INTERNATIONAL JOURNAL OF BIODIVERSITY SCIENCE, ECOSYSTEM SERVICES & MANAGEMENT, 2017
VOL. 13, NO. 2, 40–52
http://dx.doi.org/10.1080/21513732.2017.1285815

Special Issue: Ecosystem Services Nexus Thinking

Managing for delicious ecosystem service under climate change: can United States sugar maple (*Acer saccharum*) syrup production be maintained in a warming climate?

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ABSTRACT

Sugar maple (*Acer saccharum*) is a highly valued tree in United States (US) and Canada, and its sap when collected from taps and concentrated, makes a delicious syrup. Understanding how this resource may be impacted by climate change and other threats is essential to continue management for maple syrup into the future. Here, we evaluate the current distribution of maple syrup production across twenty-three states within the US and estimate the current potential sugar maple resource based on tree inventory data. We model and project the potential habitat responses of sugar maple using a species distribution model with climate change under two future General Circulation Models (GCM) and emission scenarios and three time periods (2040, 2070, 2100). Our results show that under GFDL-A1Fi (high CO_2 emissions), sugar maple habitat is projected to decline (mean ratio of future habitat to current habitat per state = 0.46, sd ± 0.33), which could lead to reduced maple syrup production per tree and nearly 5 million additional taps required to maintain current projection levels. If global emissions are reduced and follow a lower trajectory of warming (under PCM-B1), then habitat for the species may be maintained but would still require management intervention. Finally, our results point to regions, particularly along the northern tier, where both climate change impacts and currently developing sugar maple habitat may signify viable opportunities to increase maple syrup production.

ARTICLE HISTORY
Received 9 June 2016
Accepted 18 December 2016

EDITED BY
Christine Fürst

KEYWORDS
Maple syrup; climate change; sugar maple (*Acer saccharum*); ecosystem services; Eastern United States

Introduction

Forests of the eastern United States are diverse and place a foundational role in many ecosystems. Their role in maintaining key ecosystem processes, including regulating water and carbon cycles, point to the vital supporting services they provide. Within this diverse assemblage of species, many also provide other key ecosystem services that benefit human well-being. These species provide provisioning services like timber, regulating services such as water filtration, and cultural services of heritage and sense of place. The strength of these services is influenced by their extant tree communities, diversity, and species assemblages (Gamfeldt et al. 2013). Recognizing the importance of these services while facing the mounting pressures of climate change (Allen et al. 2015; MEA 2005; Allen et al. 2010) are essential as we consider the full magnitude of climate change impacts on human well-being. The climatic trends undoubtedly also affect the ecosystem services which may gradually change with the climate or change rapidly by an increased load of disturbance events interacting with climate change.

Sugar maple services

Sugar maple (*Acer saccharum*) is an iconic species that provides multiple ecosystem services including maple syrup. For example, in the US, nearly 13 million liters (3.41 million gallons) of syrup were produced in 2015 (USDA-NASS 2015), valued at roughly $130 million. There is also considerable production value of maple as saw timber, and the relative contributions of maple species to hardwood sawtimber have been increasing in the eastern US (Luppold Miller 2014), mostly a result of limited forest management which promotes a light-limited closed canopy which favors shade tolerant species such as maples, rather than silvicultural strategies targeted toward maples (Nowacki & Abrams 2008). The strength and aesthetic properties of the wood make it a sought after hardwood species for construction and furniture manufacturing. Competing uses between timber production and maple syrup use demonstrate two important competing ecosystem services the species can provide. These contrasting uses for sugar maple trees set up challenging decisions for land owners, especially those with larger tracks of forests, and is further represented by the

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Supplemental data for this article can be accessed here.

reluctance of states to lease sugar maple trees on public land for tapping (Farrell & Stedman 2013). In addition, sugar maple is a dominant component of northern hardwood forests and serves as a key identifying species of these forest types. Indeed, the ecological importance of the species is recognized by its primary characterization of the mesic forest types of the Northeast. Its high shade tolerance and development within productive, uneven aged forests of the region forms the basis for its iconic character, especially the striking fall colors, as an example of an important cultural ecosystem service.

