There have already been significant phenological changes in hardwood forests during the 1956-2010 period, such as the start and length of the growing season (Groffman et al., 2012). Soil and below-ground phenology has changed more quickly (i.e. is happening earlier) than plant phenology in northern hardwood forests (Groffman et al., 2012). There is consensus that warming winter temperatures in the future will result in further phenological shifts to earlier in the season (Ibáñez et al., 2010; Kreyling, 2010).

It is expected that phenological shifts will result in soil warming to biologically productive levels earlier in spring (Chuine & Beaubien, 2001; Kreyling, 2010; Groffman et al., 2012), but if above-ground phenological changes in plants are not synchronous with this, it could lead to overall nutrient depletion in an ecosystem (Groffman et al., 2012). Thus, advanced and extended growing seasons may not translate to healthier or more productive trees.

Chuine and Beaubien (2001) found that in species distribution modelling, the models they tested were only accurate when survival and reproductive success of species were a function of phenology, suggesting that understanding phenological shifts are crucial to projecting future species distributions. Interestingly, research undertaken nearly a decade after that study, there is still considerable uncertainty about phenological changes, such as the rate of change and whether different components of an ecosystem will change synchronously (Groffman et al., 2012; Dormann et al., 2012; Aitken et al., 2008).

2.5 Climate change impacts on maple syrup production

Determining the impact of climate change on maple syrup production is important for the industry. Several studies have suggested that maple syrup yield could be reduced in the future, though few have quantified this. Duchesne et al. (2009), who used AR4 projected future temperature data to quantify expected changes in syrup yield, found that it could be reduced by 15 and 22% in 2050 and 2090, respectively, due to climate change (these are the median values of multiple emissions scenarios and multiple climate models). However, the issue is complex; the authors note that if the period of sap production were to occur 12 and 19 days sooner in 2050 and 2090, respectively, then current yields could be maintained. This is consistent with a sap flow study, based on temperature data from 2 AR4 emissions scenarios, that found by shifting sap collection schedules to earlier in the season, there is no net loss of sap flow days (Skinner et al., 2010). However, the Skinner et al. (2010) study was designed to assess these changes in the Northeastern United States, so they may not be applicable in a Canadian context.

There has already has been advancement in budbreak in sugar maples (i.e. budbreak is happening earlier), which suggests that maples are to some extent already adapting to a changing climate. However, sap flow for maple products requires daytime temperatures of above freezing, followed by below freezing nights; thus, significant warming could still pose a threat to production, even if phenological changes occur (Goff & Bergeron, 2011).

Duchesne and Houle (2014) suggest that generally, climate change may favour maple production further north, but negatively affect production at lower latitudes. This is consistent with changes in risk of freeze damage: in more southerly latitudes, increases in winter temperatures could result in temperatures hovering close to 0ºC, increasing the vulnerability of roots to freeze damage. While studies exist on impacts of heat stress and drought on overall tree health, these factors are not generally assessed in relation to sap flow. Brown et al. (2015) found that under both moderate and high emissions scenarios, the area of suitable sugar maple habitat is lessened considerably at both mid- and late- century (see Figure 1) in current maple syrup producing regions (the potential for sugar maples to migrate to areas that do not currently support them was not assessed).

The vulnerability of sugar maples (and forests in general) to climate change is dependent on a number of factors, including the ability for species to locally adapt to changing climates. Leading edge populations (i.e. high altitude or high latitude) trees are likely to experience less stress from climate change because gene flow from central populations would pass along alleles pre-adapted to a warmer climate (Aitken et al., 2008). Further, Goff and Bergeron (2014) find that in addition to natural adaptations, there are a number of forest management practices that can improve forest resilience to climate change. Assisted migration by planting tree stands further north, and selectively breeding sugar maples to better withstand changing climatic conditions were two of the options presented in the study. Murphy et al. (2012) and Goff and Bergeron (2014) also identified monitoring and regulatory changes as potential adaptive strategies, but these would apply to policymakers rather than individual producers.

