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EDITED BY
Renata Sõukand,
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REVIEWED BY
Ajay Maletha,
Amity University, India
Michael Benjamin Kantar,
University of Hawai'i at Mānoa, United States

*CORRESPONDENCE
David Lutz
david.a.lutz@dartmouth.edu

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Climate change and maple syrup: Producer observations, perceptions, knowledge, and adaptation strategies

Selena Ahmed[1,2], David Lutz[3]*, Joshua Rapp[4,5,6], Ryan Huish[7], Boris Dufour[8], Autumn Brunelle[3,9], Toni Lyn Morelli[4,10], Kristina Stinson[4,5] and Teresa Warne[1]

[1]Department of Health and Human Development, Montana State University, Bozeman, MT, United States, [2]Periodic Table of Food Initiative, American Heart Association, Dallas, TX, United States, [3]Environmental Studies Program, Dartmouth College, Hanover, NH, United States, [4]Department of Environmental Conservation, University of Massachusetts, Amherst, MA, United States, [5]Harvard Forest, Harvard University, Petersham, MA, United States, [6]Mass Audubon, Lincoln, MA, United States, [7]Department of Natural Sciences, The University of Virginia's College at Wise, Wise, VA, United States, [8]Département de Biologie, Chimie et Géographie, University of Quebec in Rimouski, Rimouski, QC, Canada, [9]Monroe County Parks and Recreation, Monroe County Government, Bloomington, IN, United States, [10]U.S. Geological Survey, Northeast Climate Adaptation Science Center, Amherst, MA, United States

Introduction: Climate change is impacting forest-based agricultural systems with implications for producer decision-making and livelihoods. This article presents a case study on the observations, perceptions, knowledge, and adaptation strategies of maple syrup producers in the United States to climate change.

Methods: We carried out two semi-structured surveys with maple producers on: (1) climate change and its impacts on the maple system (n = 106 participants); and (2) responses to climate adaptation scenarios (n = 98 participants). Additionally, we carried out two focus groups and key informant interviews (n = 70+) to understand barriers and opportunities for climate adaptation. One of these focus groups and follow up key informant interviews was with tribally affiliated community members with the intention to acknowledge Indigenous Peoples' voices, history, and relationships to the land.

Results: Findings highlight that most of the surveyed producers (89%) have experienced the negative impacts of climate on maple syrup production. While 40% of participants feel concerned regarding the future of the maple system, 39% feel hopeful, with significant differences based on the age of the surveyed producers. The majority of producers have adapted their harvesting practices to climate effects. Producers shared knowledge of multiple adaptation strategies in response to climate scenarios comprised of: (1) stand management practices such as diversification of sap species tapped; (2) harvesting practices such as changing the type and number of taps; (3) sap processing practices focused on the integration of technology such as the use of an evaporator and reverse osmosis; and (4) marketing practices such as innovation of products and marketing different maple syrup characteristics. Responses shared by tribally affiliated producers highlight knowledge of multiple adaptation strategies that focus on long-term ecological management of forests rather than technological solutions.

Discussion: Overall, findings emphasize the importance of cooperation and diversification at every level and dimension of the maple system for its long-term resilience.

KEYWORDS

Acer, maple, climate change, climate adaptation, Indigenous People

1. Introduction

Global change is impacting forest and agricultural systems with implications for producers and consumers. Shifts in climate, markets, and policy associated with global change have the potential to influence the viability of forest and agricultural systems. For example, increased global temperatures over the past six decades, coupled with greater variability and more extreme weather conditions such as droughts and floods, are impacting yields and geographic ranges of many crops (Raza et al., 2019; Leisner, 2020). Climate change and associated abiotic stresses further pose challenges to forest and agricultural systems through an influence on product quality (Ahmed et al., 2014, 2019; Ahmed and Stepp, 2016). Ultimately, climate effects on forest and agricultural systems can threaten farmer livelihoods as well as the benefits received from harvested products (Ahmed et al., 2014).

Sugar maple (*Acer saccharum*) and red maple (*A. rubrum*) trees have been managed, cultivated, and harvested for centuries in North America for their sucrose-laden sap used for the production of maple sugar and maple syrup. Indigenous Peoples of North America, including Ojibwe, Iroquois, and Menominee peoples, used maple syrup as a sweetener (Thomas and Silbernagel, 2003; Logan, 2014). This tradition continued by early colonists in North America due to the high costs of importing cane sugar (Perkins and van den Berg, 2009) and gradually became an important source of farm revenue (Hinrichs, 1995). The maple industry grew with the advent of maple production technology to comprise a deeply valued cultural tradition, component of tourism, and income source (Hinrichs, 1998). Maple syrup is largely produced throughout the extant range of maple trees, being most prevalent in Canada's Quebec Province and the New England region of the United States, with production also occurring in parts of Midwestern and Southeastern United States. Production continues to expand as relatively high prices drive investments and technological advancements while previously un-utilized trees are folded into production.

The maple syrup industry provides permanent and seasonal income streams to thousands of producers and farmsteads in North America. Maple producers consist of large-scale industrial producers representing the majority of production along with thousands of small-scale producers. Almost 17.5 million gallons of syrup are produced annually, with Canada producing about 13.25 million gallons and the United States producing 4.25 million gallons (USDA NASS, 2019; Statistics Canada, 2020). The maple industry in the United States is estimated to be worth over $100 million USD (USDA NASS, 2019). Maple producers are vulnerable to ephemeral price fluctuations of the complex market structure of the maple syrup industry. The vulnerability is exacerbated with a single producer group [the Federation of Quebec Maple Syrup Producers (FQMSP)], comprising approximately 80% of total annual production (Duchesne et al., 2009). In most areas that have seen an increase in maple production, the growth is mainly due to an increase in the tapping effort (number of taps) and to improvements in the production processes, but not to better environmental conditions, which are expected to decline in many places of the maple range in North America (Rapp et al., 2019).

Maple syrup production is intricately connected to the weather and climate, involving optimal variables for adequate sap flow, quality, and overall production (Tyree, 1983; Horsley et al., 2002; Whitney and Upmeyer, 2004; Graf et al., 2015; Rapp et al., 2019). Various cells and layers inside maple trees work to protect the tree during the cold months when the tree goes dormant. The excess sugar created during photosynthesis in the summer season is stored in the tree's sapwood. The xylem layer (which includes the sapwood) is made up of xylem vessels that transport water and nutrients from the tree's roots to the stems and leaves. In maple trees, the xylem vessels are surrounded by air filled fiber cells–a unique feature of maple trees. When below-freezing temperatures are present, ice crystals form within the fiber cells as a way to protect the tree cells from damage. When ice crystals form, the humidity inside the cells lowers, pulling moisture from nearby cells and thickening the ice crystals. Larger ice crystals cause the gas bubbles inside the fiber cells to compress. This causes negative pressure in the tree in relation to atmospheric pressure which suctions water from the roots up and into the tree's cells until frozen (Graf et al., 2015). If this event is followed by above freezing conditions, typically during the day, the warmer temperature will thaw the ice crystals in the fiber cells allowing the air bubbles to expand and positive pressure in the tree to develop. Expanding air bubbles, gravity, and osmosis (when water moves across a membrane to reach an equilibrium) forces the sap back down the tree and, if present, out a taphole or wound in the bark. The continued freeze-thaw cycle and the quick transitions between negative and positive pressure as it relates to atmospheric pressure causes the sap to flow or run (Perkins and van den Berg, 2009). Each step in the tree's freeze-thaw cycle relies on specific weather and climate patterns to continue the flow of sap. Without the recurring change in freezing temperature, the pressure in the tree eventually equals the pressure outside the tree, stopping the flow of sap.

Each spring, the sap from maple trees from maple-dominated forests is extracted from trunks of trees, through a process called "tapping." The tapping season is context-specific, however, sap generally runs during February to April, or when daytime temperatures (in Fahrenheit) are in the high 30s to mid-40s and overnight temperatures are below freezing (DNRC, 2023). Sap's sugar content determines the quantity and quality of syrup that can be produced from a given amount of sap. Environmental and management conditions can result in shifts in the quality of maple syrup through a wide range of specialized metabolites, minerals, and phenolic compounds which ultimately determine the flavor, nutritional profile, and health attributes of maple syrup. Phenolic compounds have also been attributed to play a defense role in maple trees against oxidative stress related to climate variability and soil nutrition (Horsley et al., 2002) and linked to the characteristic flavor and quality of maple syrup (Perkins and van den Berg, 2009).

Using historical trends to model long-term climate change scenarios, Rapp et al. (2019) found that maple sap yields and quality based on sap sugar content are vulnerable to climate change and that the specific changes are dependent on geographic location (Rapp et al., 2019). Specifically, maple sap sugar content declined by 0.1°Brix for every 1°C increase in previous May–October mean temperature. Decreased sugar content translates into more sap required to produce a gallon of syrup. However, this is not uniform across the maple range and varies based on geographic location. Rapp et al. (2019) projected that the sap collection season midpoint will be 1 month earlier and sap sugar content will decline by 0.7°Brix across sugar maple's range by the year 2100. Increased variability and decreased yields in sap flow are more likely near the southern range of sugar maple while increased sap flow is more likely in the northern range. Specifically, locations expected to have the maximum amount of maple sap flow are expected to shift northward by 400 km, presently from near the 43rd parallel to the 48th parallel, by 2100.

Forest-based agricultural systems that are dependent upon perennial tree species, such as maple syrup production, face unique complications regarding their adaptability to climate change compared to agricultural systems of annual crops because they cannot be easily transplanted. Thus, forest-based agricultural systems call for management decisions that consider long-term resource vitality (Price and Wetzstein, 1999; Feinerman and Tsur, 2014). Further, forest-based agricultural systems are compelling to protect with their positive contribution to carbon sequestration (Jose, 2009). While a wide range of research exists regarding the effects of global change on annual crops, research is lacking for tree-based perennial crops despite their vulnerability to climate change (Lobell and Field, 2011; Lobell et al., 2011).

Given that the resilience of a system depends on the environment as well as resource management decisions (Walker et al., 2006), optimal management of forest-based agricultural systems necessitates an understanding of both social and ecological dimensions. Previous work highlights that there is tremendous diversity in the social dimensions of natural resource management (Nowak and Cabot, 2004). While producers can reduce climate effects on their production systems through climate adaptation practices, in order for adaptation to occur, producers must first have knowledge of how the climate is changing (Maddison, 2007) and impacting species within their systems, including both yields and quality of forest and agricultural products.