How the non-timber product use of maple sap has been utilized through time reflects the changing role economic opportunities have played in establishing the industry across its range. First developed and integrated into First Nations societies, the ability to extract maple sap and render maple sugar and syrup not only provided novel resources but also played a role in signifying the changing of seasons where family groups were brought together to extract this sweet resource (Whitney & Upmeyer 2004). With expansion of European settlements across North America, the use of sugar maple in production for granular sweetener and syrup took root in the early 19th century. This production expanded and by the mid-1800s, had expanded to encompass the entirety of the species range but the spatial extent of maple sugar production later contracted, due to economic drivers, toward the northern tier (Whitney & Upmeyer 2004). Maple syrup is now predominately a product of the northeastern United States and southeastern Canada. Approximately 70–75% of the world's sugar maple syrup is produced in Canada, with Vermont (41%), New York (18%), and Maine (16%) leading the US production (USDA-NASS 2015). Today, sugar maple (and to a lesser extent red maple) trees are tapped in the early spring with taps and collection systems. The sap is then concentrated through evaporation (dominant process historically and with hobby producers) or reverse osmosis (dominant process commercially) to complete the process. With the advent of newer technology, renewed interest in local foods, and increased marketing outside the Northeast, supply and demand for maple syrup has increased. Further, the production of maple syrup still retains a strong cultural presence for communities as evident by the success of Vermont's maple syrup production and its integration into the New England way of life.

It is at the interactions of these values, the production of timber and non-timber products, the cultural services with strong historical roots, and the sense of place, that we must consider how climate change may impact this vital resource. For this paper, we focus on potential impacts on maple syrup production for sugar maple.

How a changing climate translates to changes in maple syrup production

Evidence for a changing climate abounds, with multiple indicators of a warming world ranging from melting sea ice to increasing air temperatures to changes in location and behavior of species and functioning of ecosystems (Melillo et al. 2014). Temperatures have increased across the US, especially since ~1970, and each of last few decades have been warmer than the previous. Coupled with these changes has been a more vigorous hydrologic cycle, causing an increase in extreme weather events including a higher proportion of rainfall in downpours and in some regions, more severe droughts. A lengthening of the frost-free season is also apparent. These trends are expected to accelerate, depending on human choices related to emissions of heat-trapping gases such as CO_2 (Melillo et al. 2014).

In understanding how these impacts may influence maple syrup production, several ecophysiological characters interact to influence the amount and quality of sap produced each spring. Sap flow is primarily temperature dependent. Initially, low winter temperatures are needed to stimulate both sugar formation within the stem and sap flow during spring time (Duchesne et al. 2009). Then, during the sap collection season, cold nights (<0°C) followed by moderately warm days (~3–7°C) create a positive pressure to cause sap to flow down from tree branches and out the tree through a tap and collection system (Wiegand 1906; Marvin & Erickson 1956). Negative pressure (suction) at night replenishes sap from roots at night, and sap production continues as long as the freeze-thaw period continues. Low winter temperatures and repeating freeze-thaw are thus more sustained in the northern latitudes. At southern latitudes, the warmer winter and early spring warm-up conditions limit sustained sap production. A slow spring thaw is best for syrup production. When temperatures are consistently too warm (>10°C) and bud break begins, the traditional sap season is over (Wiegand 1906). This happens much more quickly in southern locations, and, presumably, more quickly as climate warms in the next decades. Earlier tapping has the potential to maintain similar production to accommodate the shift in optimal sap flow days; Duchesne et al. (2009) modeled a uniform shift where mean and variance in sap flow is shifted 14–19 days earlier by 2090. However, this shift is not expected to occur uniformly across the range of sugar maple. Southern latitudes have the potential of shifting to climates where optimal sap flow days are curtailed by too few cold day-warm night cycles (Duchesne & Houle 2014). The contrast between northern and southern potentials for sap production going forward with intensifying climate change suggests that a broad-scale analysis of both potential for maple syrup and climate change impacts on tree species habitats is needed.

We have modeled the potential impacts of various scenarios of climate change on 135 species, including sugar maple, of the eastern United States (Iverson et al. 2008; Landscape-Change-Research-Group 2014; www.fs.fed.us/nrs/atlas). We perform a series of analyses to assess the risk of climate change for each species based on the likelihood of suitable habitat change and adaptability of the species to a changing climate (Iverson et al. 2012). These analyses have provided a source for a number of vulnerability assessments across several regions of the eastern US (Brandt et al. 2014; Janowiak et al. 2014; Butler et al. 2015). These models show that sugar maple is forecast to lose significant suitable habitat in the southern and southwestern portions of its US range, but maintain reasonable habitat in the northeast, depending on scenario.