The vulnerability of maple syrup producers to climate change will depend not just on adaptive measures to maintain forest health, as noted above, but also on adapting to changes in the timing of the sap flow season. Beginning sap collection earlier in the year may be necessary to ensure that sufficient volumes of sap are collected before buds break and the sugar content in the syrup becomes too low.

2.6 Assessing research gaps

There is a considerable body of research that establishes ideal climatic conditions for optimum health and sap flow in sugar maples, as well as climatic factors that can be deleterious to tree health and sap flow. There is also a fair amount of research discussing the potential impacts of climate change in maple syrup producing regions. However, there is much less research connecting climate change with maple syrup production, and even less connecting climate change to sap flow. Indeed, only a few studies were found that explicitly discussed sap flow, and the study areas were restricted to either or the Northeastern United States. In most studies, spring temperatures are the primary or exclusive indicator of sap flow. Only one study, Houle (2019), used a full range of indicators to determine the likelihood of a given week being ideal for sap flow. However, even in that study, it is acknowledged that temperature is the single most important predictor of sap flow.

There is a major research gap in examining the impact of climate change on maple syrup production in general, but there is virtually no information that pertains directly to Ontario, with the exception of Brown et al. (2015), but this study discusses changes in suitable habitat for maples rather than impacts on maple syrup production itself. There is then, a need for more research on climate change impacts on sap flow specific to Ontario. This project can provide stakeholders with information about both what changes in sap flow are expected to occur in current syrup-producing regions and provide insight into whether these regions are still ideal habitats for maple trees in the future. Results generated from this research can be used as a tool for identifying potential areas where specific adaptive strategies should be utilized.

3.0 Methods

3.1 General approach

This research used a sap flow model, based on the optimum temperature range of -5°C to 5°C, to determine the beginning of sap flow seasons for early (2005-2015), mid-century (2045-2055), and late-century (2085-2095). Prior to running the sap flow model, the climate data had to be transformed into a format compatible with GIS software. The projections were completed using the RCP4.5 emissions scenario (low-medium radiative forcing) and RCP8.5 emissions scenario (high radiative forcing), and the results were aggregated and displayed using a GIS application. The process is shown in Figure 2.

3.1.1 Study Area

This project will focus on projecting the future sap flow conditions in southern Ontario. The study area is focused on the current Ontario Maple Syrup Producers' Association (OMSPA) boundaries. OMSPA does not have a clear limit to the extent of the northernmost syrup producing regions, so the extent of maple habitat as established in Brown et al. (2015) is used as the northern border.

3.1.1 Sap flow model

The sap flow model projected the beginning of the sap flow season based on optimum diurnal temperatures of -5°C overnight and +5°C during the day (MacIver et al., 2006). The beginning of sap flow is determined as the first date that meets the condition of a minimum temperature between -5°C and 0°C, and a maximum temperature above 0°C and less than 5°C. Sap flow depends on the process of freezing temperatures at night followed by above freezing during the day, so using the range -5°C to 5°C without building in logic for freezing and below freezing temperatures could have produced false positives.

The beginning of sap flow is not well-defined in the literature; it is usually described loosely as early spring. Producers typically begin collecting sap around the beginning of March, but there is considerable variation year-to-year depending on temperatures (Legault et al, 2019). Existing studies on the start of sap flow in Canada (Houle et al., 2015; Houle, 2019; Legault et al., 2019) show sap flow beginning earlier, but no results indicate that it is expected to begin in January, or that producers begin tapping in January even if sap flow conditions are ideal. To avoid artificially early start dates of sap flow, a further rule that February 1st was the earliest acceptable day for the beginning of sap flow was included as well.

The sap flow model is designed to determine the onset of sap flow. It does not evaluate the quantity of sap or sap sugar content, nor does it take into account potential frost damage or other events that may affect the health of trees.