This article presents a case study on the perceptions and responses of maple syrup producers in the United States to climate change. The maple forest-based agricultural system provides a compelling case study to examine the effects of climate change because of its cultural importance as a native non-timber forest resource in North America linked to regional identity as well as ecosystem services of forests in the areas where it grows. Our study addressed the following research question: "What are maple producer observations, perceptions, knowledge, and adaptation strategies to climate change and its impacts on maple syrup production, and what factors influence these attitudes?" The ultimate goal of this study is to understand the potential for climate adaptation of maple syrup producers in the context of global change toward informing solutions to strengthen the resilience of the maple system.

2. Materials and methods

We carried out two semi-structured surveys with producers of maple syrup in the United States. The first survey focused on examining perceptions of producers regarding climate change and its impacts on the maple system. The second survey focused on examining maple producer responses to climate and climate adaptation scenarios in order to better understand potential resource management decisions. Additionally, we carried out two focus group workshops to further understand barriers and opportunities for climate adaptation with regards to the maple system. One of these two focus groups was held with tribally affiliated community members, and included follow-up key informant interviews.

The authors of this article acknowledge that it is crucial to include Indigenous Peoples' voices with regards to natural resource management given their historical and present-day traditions tied to the land, including the harvesting of maple syrup. One of the coauthors is a citizen of the Turtle Mountain Band of Chippewa and a descendent of the White Earth Band of Ojibwe and aided in connections to tribally affiliated community members. She was raised on the Leech Lake Band of Ojibwe reservation and has deep knowledge in Native American Studies, intertribal relations, and Native American history.

The semi-structured survey tools and focus group prompts were designed and implemented based on previous research on producer perceptions and responses to climate change (Mertz et al., 2011; Ahmed et al., 2014; Grimberg et al., 2018) along with findings from preliminary interviews with maple producers in northeastern United States. The study team who led the development of the survey and focus group prompts have training in cultural anthropology, Native American studies, ethnobotany, environmental sciences, plant sciences, ecology, forest management, and climate science. Additionally, five members of the study team had experience in tapping maple syrup prior to the study.

The two survey tools were reviewed for validity based on a panel of maple producer stakeholders and experts in the fields of forest management, ethnobotany, and climate. Revisions were made upon receiving feedback from the stakeholders and field experts. The surveys were administered online using the Survey Monkey platform. Participants were recruited by sending the survey to various maple producer organizations that have listservs of community members who tap maple trees. Both surveys were each distributed to over 500 maple producers.

Prior to administering both surveys and the focus group workshops, the approval of human subjects to participate in this study was obtained by the Institutional Review Board (IRB) at Montana State University and the University of Massachusetts at Amherst. Prior informed consent was collected from all of the survey participants following IRB guidelines before taking the surveys. All survey responses were anonymous and no unique identifiers were collected associated with each survey. Inclusion criteria to participate in the semi-structured survey included that participants must have tapped maple syrup in the United States during their lifetime for more than 1 year.

A total of 106 participants completed the first survey on perceptions of climate change and its effects on the maple system. A total of 98 participants completed the second survey on climate adaptation scenarios. Participants that completed the majority of each survey received a gift card as a small token of appreciation for sharing their perceptions, knowledge, experiences, and time. Over 20 tribal stakeholders were engaged in the tribal focus groups and follow-up key informant interviews. A total of 50 stakeholders participated in the second focus group with maple producers and forest managers. Specific methodological details on the final survey tools and focus group workshops are outlined below.

2.1. Producer survey on perceptions of climate change and impacts on maple

The first survey administered (**Supplementary Survey 1**) was intended to elicit maple producer perceptions of climate change. This survey was composed of 38 questions grouped into three sections: (1) Background, (2) Perceptions of Climate Events, and (3) Perceptions of Environmental Effects on Maple Sap and Syrup.

The Background section of the survey elicited demographic information on producers including years tapping maple trees, amount tapped, contribution of maple sales to income, and tapping and processing methods. The section on Perceptions of Climate Events elicited perceptions of changes in specific weather patterns and the sugar maple tapping season during producers' lifetimes such as changes in snowpack, temperature, rainfall, duration of the tapping season, start and end dates of the tapping season, and budding time of maple trees. The final survey section included questions that focused on understanding perceptions regarding how environmental factors impact the quality of maple sap and syrup including variables such as soil quality, slope, amount of snowfall and rainfall, duration of snowpack, tree density, insect infestation, barometric pressure, altitude, air pollution, and temperatures.

2.2. Producer survey on responses to climate scenarios

The second survey administered (**Supplementary Survey 2**) was intended to elicit maple producer responses to climate adaptation scenarios. This survey was created following analysis of the first survey detailed above on the basis of findings and emerging questions. This survey was composed of 13 questions including two sections: (1) Background, and (2) Scenarios (related to climate, tapping season, tree health, and socio-economic factors).

The Background section of the survey included questions related to basic demographic information. The survey section on Scenarios included questions based on whether producers would change specific aspects of their maple production based on various climate, tapping season, tree health, and socio-economic scenarios over a 10 years timeframe. Specifically, questions were designed to understand how producers would or would not change management practices of their maple production with regards to maple stand management, sap harvesting practices, maple sap processing, and maple syrup marketing.

The climate scenarios presented focused on more variable weather patterns and more frequent extreme weather events as well as warmer weather in the winter and spring. The tapping season scenarios focused on decrease in the duration of the tapping season, decrease in sap quantity, and decrease in sap quality. The tree health scenarios focused on higher pest prevalence in maple stands, and northward shift in the geographic area most suitable for tapping maple. The socio-economic scenarios focused on increase in consumer demand for maple syrup grown in an environmentally sustainable way (such as organic certification and/or diversification of stands), financial policy incentives such as subsidies for organic certified maple production, and higher prices for maple syrup.

2.3. Focus group interviews with tribal stakeholders

To better elicit the Indigenous Peoples voices, a focus group workshop was carried out at the Intertribal Food Summit on the Red Lake Nation land in Red Lake of Minnesota with tribal stakeholders. Along with the focus group at the Summit, 10 interviews with key informants were completed. Tribal participants included teachers, scientists, professors, local community members, business owners, and environmental protectors. Additionally, the Producer Survey on Responses to Climate Scenarios was sent to 49 tribal contacts. The questions asked during the focus groups and key informant interviews with tribally affiliated participants focused on addressing changes in weather, observations from season to season, and quality of sap. Following the Summit, tribal participants were contacted to express gratitude for sharing their knowledge and experiences.

Specific questions asked during the focus groups with tribal members included: (1) Have you ever had to change your management/tapping practices due to weather? (2) Do you think maple growing in certain areas is more impacted by extreme weather? (3) Have you noticed flow/quantity/quality changes in your maple trees or syrup? (4) Have you noticed if some trees produce differently than other trees (e.g., do older trees produce differently than younger trees) (5) Do you think there are actions needed to promote the health of maple resources into the future? If so, what are they? (6) Are you concerned, hopeful, or neutral about the future of sugaring and maple syrup production? and (7) What is your history with and experience with producing or consuming maple syrup?

2.4. Focus group interviews with producers and forest managers

We carried out a focus group workshop with 50 stakeholders at the Forest Ecosystem Monitoring Cooperative (FEMC) meeting. Focus group participants included tribal members, maple producers, foresters, forest service representatives, and researchers. Participants were divided into three groups based on their affiliation: producers; forest managers and forest service representatives; and researchers. They were asked to respond to the following three prompts: (1) What changes are you seeing in sugar maple stands and maple syrup that might be related to climate change? (2) Related to syrup production or sugar maple management, what are you doing to respond to climate change? and (3) What is your biggest concern related to sugar maple and maple sugaring?

2.5. Data analysis

Survey responses were tabulated for frequency. In addition, JMP statistical software (version 12.0 SAS Institute Inc., Cary, NC, USA) was used to carry out a contingency analysis to understand relationships between geographic region of the producer and their responses. Using qualitative analysis methods identified by Saldaña (2015), the open-ended responses were coded to find prevalent themes (Saldaña, 2015).

3. Results

3.1. Producer perceptions of climate change and impacts on maple

A total of 106 participants completed this survey; the sample size varies for different survey questions as not all participants responded to every question (for survey questions see **Supplementary Survey 1**).

The majority of surveyed producers were from New England (53%) or Mid-Atlantic (44%) regions, with a few producers from the Appalachian region (3%). Specifically, producers were from the states of New York (34%), Massachusetts, (17%), Vermont (15%), New Hampshire (14%), Pennsylvania, (11%), Maine (6%), and Virginia (3%). Producers varied in range of age and experience tapping with the majority of respondents being 50 years of age or older (64%) (**Figure 1A**) and over one-third with 30 years or more background experience tapping sugar maple trees over their lifetime (38%) (**Figure 1B**).

Almost half of the producers have/had parents (46%) and grandparents (47%) that tapped maple trees (**Figures 1C, D**). Most respondents primarily learned to tap from family, friends, and neighbors (79%) (**Figure 1E**). Producers shared that they value producing maple syrup for multiple reasons with the most prevalent reasons being: to have the opportunity to be outdoors, engaging in an activity with family and friends, carrying on a family tradition, enjoying the process, and earning income.

With regards to attributes of the maple systems that producers manage, almost half the producers tap maples growing between 500 and 1,500 feet in elevation (49%), are small-scale with 1,000 taps or less (48%), and harvest either between 1,001 and 10,000 gallons (31%) or 10,001 and 50,000 gallons of sap (32%) annually (**Figure 2**). Over a third of the respondents (41%) tap sap from species other than sugar maple with the highest proportion coming from New England (48%). The red maple (*A. rubrum*) was the second most commonly tapped species (tapped by 78% of producers who tap species in addition to sugar maple). Other species tapped by respondents include black maple (*A. nigrum*), silver maple (*A. saccharinum*), Norway maple (*A. platanoides*), and birch (*Betula* spp.).

The most prevalent mode of harvesting among respondents is tubing (83%). Following harvest, over half the producers reported they only use evaporation (62%) for processing sap into syrup while the remaining first start with reverse osmosis and then evaporation (**Figure 3**). Wood (71%) is the primary energy source for processing sap into syrup by the surveyed producers (**Figure 3**).

A large majority of producers sell their maple commercially (78%); with few producers (12%) reporting maple sales as their primary source of income (**Figures 4A, B**). Almost half reported maple production sales accounts for 0-5% of their income (51%) with the sale of maple generating minimal income (49%) (**Figures 4C, D**). The primary outlet for maple product sales are direct sales such as through personal stores (60%), family and friends (55%), maple festivals (20%), and farm stands (20%). Almost a third of producers rely on sales through a middleman (28%). Producers sell a range of maple products including maple syrup (100%), maple candies (54%), and maple sap (9%), as well as a range of other specialty maple products such as candied nuts, flavored beverages, and maple cream. A large majority of respondents (86%) shared that maple products are part of local agri-tourism in their area.