In order to evaluate the potential impact of climate change on sugar maple with a specific focus on how it may influence maple syrup production, we bring together our extensive habitat modeling with an evaluation of the maple syrup production across the species range. By considering the potential tappable trees under current conditions, we can then estimate the potential future tap distribution across the species range in light of likely habitat changes induced by climate change. This assumes that the change in potential habitat corresponds to changing conditions that reflect changes in tap potential. Our focus here is directed specifically at considering a broad view of the impacts and evaluates the sugar maple resource focused on maple syrup production. Another effort has demonstrated the incredible potential for maple syrup production within the US (Farrell 2013); this analysis incorporated industry-specific constraints, such as a minimum density of maple trees, a maximum distance from access roads, and the inclusion of red maple (*Acer rubrum*) trees, which although can also be tapped for maple syrup, has a lower sap sugar content. With our goal of evaluating ecosystem production services as related to potential climate change impacts, we incorporate the latest national inventory data (FIA) to estimate the current extent of tappable trees, then use our species habitat distribution model for sugar maple outputs to calculate the increase of taps required to meet current production levels at three time intervals throughout this century and under two contrasting scenarios of climate change. We use a broad calculation to assess tap potential that considers both current and potential tappable trees as the resource develops or is likely constrained through time. Our intention is that this assessment provides a model of how considering multiple ecosystem services of trees can be considered in light of climate change impacts. This model can be applied to other systems where multiple services (e.g., timber harvest and agroforestry, non-timber forest products, or cork in Mediterranean oaks) need to be managed simultaneously in the face of a changing climate.

Methods

Sugar maple abundance and potential taps in eastern US

The analysis relies on the comprehensive sampling of USDA Forest Inventory and Analysis (FIA) program (www.fs.fed.us/fia, Woudenberg et al. 2010), which provides a thorough, plot-based inventory of forest conditions throughout the United States. The FIA data were queried for the most recent 5-year period (mostly 2010–2014) to obtain the number of sugar maple trees for all plots east of the 100th meridian by state and by size class. Data for each plot were evaluated and the occurrence of sugar maple in the overstory was extracted as well as other plot information of extant vegetation community. To conservatively estimate the number of taps potentially placed into sugar maple trees, we calculated one tap for each tree recorded by FIA of diameter at breast height (dbh) 33–53 cm (13–21 in), and two taps per tree for trees >53 cm. This is a conservative estimate as most extension publications allow tapping starting at 25.5 cm dbh (10 in) and a third tap allowed in trees exceeding 63 cm (25 in) (Blumenstock 2007). In this assessment of maple syrup, we included only sugar maple as a source for syrup, and did not include red maple. In our assessment of potential taps, we did not consider other management factors such as distance to an existing extraction facility, road access, topographic limitations, or land ownership. We used the National Agriculture Statistics Service (NASS online: https://quickstats.nass.usda.gov/), using the Census of Agriculture data from 2012, to estimate the number of maple trees tapped by state. The ratio of taps as of 2012 to potential taps from current sugar maple trees gives an estimate of the proportion of trees tapped, and thus enable calculation of potential tappable trees.