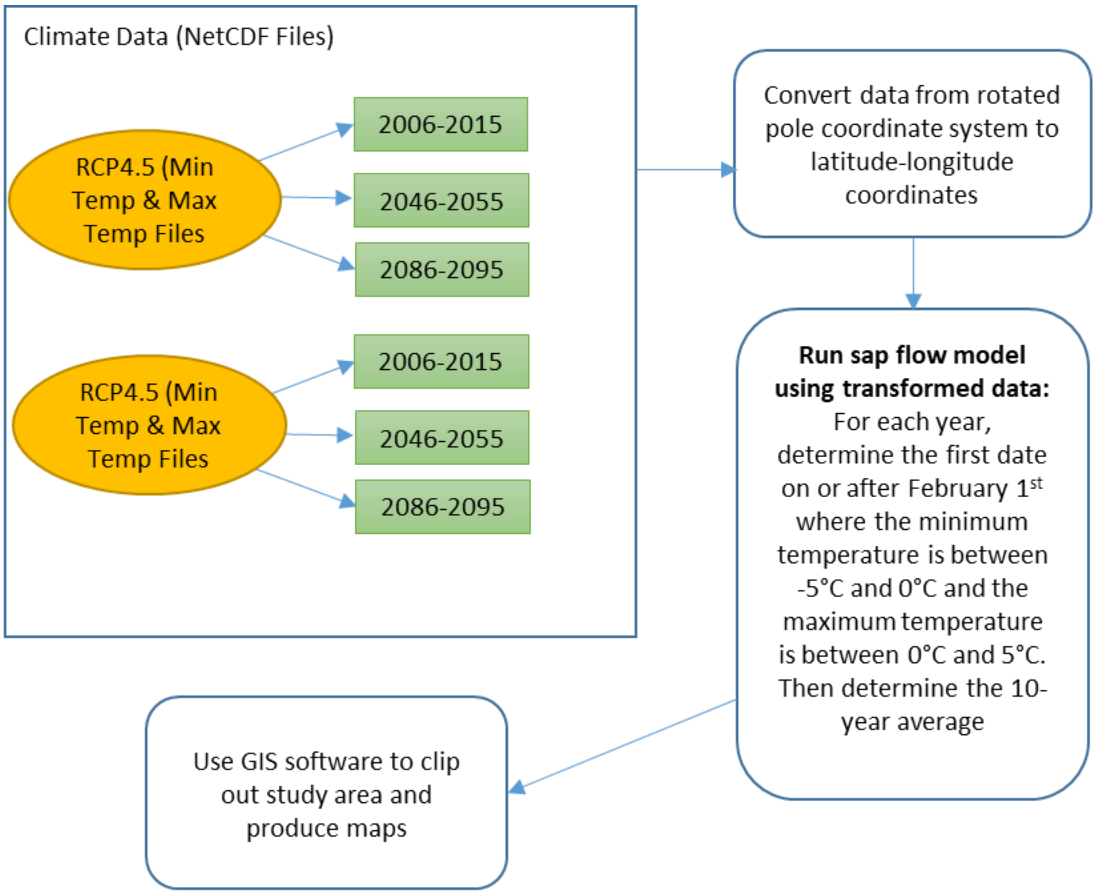

Figure 2: Data processing flow diagram.

3.2 Data sources

The principal datasets needed to complete this project were the temperature projections for the 21st Century for the AR5 RCP4.5 and RCP 8.5 scenarios (daily minimums and maximums) from the CRCM CORDEX runs. These regional datasets cover all of North America, and come in 5-year data arrays; only the files for relevant years 2006-2015, 2046-2055 and 2086-2095 were used in this study. The data has a 25 km2 resolution, and comes in NetCDF format. The map projection used in these files was a rotated pole coordinate system; this means that the North Pole is not in the usual position, but rather near the equator. In order to analyze and display the results from the sap flow model, the data had to be transformed from a rotated-pole to standard latitude-longitude coordinates.

The data from the CORDEX experiments begin with the period 2006-2010. The 10-year periods for early, mid, and late century were based on 2006 being the earliest available year with data, and having equal intervals (40 years) between each period.