The majority of producers responded that they were not aware of the range of nutritional and health attributes of maple syrup. The most prevalent nutritional and health attributes of maple syrup recognized by producers are mineral and antioxidant content (31%) and that maple is an alternative for sugar (20%). More than half of the respondents perceive that high-quality maple is based on its flavor (58%) with some also perceiving that light color is a key characteristic of high-quality maple syrup (25%). A few respondents perceive that high-quality maple syrup is based on density, being free from impurities, a medium color, and meeting high-quality production standards of the maple industry.

A large majority of respondents perceive that the maple sugar tapping season is starting earlier each year (76%), regardless of the geographic region where the producer is located. Additionally, almost half the producers perceive that the maple sugar tapping season is ending earlier (46%) and sugar maple trees are budding earlier each year (53%) (**Figure 5**). Further, around half of producers reported they perceive more variability in daytime temperature (51%) and night-time temperature (45%) during the tapping season, and total number of days when each grade of syrup is produced (45%). Around one-third of surveyed producers reported more variability in duration of the sugar tapping season (33%), or that number of days of January thaw were the same (45%) over their lifetime (**Figure 6**).

Approximately half of the producers perceive there has been increased variability in the following climate variables during the

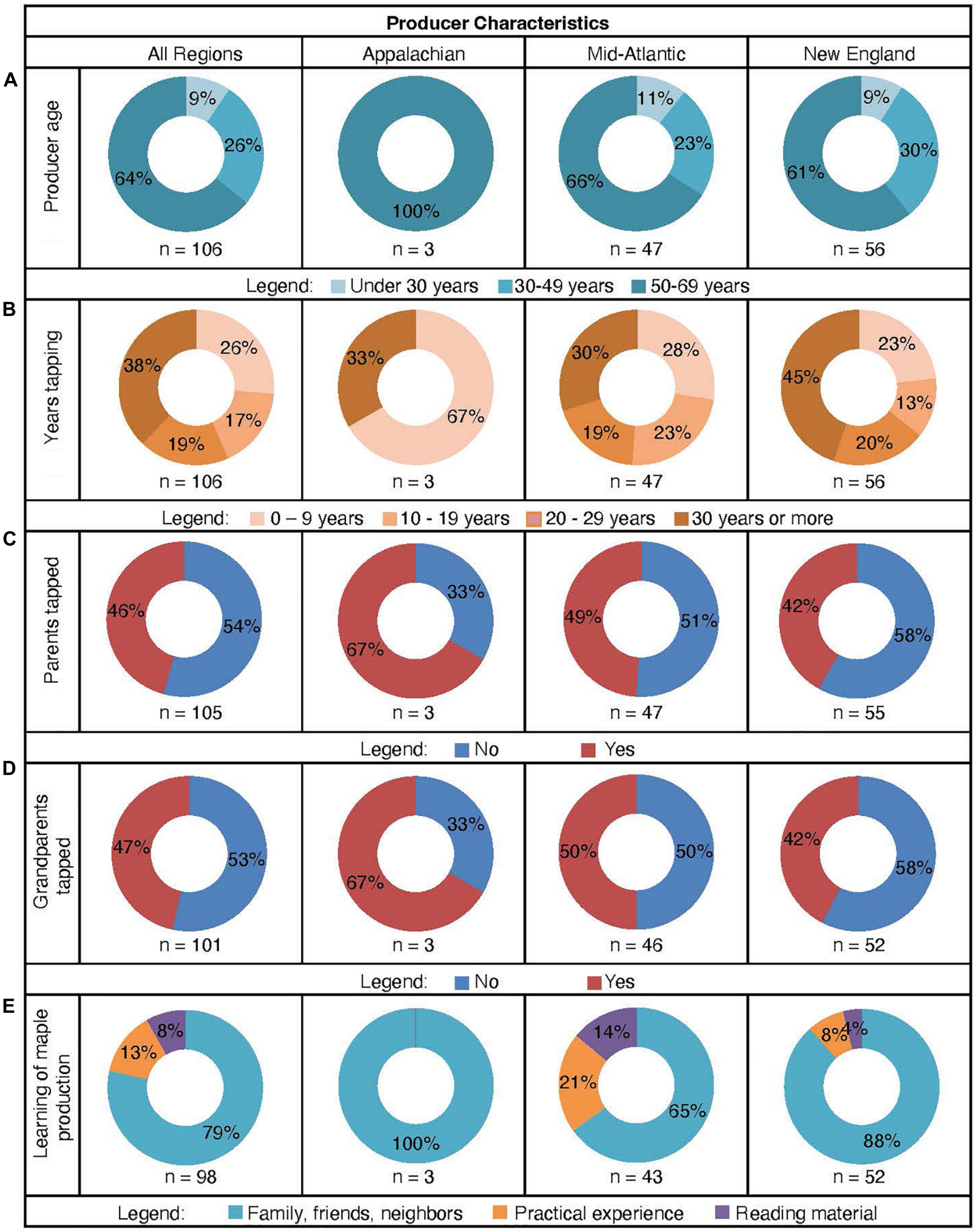

FIGURE 1
Maple socio-ecological system: producer characteristics. Characteristics of respondents from all regions (column one), and in the Appalachian (column two), Mid-Atlantic (column three), and New England (column four) maple producing regions based on **(A)** producer age range, **(B)** producers' years of experience tapping maple, **(C)** whether or not parents tapped, **(D)** whether or not grandparents tapped, and **(E)** how producers first learned to produce maple syrup (from Survey Tool 1).

past decade: snowpack (48%), temperature (50%), and suitable conditions for sap flow (51%) (Figure 7). Comparison of these variables based on the geographic region of the producer found significant differences in means for perceptions of snowpack ($p < 0.0019$) and temperature ($p < 0.005$). The variables that the near majority of producers perceive have stayed the same in the past decade are wind (45%) and rainfall (45%) (Figure 7). No significant differences were found based on perceptions regarding rainfall and wind on the basis of the region of the producer. Producers were overall split in their perceptions of snowfall, duration of snow cover on the ground, and storms with no significant differences found regarding responses based on the geographic region of the producer. Overall, there were no environmental variables that the majority of producers perceived that either increased or decreased in the past decade.

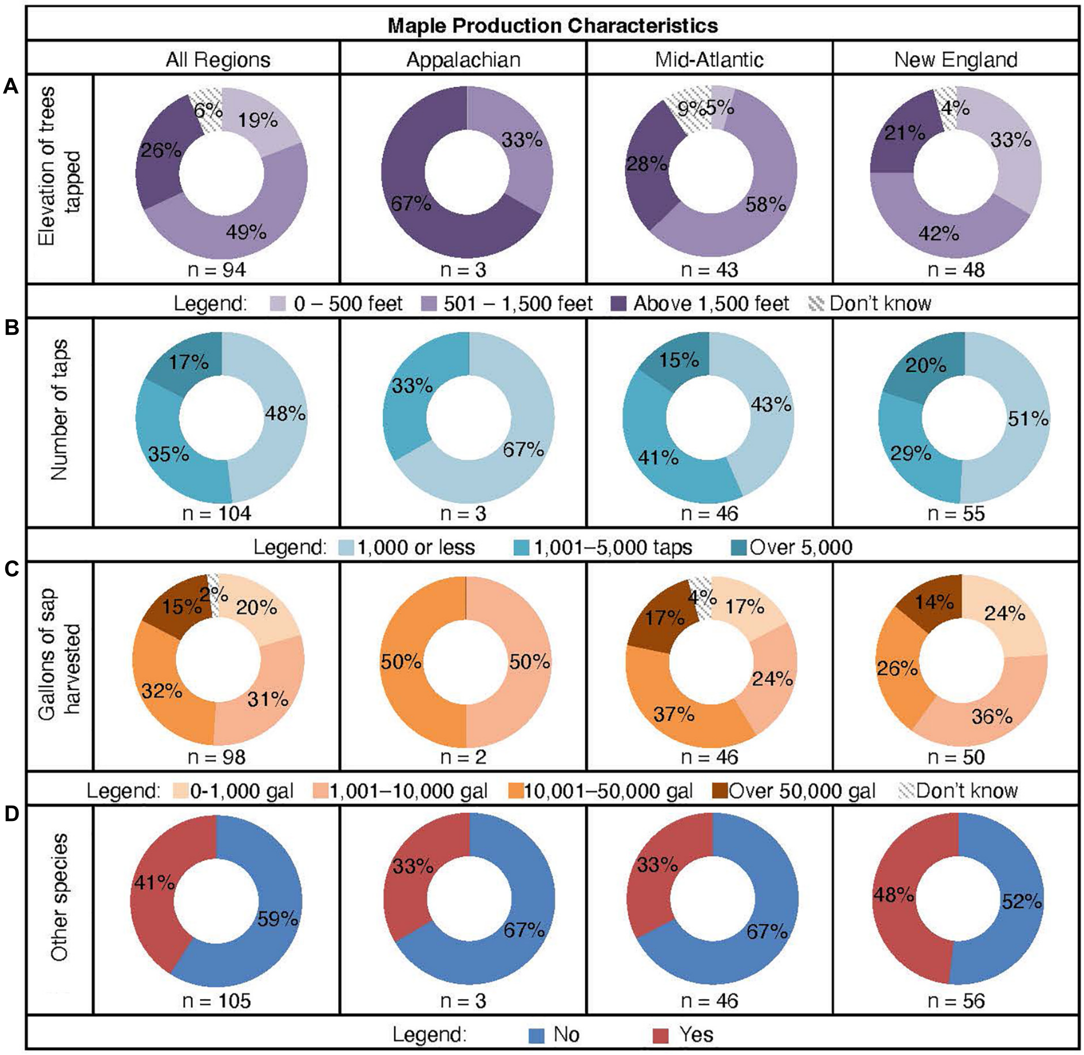

FIGURE 2
Maple socio-ecological system: maple production characteristics. Characteristics of respondents from all regions (column one), and in the Appalachian (column two), Mid-Atlantic (column three), and New England (column four) maple producing regions based on **(A)** elevation of trees tapped, **(B)** number if taps, **(C)** gallons harvested, and **(D)** whether or not other species are tapped.