Modeling potential change in sugar maple in US

The climate change analysis builds on species distribution models (SDMs, called DISTRIB in our case) for 135 tree species at a 20 × 20 km pixel resolution across the eastern United States, and are presented in a web atlas (www.nrs.fs.fed.us/atlas). These data and modeling approaches have been the focus of several papers (e.g., Iverson et al. 2008, 2011). Briefly, the response variable of importance value (IV, a metric incorporating basal area and number of stems of all species relative to the focal species) for sugar maples was derived from FIA, and the predictor data set included 38 variables that incorporate patterns of temperature, precipitation, soils, elevation, and landscape composition. Models of current species distributions were elucidated using decision tree ensemble models, with the Random Forest (Breiman 2001) technique providing a robust assessment of the environmental associates within and across a species' distribution (Prasad et al. 2006; Cutler et al. 2007). Next, we evaluated all tree species within each location to quantify the individual and cumulative contribution to overall tree species importance, and to identify how these species' habitats change under climate change simulations. These models project suitable habitat with IV ranging from 0 to 100, capturing the intensity of suitable conditions. Because actual responses of tree abundance will be influenced by complex, dynamic processes that cannot be fully captured, we cannot infer from these models that the species changes will be realized during these time intervals (Iverson et al. 2011). For this analysis, we used two model simulations that generally spanned the range of potential future conditions by 2100 to evaluate potential change in sugar maple habitat. The mild scenario was the Parallel Climate Model (PCM) and has lower sensitivity to changes in greenhouse gas concentrations (PCM, Washington et al. 2000) and was combined with the B1 emission scenario, which represented a rapid conversion by humans to low carbon energy sources (Nakicenovic & Swart 2000). In contrast, the Geophysical Fluid Dynamics Laboratory (GFDL) model is moderately sensitive to changes in greenhouse gas concentrations (Delworth et al. 2006) and was considered under the A1FI emission scenario (hereafter called harsh scenario), which predicted much higher greenhouse gas emissions (Nakicenovic & Swart 2000). These were modeled for 30-year periods ending in 2040, 2070, and 2100. A risk matrix framework incorporated both the likelihood and consequence of climate change (Iverson et al. 2012) for sugar maple. This risk framework provides a location specific (i.e., states in this context) assessment of the immediacy to develop management strategies based on the evaluation of the consequence of climate change for the species. It is based on 21 life history traits that capture the species inherent adaptive capacity (Matthews et al. 2011), and likelihood of change based on projected changes in suitable habitat.

We then estimated the change in syrup production anticipated by the changing climate conditions, according to the GFDL-A1Fi and PCM-B1 scenarios, for 2040, 2070, and 2100. The ratio of sugar maple suitable habitat in the future scenario to suitable habitat currently was assumed to also apply to the production of syrup so that a ratio of 0.5 indicates a 50% reduction in syrup potential for that state for that date. Finally, we calculate the number of additional taps that would be needed to replace the reduction in syrup production due to the changed climate. The percentage reduction of habitat (and syrup) was used to calculate the volume of shortfall to reach 2012 production levels for each time and scenario. Using data from NASS (USDA-NASS 2015), we acquired the average syrup production per tap by state (for some states with unreported average yields, an overall single tap average syrup yield of 0.287 US gallons per tap in 2015, or 1.09 l, was used); this number was divided into the shortfall to calculate the number of additional taps needed to replace the 2012 volume of syrup. These values were mapped by state and summarized within the US.

Finally, the modeling approach was optimized to relate the environmental variables that are key to capturing the distribution extent of the species and not focused on determinates of sap flow. Therefore, we also consider a direct measure in capturing sap production and evaluate the potential change in optimal sap flow season by deriving the mean number of days it takes to reach an accumulation of 75 growing degree days (GDD75). Duchesne and Houle (2014) identified GDD75 as a key predictor of actual maple syrup yield across the extent of our study area and at the state level resolution. Here, we evaluate the accumulation of growing degree days cumulated above a base of 5°C (41 F) (Rehfeldt et al. 2006, Sork et al. 2010; Franklin et al. 2013), and identify the Julian date each year from 1980 to 2099 when growing degree days reach 75 (GDD75). A growing degree day is the sum of average temperature per day (mean of daily minimum and maximum temperature) above the base temperature (5°C). The mean Julian date was then calculated for each of the four 30-year time periods. We then calculated change in days of GDD75 for each future 30-year period by differencing the mean number of days during the three time periods compared to GDD75 from current (1980–2010). Then to compare change in potential habitat to this metric of sap production, we tested for the strength of the association with Pearson's correlation coefficient (r).