All of the temperature data from the CRCM is modelled - the temperatures for the 2006-2015 period are not observed values, so there are differences in the baseline values between the two scenarios.

4.0 Results

4.1 RCP 4.5 Scenario

4.1.1 Beginning of Sap Flow

During the 2006-2015 period, a majority of the province experienced the beginning of sap flow during the first 3 weeks of February, with a general trend of earlier in the south and later further north. In the northernmost extent of sugar maple habitat, the beginning of sap flow can occur as late as the first week of March. By mid-century, most of the study area, even the far north, sees sap flow begin by mid-February. The spread in the onset of sap flow dates increases slightly for the late-century period, but the latest instance of onset of sap flow does not exceed mid-February in part of the study region (Figure 3).

Figures 4a and 4b show the percent change in sap flow start dates for the mid-century and late-century periods relative to the early-century baseline. The change from the early to mid-century periods sees a few small areas with large changes in the start of sap flow season. However, a majority of the study area sees sap flow begin 10-15% earlier than in the 2006-2015 period.

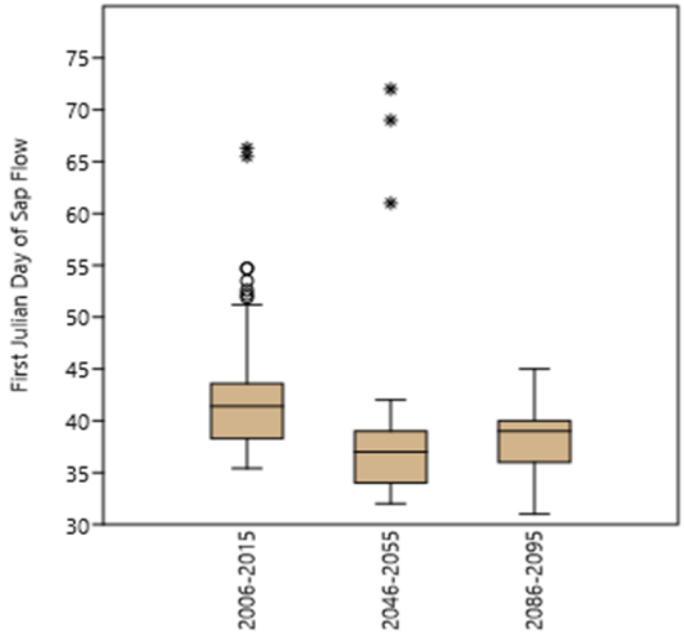

Figure 3: Model projections of the first Julian day of ideal sap flow conditions under the IPCC RCP4.5 scenario for early, mid, and late century periods. Circles represent outlier values, asterisks represent extreme outlier values.

Towards the end of the century, there are very few areas with an onset of sap flow later in the season, and the increase does not exceed 3% in most cases. The trend towards earlier onset of sap flow in most of the study area is less pronounced than the results from mid-century, with most areas seeing the start of sap flow only slightly below the 2006-2015 period – less than 10% earlier in most places. In some areas, the onset of sap flow is slightly later for the 2086-2095 period than for the 2046-2055 period, but the magnitude of the difference is negligible (2-3 days difference).

In both the mid-century and late-century periods, there are areas where the criteria of a minimum temperature between -5°C and 0°C and a maximum temperature above 0°C and less than 5°C are not met in one or more years of the period. A few isolated spots are impacted by mid-century, but by late century a pattern emerges of most of the southern shore of Lake Huron and Georgian Bay no longer experiencing ideal sap flow conditions.