Most producers (89%) report they have experienced the negative impacts of climate on maple syrup production. The producers who report they have not experienced the negative impacts of climate on maple syrup production are mostly from Massachusetts. The most prevalent factor that the surveyed producers perceive has negatively impacted their maple production is warmer weather.

Many respondents are noticing changes in maple sap quality from year to year based on climate and environmental factors. More than half of producers perceive the following environmental factors impact the quality of maple syrup: outdoor ambient temperatures (89%), alternating periods of cold nights and warm days (83%), insect infestation during the previous autumn season (70%), duration of snow cover on the ground (69%), size of the tree crown (68%), amount of rainfall (66%), soil type and quality (64%), amount of snow fall (59%), age of the tree (58%), tree density (56%), and barometric pressure (52%) (Table 1). Comparison of these variables found significant differences based on the geographic location of the producer for the variable of tree crown ($p < 0.05$) with a greater prevalence of producers from the Appalachian and Mid-Atlantic regions perceiving that the size of tree crowns impacts maple sap quality.

Less than half of the producers perceive that the following variables impact the quality of maple syrup: aspect the slope faces (47%), altitude (45%), direction of the wind (44%), air pollution (44%), number of days of January thaw (37%), and steepness of the slope (20%) (Table 1). The only environmental variable that producers perceive impacts maple sap quality that has significant differences based on geographic region of the producer is days of January thaw ($p < 0.04$) with all producers from the Appalachian region perceiving days of January thaw impacts maple sap quality while producers from the Northeast and Mid-Atlantic regions were split in their perceptions.

Overall, the surveyed producers diverge regarding their perceptions of the future of the maple system. While 40% of participants feel concerned, 39% feel hopeful regarding the future

FIGURE 3
Background of maple socio-ecological system: tapping and processing methods. Characteristics of respondents from all regions (column one), and in the Appalachian (column two), Mid-Atlantic (column three), and New England (column four) maple producing regions based on **(A)** tapping method, **(B)** processing method, and **(C)** fuel source.

while the remaining feel neutral or have "other" perceptions. Significant differences were found based on the age of the surveyed producers with regards to perceptions of the future; the majority of producers older than 50 years were concerned about the future while the majority of younger producers between 30 and 49 were hopeful ($p < 0.04$) regarding the future of the maple system. Comparison of attitudes toward the future of the maple system found no significant differences in means of prevalence of specific perceptions based on the geographic region of the producer, the number of years the producer has tapped maple, the number of taps in the production system, quantity of annual sap harvest, and contribution of maple to livelihood.

The majority of producers have adapted their harvesting practices to climate effects including the addition of vacuum tubing and valves and varying tap sizes and tube lengths. Approximately a third of producers (29%) have not changed their maple sap harvesting or processing practices due to changes of environmental effects on maple sap. However, beyond tapping practices, very few producers have responded to impacts of climate on their maple production with changes in stand management of maple trees. Those who have implemented changes in their maple stands have implemented thinning of trees to support the health of individual maple trees.

3.2. Producer responses to climate scenarios

A total of 98 participants completed this survey, with variation in sample size for different survey questions as not all participants responded to every question (for survey questions see Supplementary Survey 2). Survey respondents were from the Midwest (49%), New England (39%), Appalachian (7%), and Mid-Atlantic regions (4%). Producers ranged in their experience tapping maple trees for sap with just over one-third tapping being between 0 and 9 years (36%), followed by 30 or more years (31%), 10 and 19 years (24%), and between 20 and 29 years (9%; Figure 8). The majority of those surveyed are smallholder maple producers with nearly three-quarters collecting sap from 1,000 or less taps (74%), followed by those that collect sap from between 1,001 and 5,000 taps (22%), and those that collect sap from over 5,000 taps (4%). Of the respondents that collect syrup from 1,000 or less taps, over half collect from 200 or less taps (61%) and under half collect from 201 to 1,000 taps (39%).

Producers varied in their responses to the hypothetical climatic scenarios (detailed in Table 2) and whether or not they would change maple stand management, sap harvesting practices, maple sap processing, and maple syrup marketing. The majority of participants reported they would not change stand management, maple sap processing, or marketing of maple products, but would change their harvesting practices in responses to Scenarios 1 (more variable weather patterns and more frequent extreme weather events), Scenario 2 (warmer in winter and spring), and Scenario 3 (decreased tapping season). Results were not significantly different on the basis of the geographic of where the producer (Appalachia, Mid-Atlantic, Midwest, and New England) with the exception of Scenario 1 regarding more variable weather patterns and more frequent extreme weather events, and maple syrup marketing ($p = 0.0411$).

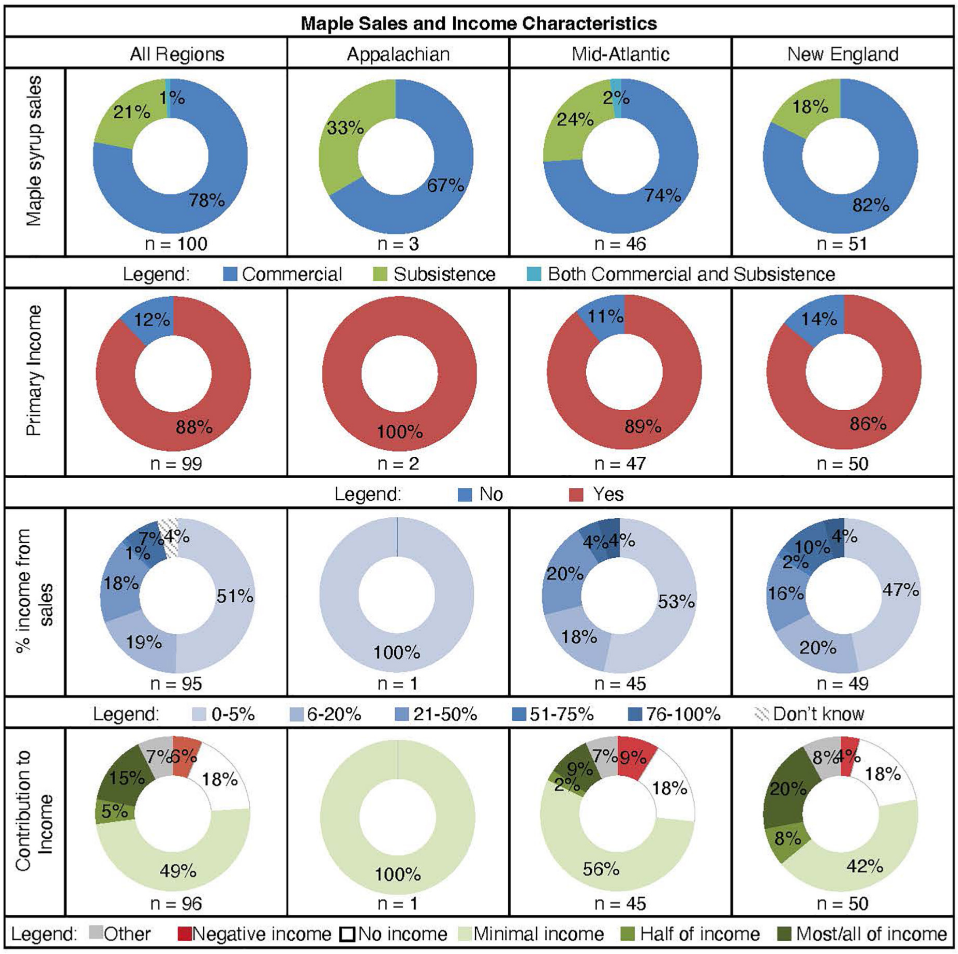

FIGURE 4
Background of maple socio-ecological system: maple sales and Income characteristics. Characteristics of respondents from all regions (column one), and in the Appalachian (column two), Mid-Atlantic (column three), and New England (column four) maple producing regions based on **(A)** type of maple sale, **(B)** whether or not maple production and sales is the primary source of household income, **(C)** percentage of income from maple sales toward household income, and **(D)** scale of contribution to household income.

Producers shared a range of stand management practices in response to climate scenarios including canopy thinning, modification of planting density, and mulching around trees. Changes in harvesting practices included shifts in time of harvesting, type of taps and drop lines, and use of a drill for tapping. Changes in sap processing practices include use of an evaporator, reverse osmosis, and use of wood for fuel. Changes in marketing practices included increased marketing and advertising or timing of marketing.

Producers were presented Scenarios 4 and 5 (Table 2) related to tree health and growth, and whether they would make a change in maple stand management, sap harvesting practices, maple sap processing, and maple syrup marketing. For Scenarios 4 and 5 on higher pest prevalence and suitable geographic range shifting north, the majority of participants reported they would not change harvest practices, maple sap processing, and marketing of maple products (Table 3). The majority of participants reported they would change stand management for Scenario 4 (pests) but were less certain about Scenario 5 (northern shift). Results were not significantly different among maple producing regions of Appalachia, Mid-Atlantic, Midwest, and New England with the exception of Scenario 4 and maple stand management ($p = 0.0342$).

Producers shared a range of practices they might change in response to an increase in pest prevalence or a northward shift in geographic area most suitable for maple syrup production. Changes in maple stand management practices included following best management practices for pests and disease, and relocation of maple systems to higher latitudes northward and higher elevations. Changes in sap harvesting practices included selective harvesting to avoid stressed trees or to tap less such as only harvesting for personal use, reducing the size of the maple operation, increasing the number of taps, and tapping more trees. Changes in sap processing practices included covering and filtering the sap, processing the sap in a more protected environment, and using new methods and technology to adapt. Changes in maple syrup marketing practices included changing the marketing message such as marketing different characteristics of maple products.