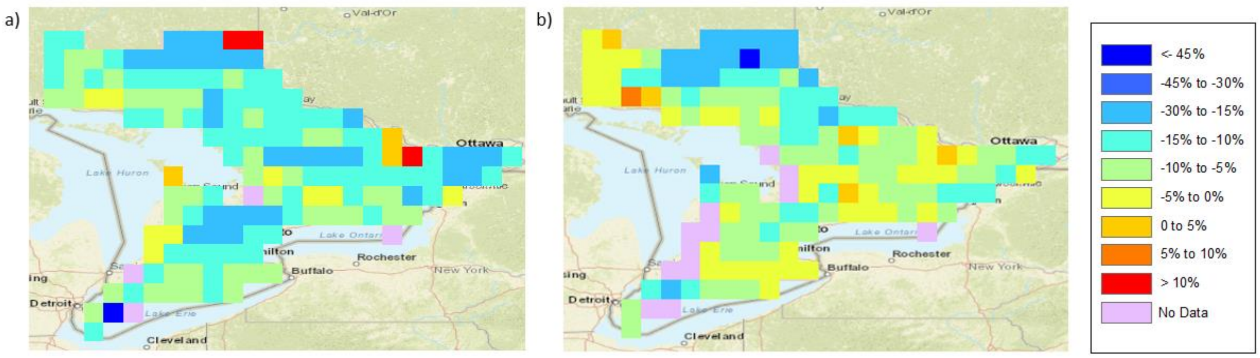

Figure 4: Percent change in earliest day of sap flow between A) the early to mid-century periods, and B) between the early and late-century periods under the IPCC RCP4.5 scenario. Cells with a no data value experienced one or more years where the conditions for ideal sap flow were not met.

4.2 RCP 8.5 Scenario

4.2.1 Beginning of Sap Flow

The onset of sap flow for the 2006-2015 period varied considerably geographically, with the northernmost part of the sugar maple range seeing the start of sap flow 4-5 weeks later than the rest of the province. The latitudinal gradient for the onset of sap flow became smaller over the course of the century. The north still generally sees later onset of sap flow, but the difference between the south and the north narrows to 2-3 weeks for most of the study area during the 2046-2055 period. Toward the end of the century, the difference between the onset of sap flow in north and the south is approximately two weeks (Figure 5). In Figure 5, the outlier values for the early-

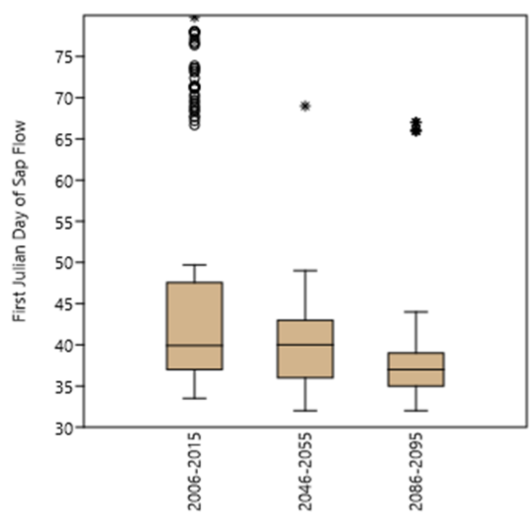

Figure 5: Model projections of the first Julian day of ideal sap flow conditions under the IPCC RCP8.5 scenario for early, mid, and late century periods. Circles represent outlier values, asterisks represent extreme outlier values.

century period are all located in the northernmost extent of the study area. For the late-century period, the outlier values are all located along the shore of Lake Erie (see section 5.3).

In both the mid and late century periods, the northern region of the study area sees a noticeably larger change (Figures 6a and 6b). In the mid-century period, sap flow begins 30-50% earlier than the 2006-2015 period in the north, while changes in most of southwestern Ontario are negligible (±5%). By mid-century, several areas along southern Lake Huron did not meet the criteria for sap flow in at least one year.

Towards the end of the century, sap flow begins 10-20% earlier for most of the study area, excluding the northernmost region, where it begins 30-50% earlier, and the southernmost region, where sap flow criteria is either not met, or is taking place much later. The change approaches 100% in some areas around Lake Erie (~4 weeks later).

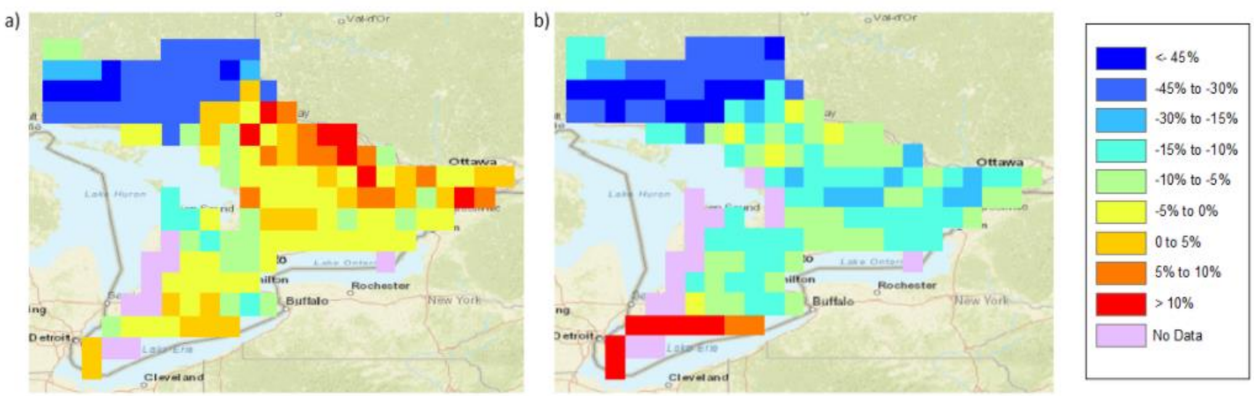

Figure 6: Percent change in earliest day of sap flow between A) the early to mid-century periods, and B) between the early and late-century periods under the IPCC RCP8.5 scenario. Cells with a no data value experienced one or more years where the conditions for ideal sap flow were not met.

5.0 Analysis

5.1 End of Sap Flow Season

The end of the sap flow season for maple syrup producers occurs once buds break, as this results in the sugar content of the sap becoming too low for economical syrup production.

MacIver et al. (2006) determined that sugar maples come out of dormancy after 10 consecutive days with minimum temperatures above 0°C and/or 10 consecutive days with maximum temperatures above 10°C.

Experiments were run using both the minimum and maximum temperature rules. The resulting end dates were markedly different between the two experiments. While the general trend in both cases was earlier end dates in most of the study area, the condition of 10 days with a minimum temperature above 0°C was reached much earlier than the condition of 10 days with a maximum temperature over 10°C in some regions. This was particularly noticeable for the 2086-2095 period.

The expectation was that the results from the two experiments would provide a window for the end of sap flow. However, the large differences meant that this window spanned several weeks for some areas – too long to make a meaningful assessment of when the end of the season would be. The results of the experiments suggest that a model based only on temperature is inadequate for determining the end of the sap flow season.

A 2019 study by Houle used a complex probabilistic model to determine the onset and length of the sap flow season for regions in Quebec for given weeks throughout the spring. Despite using a comprehensive set of variables, the margin of error for the end dates of sap flow was large enough to alter the sign of the change in the length of the sap flow season in most of the regions. The results suggest that even with a more complex model, the drivers for bud break are not fully understood, and more research in this area is warranted. Houle notes, however, that while determining exact dates for sap flow is unlikely to be accurate, the general trends in models are useful to producers and can provide a framework for adaptive planning.

5.2 No DataValues

Cells that were assigned a no data value had at least one year in the ten-year periods where the criteria for sap flow was not met. While the threshold for assigning a no data value was one year, a majority of the cells had multiple years where sap flow criteria was not met. In both the RCP 4.5 and RCP 8.5 scenarios, there were cells that had no years that met the conditions for sap flow for the late-century period.

All of the cells not meeting the sap flow criteria are located along the Great Lakes, with the highest concentration along Lake Huron. This pattern suggests that lake effects change under any radiative forcing scenario. The model only assessed whether cells met the criteria, so further investigation into whether changes in minimum or changes in maximum temperature are the primary driver for not meeting sap flow conditions.