Producers were presented with tapping Scenarios 6 and 7 (Table 2) related to sap and syrup yields and quality inquiring whether they would make a change in maple stand management, sap harvesting practices, maple sap processing, and maple syrup

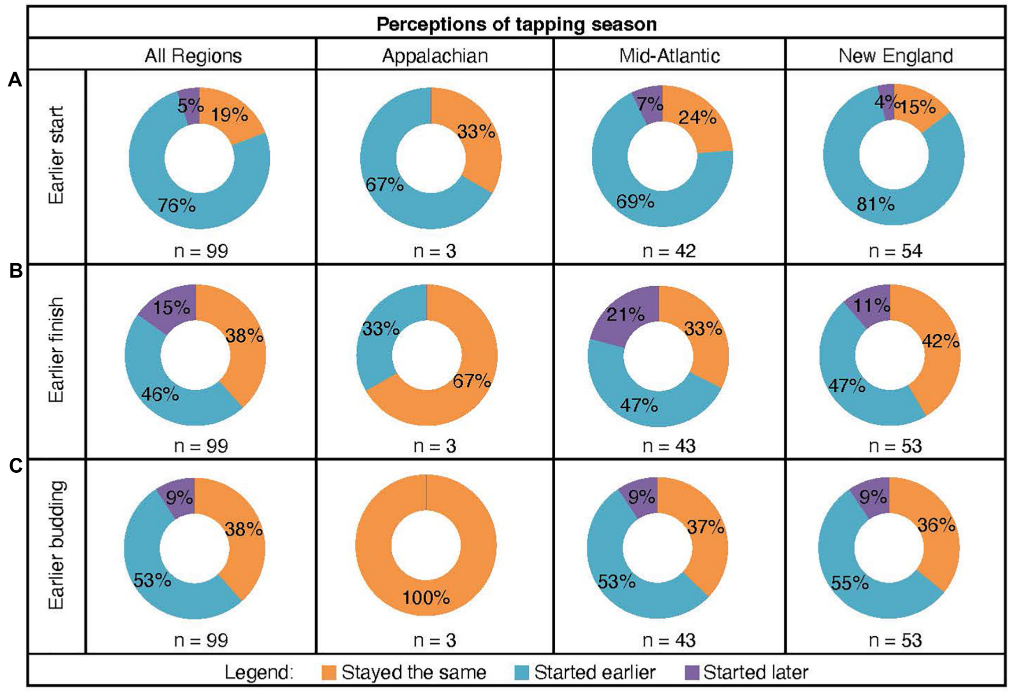

FIGURE 5
Producer perceptions of climate events: changes in sugaring season. Changes perceived over a producer's lifetime regarding maple sugaring season reported from all regions (column one), and in the Appalachian (column two), Mid-Atlantic (column three), and New England (column four) maple producing regions for **(A)** start date and **(B)** end date of the tapping season, and **(C)** budding time of maple trees.

marketing. For Scenarios 6 and 7 regarding decrease in sap quantity and quality, the majority of participants reported they would not change maple sap processing and marketing of maple products (Table 3). Further, the majority of participants reported they would change harvesting practices for Scenario 6 while a minority of participants reported they would change harvested practices for Scenario 7. Finally, for stand management, there was greater uncertainty regarding making changes for both Scenario 6 and Scenario 7. Results were not significantly different among maple producing regions of Appalachia, Mid-Atlantic, Midwest, and New England with the slight exception of Scenario 7 (decrease in sap quality) and maple syrup marketing ($p = 0.0499$).

Producers shared a range of practices they might change in response to a decrease in the duration of tapping season, sap quantity, and sap quality. Changes in maple stand management practices included thinning maple stands, improving the general health of maple stands through enhancing soil organic matter such as use of fertilization and mulching, integrated pest and disease management, tapping different maple varieties, planting more trees, diversifying tree varieties, and overall implementation of best management practices. Changes in sap harvesting practices included adjusting timing of harvest such as harvesting earlier, re-tapping, or tapping as long as weather allows, reducing or ceasing operations, tapping more or finding more trees to tap, utilizing available harvesting technologies, tapping more trees, and increasing taps. Changes in sap processing practices included processing sooner, faster, or in smaller batches and earlier in the season, boiling smaller batches, spending more time processing, using new methods or changing processing equipment, processing to a higher brix value, processing faster, and changing or experimenting with processing methods. Changes in maple syrup marketing practices included selling value-added maple products, increasing price or selling in smaller containers, stopping sale of maple products, only producing maple products for home/personal use, increasing marketing efforts, adjusting the price of maple products, and marketing dark syrup that is produced at the end of the season.

Producers were presented with Scenarios 8, 9, and 10 (Table 2) related to socio-economic conditions to determine if they would make a change in maple stand management, sap harvesting practices, maple sap processing, and maple syrup marketing. For Scenarios 8 (more consumer demand), Scenario 9 (financial policy incentives), and Scenario 10 (higher prices for maple syrup), the majority of participants reported they would not change harvest practices, maple sap processing, and marketing of maple products (Table 3). For stand management, there was a greater prevalence of uncertainty regarding making changes for all three scenarios. Results were not significantly different among producers on the basis of their geographic region.

Producers shared a range of practices they might change in response to consumer demand for sustainability, subsidies, and higher maple price. Changes in maple stand management practices included becoming certified organic or expanding operation; increasing size of the maple stand and production, organic certification; adding more workers and investing money back into maple stands. Changes in sap harvesting practices included investing in equipment, tapping more trees, and maintaining high vacuum taps. Changes in sap processing practices included reverse osmosis, buying more sap, and investing in technology and better equipment. Changes in maple syrup marketing

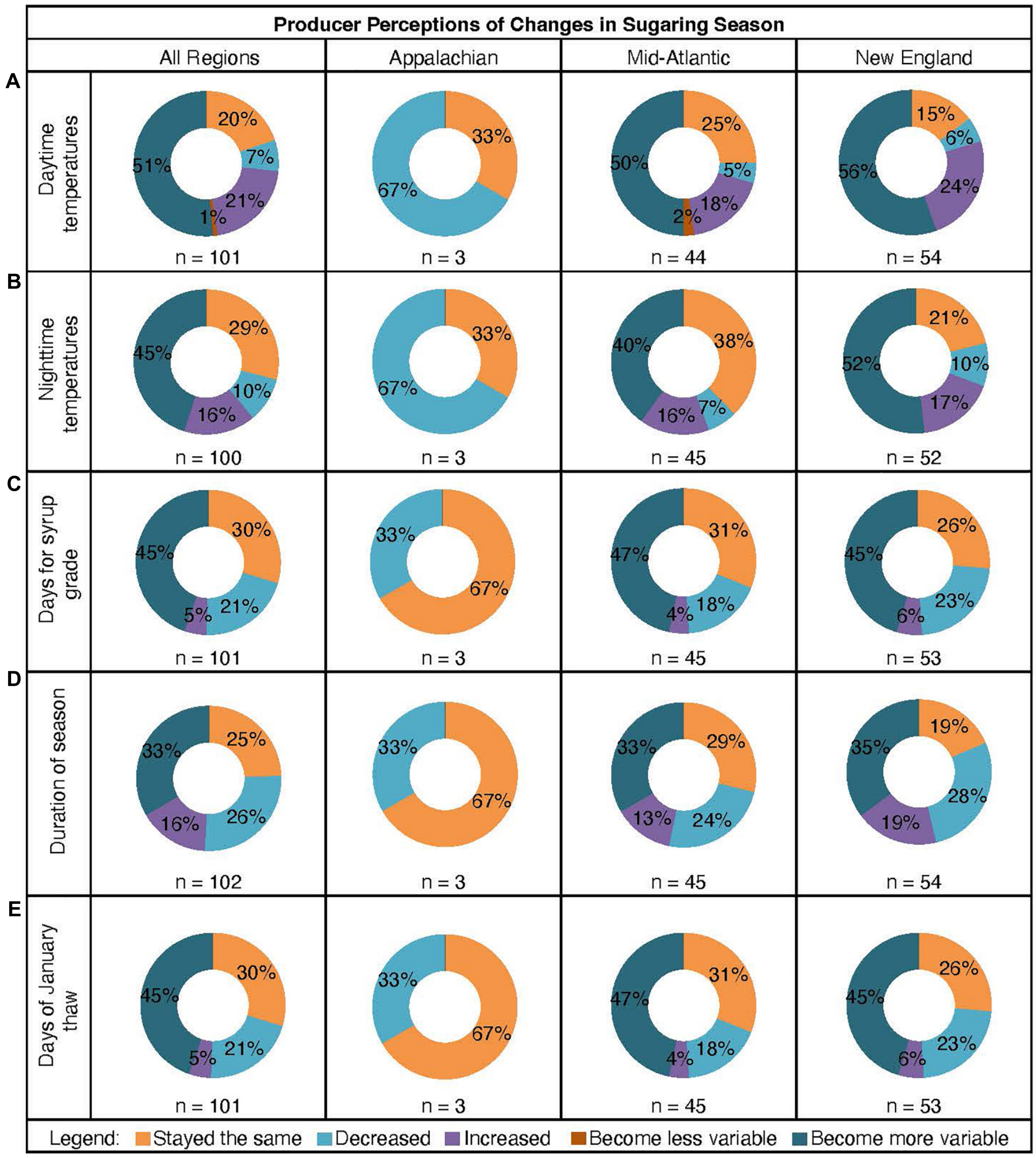

FIGURE 6

Producer perceptions of climate events: changes in sugaring season. Changes perceived over a producer's lifetime regarding maple sugaring season from all regions (column one), and in the Appalachian (column two), Mid-Atlantic (column three), and New England (column four) maple producing regions reported for **(A)** daytime and **(B)** nighttime temperatures during tapping season, **(C)** number of days when each grade of syrup is produced, **(D)** duration of sugar tapping season, and **(E)** number of days of January thaw.

practices included adding labeling regarding the attributes of maple products (ecological, social, nutritional, and health), selling different quantities of syrup, focusing on value-added products and marketing, adjusting prices of maple syrup, changing labeling and branding, and spending more resources on advertising.

3.3. Focus group workshop with tribal stakeholders

Findings from focus group interviews with tribal stakeholders from the Onondaga, Potawatomi, Anishinaabe, Oneida, Ojibwe, and Meskwaki communities (located in New York, Michigan, Minnesota, Wisconsin, and Iowa) emphasized the traditional role of producing maple syrup for their cultural heritage as well as gratitude to the land for this gift. Interview findings demonstrate that Native communities have long observed climate change. One tribal interviewee shared a story learned from oral tradition that predated colonial times and cited significant climatic events specifically relating to maple sap harvesting.