It is also interesting to note that the cells not meeting sap flow criteria, while concentrated around the same areas, do have some variation between the two radiative forcing scenarios. At mid-century, the RCP 8.5 scenario has more than double the number of cells not meeting sap flow criteria than the RCP 4.5 scenario. For the late-century period, the RCP 4.5 scenario has more cells not meeting sap flow criteria than the RCP 8.5 scenario because of an additional cluster of cells around Georgian Bay.

5.3 Comparison of RCP 4.5 and RCP 8.5

The results of the experiments show that the change in sap flow start dates is more linear for the RCP 8.5 scenario than for the RCP 4.5 scenario. In the RCP 8.5 scenario, there is a clear trend of an earlier onset of sap flow over the course of the century, whereas in the RCP 4.5 scenario, the mid-century period shows earlier start dates than the late-century period.

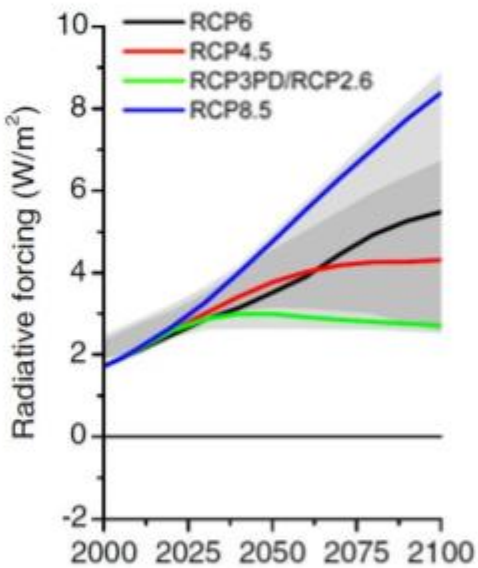

Figure 7: Radiative forcing in the RCP scenarios. From van Vuuren et al., 2011)

The spread in data is also quite different between the two scenarios. In the RCP4.5 scenario, the difference between the earliest and latest instances of sap flow is smallest in the mid-century period and increases for the late-century period. For RCP 8.5, the range of values becomes consistently smaller over time.

The larger changes in mid-century for the RCP 4.5 scenario is likely because in that scenario, radiative forcing reaches its maximum of 4.5W/m2 around mid-century and then levels off (Figure 7). In that case, it is logical that conditions stabilise by the late-century period since the radiative forcing peaked and then remained at a consistent level for several decades prior. In the RCP 8.5 scenario, radiative forcing increases over the century, reaching 8.5W/m2 at 2100. Since there is no stabilisation of radiative forcing, the linear-type trend in earlier sap flow dates is to be expected.

The patterns for the start of sap flow differ spatially between the two scenarios as well. In the RCP 4.5 scenario, there is a clear trend of an earlier sap flow season in the north for the mid-century period, but by the late-century period, the change is much smaller, and in some parts the sap flow season begins slightly later. In the RCP 8.5 scenario, there is a strong and consistent signal that the northern region of the study area will experience sap flow earlier. Some parts of the north see sap flow begin about 50% earlier in mid-century, and the changes late-century show a similar limit of sap flow beginning about 50% earlier. The late-century period shows a larger portion of the north approaching the start of sap flow about 50% earlier than the mid-century period.

Many of the differences between the two scenarios are likely due to RCP 4.5 having a consistent level of radiative forcing from mid-century onward, but it is also important to note that the two scenarios are not directly comparable – underlying assumptions about consumption, economics, and land use are not the same (van Vuuren et al., 2011). While both radiative forcing and GHG emissions are higher in RCP8.5 for the entire 21st century, emissions from land use change, specifically deforestation, are markedly higher in RCP4.5, and the emissions from deforestation peak in 2050 (Clark et al., 2007, Smith et al., 2006, Wise et al., 2009). The mid-century results for RCP4.5 may partially be explained by this difference in the two scenarios.