The tribal members we engaged with relayed that their belief system is their main management strategy when dealing with climate impacts on sugar maple trees. When it comes to living beings and all things with a spirit including trees, animals, and waterways, all tribal participants shared they believe that these beings have their own voices and have an ability to make their own

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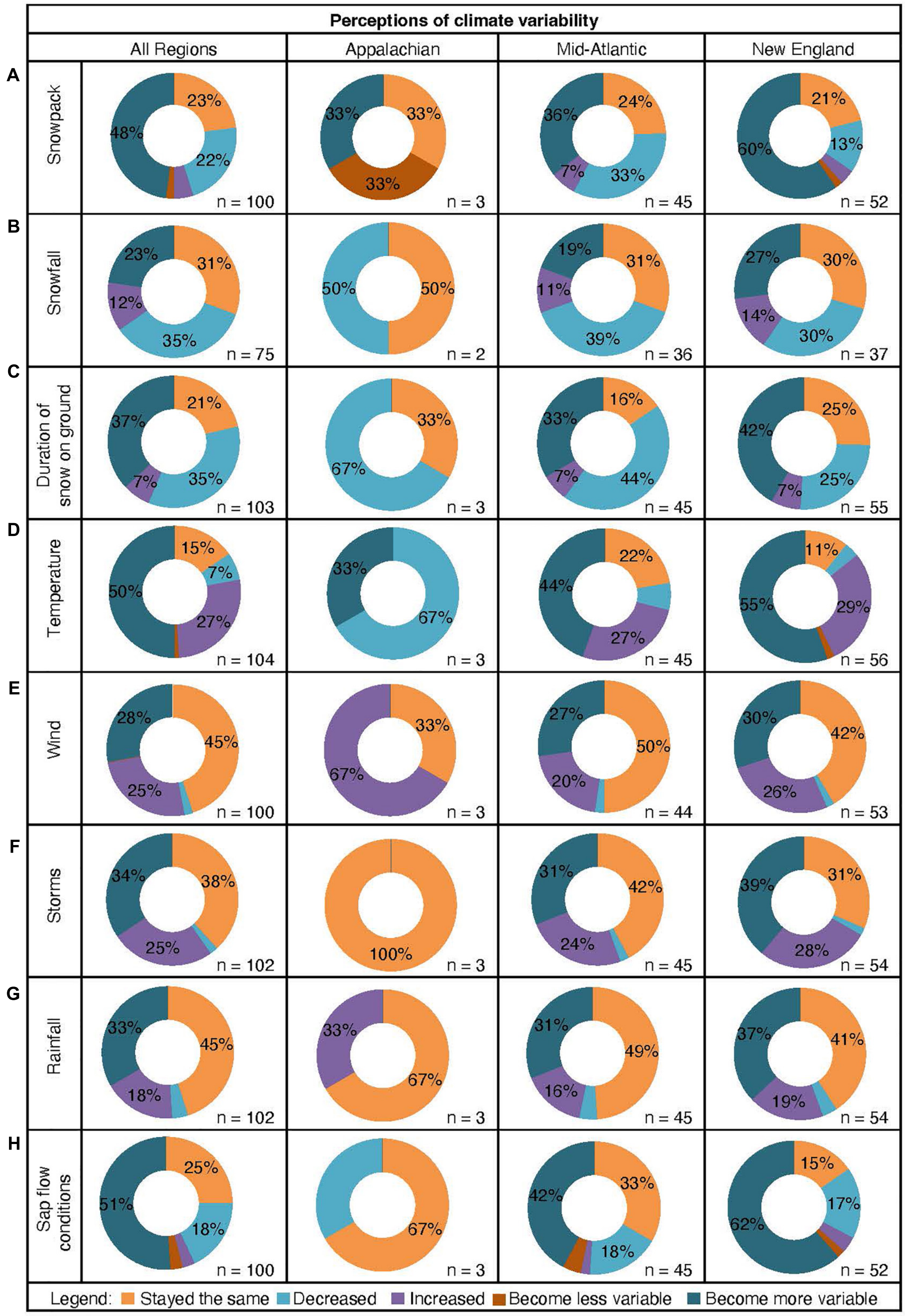

FIGURE 7
Perceptions of changes in climatic variables. Perceived changes in variability reported by producers from all regions (column one), and in the Appalachian (column two), Mid-Atlantic (column three), and New England (column four) maple producing regions for **(A)** amount of snowpack, **(B)** and snowfall, **(C)** duration of snow cover on ground, **(D)** temperatures, **(E)** wind, **(F)** storms, **(G)** rainfall, and **(H)** sap flow conditions.

decisions. It is important to note that this worldview is not a way to anthropomorphize what western cultures generally consider to be inanimate objects. Instead, this worldview is a way to observe, respect, and learn from other types of beings. When it comes to sugar maple trees specifically, a Potawatomi tribal member from Michigan stated that Tribal stakeholders in Michigan recognize

TABLE 1 Perceived changes in maple sap quality from year to year reported by producers based on climate and environmental factors.

Factors that affect maple sap quality	All regions (%)	Appalachian (%)	Mid-Atlantic (%)	New England (%)
Age of the tree	58	100	58	55
Air pollution	44	67	37	48
Alternating periods of cold nights and warm days	83	100	77	87
Altitude	45	67	45	44
Amount of rainfall	66	67	76	58
Amount of snowfall	59	33	55	63
Aspect/direction that slope faces	47	33	57	40
Barometric pressure	52	67	55	48
Days of the January thaw	37	100	41	29
Direction of the wind	44	67	48	40
Duration of snow cover on the ground (snow pack)	69	100	60	75
Insect infestation during the previous autumn season	70	100	73	65
Outdoor temperatures	89	100	87	90
Size of the tree crown of the sugar maple tree	68	100	77	59
Soil type/soil quality	64	100	67	59
Steepness of slope	20	0	30	13
Tree density (amount of trees in an area)	56	67	66	46

The dark green shading represents 75–100% of respondents that reported they perceived the respective factor while light green shading represents 50–74.9% of respondents, dark yellow represents 25–49.9% respondents, and red shading represents less than 25% of respondents.

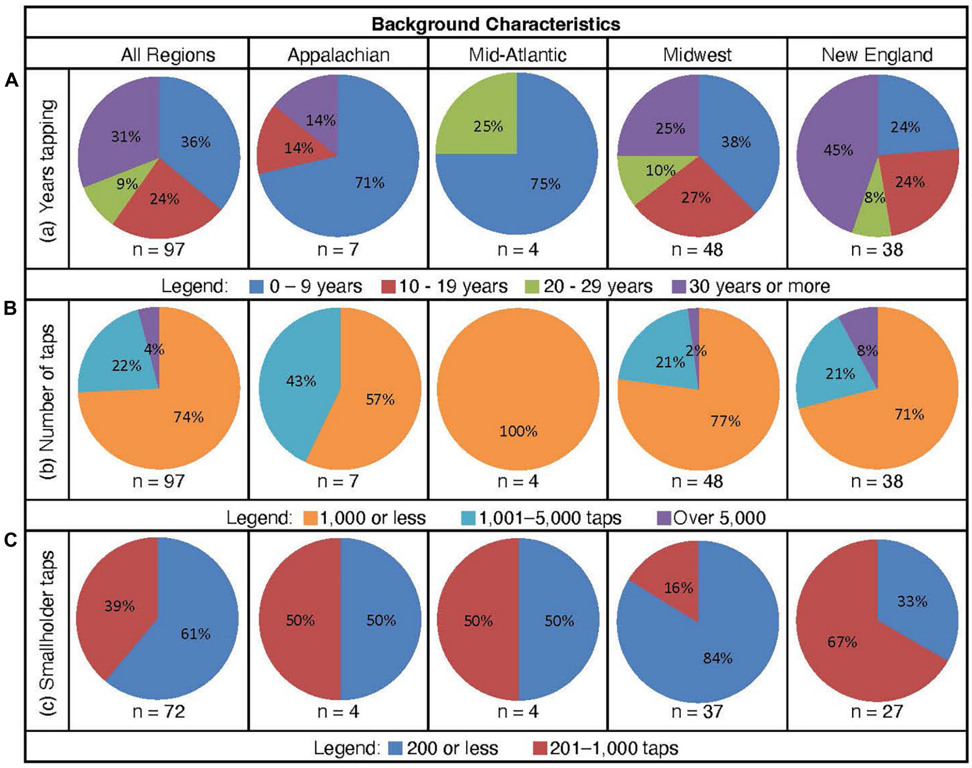

FIGURE 8
Background characteristics of maple production system. Characteristics of system from all regions (column one), and in the Appalachian (column two), Mid-Atlantic (column three), Midwest (column four), and New England (column five) maple producing regions based on **(A)** number of years tapping experience, **(B)** number of taps in maple system, and **(C)** proportion of taps in the smallholder maple systems only (from Survey Tool 2).

TABLE 2 Description of each of the 10 scenarios influencing the maple socio-ecological system.

	Scenario
Climate	Scenario 1: If you knew that there would be more variable weather patterns and more frequent extreme weather events such as warmer winters in the next 10 years, would you change the following?
	Scenario 2: If you knew that the weather was going to become notably warmer in the winter and spring during the next 10 years, would you change the following?
	Scenario 3: If you knew that the duration of the tapping season would decrease during the next 10 years, would you change the following?
Pests and geographic range	Scenario 4: If you knew that there would be notably higher pest prevalence in maple stands during the next 10 years, would you change the following?
	Scenario 5: If you knew that the geographic area most suitable for tapping maple would notably shift north during the next 10 years, would you change the following?
Tapping season	Scenario 6: If you knew that sap quantity would decrease during the next 10 years, would you change the following?
	Scenario 7: If you knew that sap quality would decrease during the next 10 years, would you change the following?
Socio-economic	Scenario 8: If you knew that there would be more consumer demand for maple syrup grown in an environmentally sustainable way (such as organic certification and/or diversification of stands) during the next 10 years, would you change the following?
	Scenario 9: If you knew that there would be financial policy incentives such as subsidies for organic certified maple production during the next 10 years, would you change the following?
	Scenario 10: If you knew that there would be higher prices for maple syrup during the next 10 years, would you change the following?

the gift of syrup through their Sugar Maple ceremonies held each winter. Numerous participants of the focus groups interviews spoke of the cultural importance of maple syrup and the general practice of traditional tapping methods. Tribal members emphasized the value of using only what is offered to them by the land.

All tribal participants continue to use traditional methods to harvest maple sap as well as modern materials. Tribal participants reported using sumac branches, metal taps, hand drills, and aluminum taps for tapping sap. Metal buckets, coffee cans, and bags are used to collect the sap from the spouts of taps. Tribal members reported using "*big metal pans,*" metal drums, open flat boards and pans, and fire for processing sap into syrup. One Potawatomi tribal member from Michigan reported using a reverse osmosis machine for over 2,000 acres and 800 taps.

Overall, tribal members from various parts of the country are experiencing and noticing changes in weather and climate during the maple tapping season. In Iowa, a Meskwaki representative found that "*there was less snow…* " In northeastern Minnesota, an Anishinaabe tribal member noticed that the winter lasted longer even though there was "*barely any snow*." This tribal member also noticed that the winter was significantly "*less windy*" than all previous years. In Red Lake, Minnesota, it was noted that when "*bad weather comes [the maple sap] stops running*." In Michigan, Potawatomi members are having difficulty predicting the sap season. As one Potawatomi member stated: "*…the weather has been more erratic and is less consistent in when the weather begins to warm. All of which make it hard to predict the sap season. Has noticed that people have been tapping too early*." Not only have the tribal participants noticed changes in the winter months, but they are also recognizing changes in the summer months. Members from the Onondaga Nation in New York remarked on the extreme heat waves and few rains that they experienced the previous summer.