The general patterns are largely consistent with the literature showing that higher latitudes will warm faster than lower latitudes; a study by Zhang et al. (2020) found that even within the Great Lakes Basin, warming was greatest in the north. The difference in late-century conditions between the two scenarios suggests that stabilising radiative forcing around mid-century may avoid large changes in the start of sap flow later in the century. Conversely, continued pressure on natural systems with increasing radiative forcing may push further changes.

The presence of areas seeing later start dates for sap flow, in some cases directly adjacent to areas seeing earlier dates, indicates that there may be increased climatic variability in both RCP scenarios. An assessment of variability in temperatures would be an area for further research, as this would help to determine the consistency of sap flow, and not just the onset.

There is currently very little literature that explores changes beyond 2100, but coming the RCP 4.5 and RCP 8.5 scenarios beyond 2100 may offer some further insight into what effect a consistent level of radiative forcing, as is modelled in RCP 4.5, has on systems in the long-term relative to increasing radiative forcing.

5.4 Adaptive Strategies

From an industry-wide viewpoint, increasing production further north in Ontario will likely need to be part of an adaptive strategy. Some studies (e.g. Skinner et. al., 2010) have found that Minnesota is likely to become more suitable for maple syrup production over the course of the century. While OMSPA does not currently include the area around the Minnesota border as a syrup-producing region, there may be potential to expand production there.

Within the existing syrup-producing region in Ontario, producers will need to be prepared for an earlier start to sap flow in most regions. Since conditions change from year-to-year, experienced producers are already well-equipped to make decisions on when to begin tapping trees. While this study was unable to successfully project end dates, the existence of cells not meeting criteria for sap flow to begin does indicate that some areas in the south are likely to see a significant shift in how consistently and for how long sap flows. Producers in those areas will most likely require technological solutions in addition to tapping earlier.

An important tool available to producers is vacuum technology and tubing to collect sap, rather than traditional taps and buckets. Vacuum technology allows producers to begin collecting sap earlier than traditional collection methods, and ensures a more consistent supply of sap that is less reliant on ambient temperatures (Snyder et al., 2019). Implementing this technology will likely become increasingly important for producers to remain competitive. In addition to technological interventions, many producers are already implementing forest management strategies to improve tree health, which ensures trees are more productive (Snyder et al., 2019; Kuehn et al., 2017).

5.0 Conclusion

The results of the experiment show that there will be significant changes to the start of the sap flow season in most of Ontario, irrespective of RCP scenario, and a majority of the province will experience sap flow earlier in the year. In a lower radiative forcing scenario, the largest changes occur in the mid-century period, and stabilise more at the late-century period as radiative forcing stabilises as well. Under a higher forcing scenario, changes continue through the end of the century. Areas along Lake Huron and parts of Lake Erie do not meet the criteria for ideal sap flow conditions. In these areas, it is possible that maple syrup production will not be possible, or that volumes will be too low to be economically viable.

The methods used in this research are valuable as a baseline for when sap flow can be expected to start in Ontario, but it does not assess the quality or quantity of sap, both of which dictate the economic value of the syrup. The model also does not effectively determine end dates of sap flow. More complex sap flow models do exist in the literature, but none have studied Ontario. The existing literature also lacks GIS-focused analysis, so variation within defined regions is difficult to assess. Future research combining more sophisticated sap flow models with a GIS-focused analysis would be extremely valuable in determining where specific adaptive strategies could be implemented in Ontario (and in other maple syrup-producing regions).

Further research into temperature fluctuations may also be helpful to assess the consistency of sap flow for producers who do not have access to vacuum technologies, or who choose to continue using traditional methods for sap collection. Forest management strategies to protect sugar maples from known stressors like freeze-thaw damage will become increasingly important for producers, particularly around the Great Lakes, where sap flow conditions are not being met by mid-century in both RCP scenarios.

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