When asked explicitly about observations of climate change and its impacts on maple sap and syrup quality, tribal members shared that key observations they have seen are sporadic seasons, shorter seasons, "*on and off*" seasons, and sap starting to run later in the spring. For example, an Onondaga Nation tribal member from New York stated that the latest maple harvest season (2016) was the shortest season by far and that they were only able to collect sap for about 1–2 weeks. A Meskwaki representative from Iowa also reported that the season was "*super early and really short!*" and that they collected almost no sap. A Potawatomi tribal member from Michigan stated: "*The last two seasons have been short…three years ago, the season lasted for 2 plus months; now the seasons are getting shorter*." An Anishinaabe tribal member from Minnesota stated, "*The season started early and [had] smaller amount of sap. [sic]…sap was running on and off.*" Overall, tribal participants noted that climate change is resulting in the declining health of sugar maple trees and changes in the tapping season that involve more sporadic tapping seasons.

Aside from observations of climate patterns, it is important to point out that tribal people observe multiple environmental indicators that are being impacted by climate change such as start of a season. Anishinaabe and Onondaga members indicated that they wait for environmental indicators such as the first thunder and singing of specific birds as a mark of the maple tapping season. One Oneida/Ojibwe tribal member from Wisconsin has seen more abundance of insects during the past tapping season, specifically moths, wood ticks, and mosquitos – many of which were found frozen in the sap.

The majority of the tribal stakeholders interviewed do not measure the quality and sugar content of the sap that they tap. Of those interviewed, two tribal members had tested their sap and had knowledge regarding changes in its quality with climate change. An Anishinaabe member who taps in both northern Minnesota and south-central Minnesota noticed that syrup from the latest harvest season had a higher sugar content than previous years. A Potawatomi member from Gun Lake Band of Potawatomi of Michigan tests their syrup for quality and has found that their product is now more consistent with a higher quality. This tribal member also reported having a lower sugar content than previous years.

The tribally affiliated participants emphasized that nature will manage itself with regards to climate solutions. Participants shared the sentiment that they are choosing to accept what nature has

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TABLE 3 Producer responses regarding whether they thought they would change their maple stand management, harvest practices, maple sap processing, or maple syrup marketing in response to each of the 10 scenarios influencing the maple socio-ecological system detailed in Table 2.

Stand management		Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6	Scenario 7	Scenario 8	Scenario 9	Scenario 10
	I do not know	21%	18%	16%	26%	64%	56%	53%	71%	70%	68%
	No	55%	60%	60%	26%	15%	17%	32%	12%	15%	10%
	Yes	25%	22%	24%	48%	21%	27%	15%	17%	15%	22%
	Sample size	97	94	94	96	95	93	91	89	86	90
Harvest practices											
	I do not know	8%	6%	7%	20%	13%	11%	25%	8%	15%	5%
	No	30%	21%	41%	49%	56%	38%	38%	78%	66%	63%
	Yes	62%	73%	51%	31%	32%	52%	36%	15%	19%	32%
	Sample size	97	96	94	96	95	93	91	89	88	91
Maple sap processing											
	I do not know	5%	2%	3%	16%	11%	8%	16%	9%	14%	5%
	No	73%	69%	75%	78%	71%	71%	46%	75%	69%	75%
	Yes	22%	29%	22%	6%	19%	21%	37%	16%	17%	20%
	Sample size	97	96	93	95	95	91	91	89	88	91
Maple syrup marketing											
	I do not know	14%	8%	9%	16%	10%	7%	19%	10%	14%	7%
	No	74%	80%	80%	79%	72%	77%	68%	67%	64%	65%
	Yes	13%	13%	11%	5%	18%	16%	13%	22%	22%	29%
	Sample size	96	93	91	94	94	91	91	89	87	91

The dark green shading represents 75–100% of respondents that reported they perceived the respective factor while light green shading represents 50-74.9% of respondents, dark yellow represents 25–49.9% respondents, and red shading represents less than 25% of respondents.

TABLE 4 Themes identified by a focus group comprised of producers and forest managers.

Concerns	Challenges	Maple syrup yields and quality	Proposed solutions
Warmer winter/spring Main concerns: influence on pests, nutrient cycling, weather unpredictability	More invasive earthworms – loss of leaf litter layer/beech dominance, lack of germination, faster cycling of nutrients No snow cover – more erosion, less litter, root damage Forest pests (e.g., forest tent caterpillar and gypsy moth) Summer drought – regeneration failure Problems with regeneration if some populations require low temperatures	Fewer freeze/thaw cycles in southern locations Crown dieback – fewer leaves, less sugar High calcium magnesium soils leads to the best quality syrup Soil leaching from erosion and different forest stand makeup, less calcium and magnesium soils Warming – trees heal wound faster, shorter tapping season Warming earlier in spring – budburst or microbial activity can interfere with production Decreased sap quantity and quality Harder to manage without frozen ground for access Change in species composition might affect soils and thus taste	Foresters and sugar maple producers must allow for regeneration to aid in adaptation of sugar maples to a warmer climate Tap early Tap other species – other maples, birch, beech Sanitary taps Vacuum tubing Prewarmers Smaller taps Disposable taps Pull taps earlier Fertilize Liming Homogenization of syrup Bulk production Consider different sites Deer management: wolves, doe hunting Manage invasive species, spraying Structural and species diversity, including more red maple and ash; promote harvesting Note that the northern end of the sugar maple range is likely to benefit from warmer conditions Source seeds from farther south Maintain closed canopy
More variable weather	Increase in pest outbreaks Pressure changes are different in other species – requires vacuum tapping, no long term viability Warm weather near end of season can end season prematurely	Increase in fungal and bacterial spread Shorter tapping season Less reliable tapping season	Begin tapping earlier (i.e., January first) to catch a false spring Manage for pests and disease by avoiding monocultures Sanitize spouts regularly to lower the spread of fungal/bacterial disease Adapt to tapping other species
Extreme weather events Main concerns: false springs, ice storms, wind blow down, wildfire, flooding, drought, and other extreme weather patterns that damage maple populations	Drought destroy an entire season's crop + "bud taste" False springs – leaf damage + more microbes in tap hole, disease and lower quality syrup Storms – windthrow kills trees + damages tubing systems (loss of time/opportunity) Catastrophic wind events can reduce recruitment or even wipe out a population Flooding/extreme precipitation – soil erosion, leaf litter loss/leaching, little regeneration	Early season = light syrup, less microbial activity Late season (or warmer weather conditions) = darker syrup, lower quality, high microbial activity	Tap earlier in season to avoid false springs – still risk a low yield Tap in fall Tap silver/black maple (but harder to heal; more brown) More work needs to be done to manage maple stands/production to account for extreme weather Testing smaller tap holes to combat effects of increased microbial activity due to false springs Nanofiltration (i.e., reverse osmosis, raises the sugar content of low-sugar syrup by placing next to high-sugar syrup separated by permeable membrane; important in false spring years when sugar content is lower) Using "certification" status to achieve goals (e.g., to be deemed "certified organic," at least 25% of syrup must come from red maple)

given them and finding ways to work with nature. Responses shared by tribally affiliated producers highlight knowledge of multiple adaptation strategies that focus on long-term ecological management of forests. They shared that their communities are including other culturally significant, sap-producing species in their practices as a way to adapt to the challenges of climate change.

Members from the Potawatomi stated that they are tapping other trees to establish more relationships to the trees. They are further practicing using different medicines as sap is viewed as a medicinal gift. Other species being tapped include basswood (*Tilia americana*), yellow birch, ironwood, and other varieties of maple.

Many tribal members expressed concern when asked about using technology as a solution for tapping maple trees in the context of climate change. The majority of tribal members that participated in the focus group stated that one should only harvest as much as they need and that nature will provide resources as needed. For example, one Anishinaabe tribal member summarized tribal concerns as follows: "[*sic*] *worried about people's actions like* *using tubing, pumping, and technologies that are different than the traditional ways. . . greed is a spirit.*" People are always worried about "*how much*" they get when the trees will "*always give enough*."

3.4. Focus group interviews with producers and forest managers

Focus group participants at the FEMC focus group agreed that sugar maple trees and producers face serious threats due to climate change. Prevalent climate observations include warmer winter and spring seasons, more variable weather, and greater extreme weather events. The specific extreme weather events that are damaging maple populations noted by focus group participants include false springs, ice storms, wind, wildfire, flooding, and drought. Specific challenges and solutions that were brought forward by the focus group participants are outlined in **Table 4**.

Prevalent challenges perceived by the participants with warmer winter and spring seasons include lack of snow cover, forest pests, summer drought, and issues with maple seedling regeneration. Challenges perceived by the participants with more variable weather include increase in forest pests and prematurely ending the maple tapping season. Challenges perceived by the participants with more extreme weather events include multiple outcomes that destroy the maple harvest including damages to trees and tapping systems, "bud taste" to maple syrup quality, and more microbes in maple taps that reduce maple syrup quality.

Impacts on maple syrup quality noted by participants in response to warmer winters and spring seasons include decreased maple sap quality including that with less sugar. These effects on maple quality are linked to fewer leaves in the crown of maple trees and soil leaching from erosion and different forest stand makeup. Specially, participants noted that soil leaching and erosion results in soils with less calcium and magnesium for maple trees to draw from for plant health. More variable weather was perceived by participants to increase in fungal and bacterial spread in tapping systems, resulting in decreased maple syrup quality. Maple syrup harvested during the early part of the season is associated with higher quality with a lighter color and lower microbial contaminants around the taps. Syrup from sap harvested later during warmer periods is associated with darker syrup that is of lower quality and has high microbial activity.

Participants noted numerous adaptation strategies in response to climate change. Some of these strategies varied on the basis of the specific climate challenge. Stand management practices noted by participants include fertilization, relocation of production sites, and diversification of tree species in maple-dominated forests including other sap species tapped such as red maples as well as other tree species such as ash trees (*Fraxinus* spp.). Harvesting practices noted by participants as a climate adaptation strategy include changing the type and number of taps, tapping earlier in the year, regularly sanitizing tap spouts, using disposable taps, creating smaller tap holes, and vacuum tubing. Sap processing practices noted by participants as a climate adaptation strategy to climate change include use of an evaporator, nanofiltration, and reverse osmosis. Marketing practices noted by participants as a climate adaptation strategy include using product certification and labeling schemes such as certified organic.

The focus group participants' built consensus that it is the responsibility of resource managers including foresters and maple producers to adapt strategies for managing the maple system in response to climate change and its impacts. Moreover, participants emphasized that more research is needed on the direct and indirect impacts of climate change on maple systems as well as the potential for adaptation and implementation of sustainability practices.

With regards to envisioning what maple sugaring should ideally look like at the end of the century, participants described healthy trees in diverse functioning forest ecosystems. As part of this vision, maple syrup will continue as one of the many ecosystem services of forests of the Northeast and Midwest and Mid-Atlantic. Additionally, focus group participants noted that people with different perspectives are connected and working together toward common goals of enhancing the integrity of maple systems.

4. Discussion

This study provides evidence that climate change and its impacts on the maple system are being observed by maple syrup producers in the United States. Maple producers further have knowledge of climate adaptation strategies from forest-agricultural systems through harvesting of maple sap, processing of maple sap into syrup, and marketing practices. While the majority of non-tribal maple producers surveyed have implemented technological solutions in response to climate change, the tribally affiliated maple producers surveyed have focused on implementation of long-term ecological management of forests rather than technological solutions. Given the dependence of maple syrup producers on the health of sugar maples and red maples for their livelihood and cultural traditions, adapting to changes in maple production will likely be necessary under future changes in climate and markets. Indigenous forest management has been practiced for thousands of years in North America; an example of sustainable forest management can be learned from the Menominee selection system (Kern et al., 2017). Overall, findings emphasize the importance of cooperation and diversification at every level and dimension of the maple system for its long-term resilience.

Observations of maple producers with regards to climate change are aligned to evidence of climate change patterns in the United States across the range of maple forests. Observation and knowledge of climate change is a critical factor for implementing climate adaptation practices. Previous research suggests that in order for climate adaptation to occur, producers must first have knowledge of how the climate is changing (Maddison, 2007) and impacting species within their systems. Findings of this study indicate that producers have general knowledge of impacts of climate change on both yields and quality of maple syrup, while further research is called for to more precisely measure these impacts and responses to adaptation strategies toward more effective climate solutions.

While producers noted that maple quality was decreasing, they generally were unaware of the specifics of these mechanisms. Research on the biomolecular composition of maple sap to climate change and various climate adaptation practices would be informative for the development of evidence-based solutions to protect maple quality. Research is needed to identify optimal management practices for both maple syrup yields and quality, which can have an inverse relationship (Ahmed et al., 2014).

Study participants are aware of multiple adaptation strategies in response to climate change for the long-term viability of the maple system. Producers shared knowledge of multiple adaptation strategies in response to the climate scenario survey comprised of: (1) stand management practices including diversification of sap species tapped, tree planting of plantation saplings, canopy thinning, modification of planting density, mulching around trees, and application of lime fertilizer; (2) harvesting practices including shifts in time of harvesting (tapping earlier), not tapping some years to maintain tree health, type of taps and drop lines, and using a drill for tapping; (3) sap processing practices with integration of technology including use of an evaporator, reverse osmosis, and use of wood for fuel; and (4) marketing practices including increased advertising, finding new markets, innovation of products, marketing different characteristics of maple products, and investing in product labeling schemes such as organic certification.

While maple producers have knowledge of a wide range of climate adaptation strategies from forest management to marketing of product, most non-tribal producers who participated in this study have focused on implementing immediate technological solutions involving harvest and processing practices to maximize sap yields and profits such as vacuum tubing and reverse osmosis machines. Technological advancement of maple production using vacuum pressure collection techniques notably alters the magnitude of pressure gradients inside maple stems to increase sap flow (Wilmot, 2007). Relatively few non-tribal producers noted actively implementing changes in their maple stands such as diversifying species composition of forests and thinning of trees in their maple stands to support the health of individual trees.

The implementation of intensive maple sap harvesting and processing practices to extract maximum sap yields from maple resources in the context of climate change has resulted in the production of maple syrup notably increasing in the United States over the past two decades (Climate Adaptation Science Centers, 2015). The increased intensification of maple harvesting has further been driven by market opportunities of increased prices linked to strategic control of total supply in Canada by the FQMSP through a quota system (Farrell and Chabot, 2012) as well as technological advancement. Further expansion of increasing maple production in the United States is feasible under current conditions as only a fraction of trees that could be utilized for maple syrup are in production (Farrell, 2009, 2013). Expansion in the North American maple industry has generally occurred in the form of larger producers investing in large new areas for production. However, it is unclear how a rapid change in price may halt such expansion or even force producers out of the market. It is therefore important to understand the variables influencing maple producer decision making.

In contrast to the short-term technological solutions focused on maximizing maple sap and profits through intensive harvest and processing practices implemented by the non-tribal participants, the tribally affiliated producers that participated in this study have focused on implementing long-term land management practices in response to climate change effects on maple systems. The climate adaptation strategies noted by tribal producers involving management of forest resources are not only adaptation strategies, but also serve to mitigate climate change. These long-term solutions are in line with Indigenous beliefs and practices surrounding the land, including oral traditions of passing down knowledge with regards to climate change and natural resources. As shown by the interview with the key informant who shared knowledge passed down on climate change from the late 1800s, Indigenous Peoples voices can add historical knowledge that may not be available through physical records.

The authors of this study emphasize the importance of acknowledging Indigenous Peoples voices, history, and relationships to the land for the sovereignty of these communities. Additionally, it is important to bring Indigenous Peoples voices into environmental conversations to enrich these conversations with diverse perspectives including the sacred responsibility to be caretakers of the land as well as to foster resilience and stewardship of forest resources. Resilience refers to the ability of a system to absorb disturbance and retain the same structure and functions (Walker and Salt, 2006).

A resilience approach to managing maple systems would address the complex relationships within these systems as well as the interaction of multiple factors of global change such as climate change interactions with market and policy shifts. Key characteristics of resilience include diversification, connectivity, localization, sovereignty, capacity to withstand disturbances, capacity to react, rapidity and flexibility, resourcefulness, capacity to learn, and adaptability (Carpenter et al., 2001; Tendall et al., 2015). These attributes integrated into climate solutions for the maple system may enhance future outcomes. In designing resiliency solutions, efforts are further needed to build the personal, social, and emotional resilience of stakeholders themselves in response to global change as well as their adaptive capacity (Folke et al., 2002) to implement solutions. The following actions may help to promote attributes of the long-term resilience of maple systems to global change:

- **Community engagement for enhancing cooperation and evidence-based solutions:** It may be helpful to create a community engagement plan of developing partnerships between producers, researchers, and industry groups to jointly work together to develop evidence-based management plans and policy suggestions for enhancing the resiliency of maple systems. Such efforts may take a participatory approach with the inclusion of diverse stakeholders that interact and support maple systems including practitioners, consumers, and policymakers.
- **Acknowledging Indigenous ways to caretake the land:** It is important to recognize the diversity among Indigenous Peoples and the systems they manage, including the sovereignty of Indigenous Peoples' land, maple, and food systems. We acknowledge that there are many lessons to learn from Indigenous Peoples' systems including climate adaptation strategies in the context of global change while supporting numerous sustainability goals. Many Indigenous Peoples' food systems are inherently sustainable, promoting environmental, socio-cultural, and human health dimensions of sustainability with their deep connection to honor the responsibility to caretake the land, holistic concepts of health, and practices of reciprocity and gratitude (Durning, 1992; Kuhnlein and Receveur, 1996; Ford, 2009; Kimmerer, 2013; Smith et al., 2019; Chevaun, 2022).
- **Diversification and climate mitigation strategies:** Enhancing the resilience of maple systems requires diversification at every level and dimension. Rather than solely focusing on

short-term technological solutions to extract maximum sap, it is critical to implement long-term ecological solutions. Among the most promising adaptation strategies are those that also serve to mitigate climate change such as practices that build soil organic matter in forest-agricultural systems while enhancing diversity including species composition and ecosystem functioning.

• **Future research on climate effects on maple biomolecular composition:** Long-term research is needed to capture variability of climate effects on maple syrup quality which involves comprehensive analysis of biomolecular composition. Given the trends of the northward shift of maple systems with climate change, research across the geographic range of maple and at different elevations is needed. Further, research is also needed to examine how climate adaptation strategies in maple systems can mitigate climate effects on maple quality.

• **Youth education:** It is important for future generations and leaders of maple systems to be aware of climate trends and their impacts on forest-agricultural systems as well as the effectiveness of various adaptation strategies. Curriculum developed and distributed as part of STEM-education opportunities for primary, middle, and high school students that integrates research material on climate change and maple systems would educate future generations including maple producers, stakeholders, and consumers.

5. Conclusion

Global change is among one of the most pressing societal issues today. Enhancing management of forest and agricultural systems to mitigate climate risk and building capacity of producers are key strategies to address global change (IPCC, 2007). As a culturally relevant and highly flavorful forest-agricultural product, climate effects on maple systems have implications for ecosystems, maple producers, and consumers. This case study highlights that maple producers have observed the effects of climate change on their maple systems, have knowledge of a range of climate adaptation strategies, and are implementing some adaptation strategies. Community-engaged approaches are called for to inform the design of evidence-based solutions to address climate change and its effects on maple systems. Learning from diverse ways of being, such as integration of Indigenous Peoples management of maple and other forest-agricultural systems has the potential to shift our dominant approaches in response to climate change toward approaches that are more ecologically and culturally minded to advance both human and planetary health. Overall, this study emphasizes the importance of enhancing cooperation, diversification, connectivity, and sovereignty at every level and dimension of the maple system including building the personal, social, and emotional resilience and adaptive capacity of maple stakeholders themselves for resilience.

Data availability statement

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

Ethics statement

The studies involving human participants were reviewed and approved by the Institutional Review Board (IRB) at Montana State University and the University of Massachusetts at Amherst. The patients/participants provided their written informed consent to participate in this study.

Author contributions

SA, DL, JR, RH, BD, and AB conceived of the study and contributed to the development of the semi-structured survey on perceptions of climate change. SA, DL, JR, RH, BD, AB, and TM contributed to the development of the semi-structured survey on climate scenarios. AB led engagement with the tribal stakeholders. TM and JR led planning of the FEMC focus group with engagement of SA, DL, RH, and AB. TW led the data analysis. SA, TW, and AB led the drafting of the manuscript. All authors contributed to the article and approved the submitted version.

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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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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/ffgc.2023.1092218/full#supplementary-material

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