Results

Sugar maple abundance and potential taps

Sugar maple trees are presently abundant in the eastern United States, and occur in 15,572 of the 88,845 FIA plots, and with its range encompassing the whole of northeastern US (Figure 1). FIA estimates 9.25 billion sugar maple trees to be present in this region, including all size classes. However, only a small fraction (406 million, or 4.4%) of the trees are larger than 33 cm, the assumed (and conservative) sized tree that is large enough for tapping. If we assume one tap per tree for

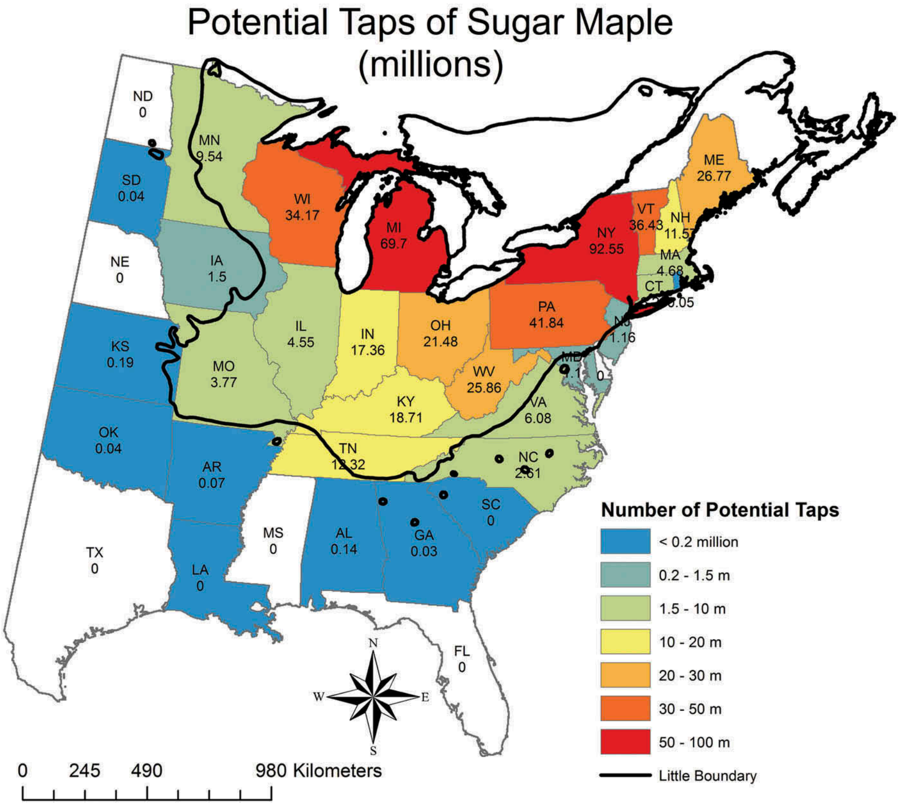

Figure 1. Potential taps of sugar maples by state, based on FIA data from 2010 to 2014. The estimate assumes that trees 33–53 cm could receive one tap, while trees >53 could receive two taps. Little's boundary depicts the sugar maple range boundary as mapped by Elbert Little (Little 1971). State abbreviations are presented in Table 2.

33–53 cm trees, and two taps per tree on trees >53 cm (Blumenstock 2007), a total of 448 million taps could be placed across the range for sugar maple now, with over half of the potential taps in three states: New York (93 million), Michigan (70 million), and Pennsylvania (69 million) (Figure 1). Particularly relevant when discussing future opportunities, there is great potential for the next smaller (23–33 cm) cohort of trees to grow into a tappable size class. This group currently consists of 682 million trees and even if only a small portion of these trees survive and move into the 33 cm+ size class, it would constitute a sizable cohort of additional potential trees for tapping into the future.

The NASS data from 2012 show a large variation in taps, with the most by far in the small state of Vermont with 4.3 million (Figure 2). New York and Maine follow with 2.1 and 1.9 million, respectively. Survey data from NASS in subsequent years shows that the number of taps have recently been increasing as technology and demand has increased (USDA-NASS 2015). The pattern also reflects a dramatic north to south gradient in taps and consequently, syrup production. The proportion of available sugar maple trees tapped, again with the assumptions on what is defined above as 'tappable', shows that up to nearly 12% of available trees in Vermont have been tapped, but that this proportion is substantially smaller in the remaining states (Figure 2).

Potential change in sugar maple habitat and syrup production

Sugar maple habitat is expected to decline in most parts of its current range by 2100, although being a long-lived species, it remains to be seen how a decline in suitable habitat translates to a decline in abundance by then (Figure 3, Supplementary Table 1). It is apparent that the southern portion of sugar maple range is in danger, while the northern range is more secure through 2100 (Figure 3). The change in habitat for each scenario/date reveals a substantial difference between mild and harsh scenarios, with some states along the western end of the range (e.g., Missouri,

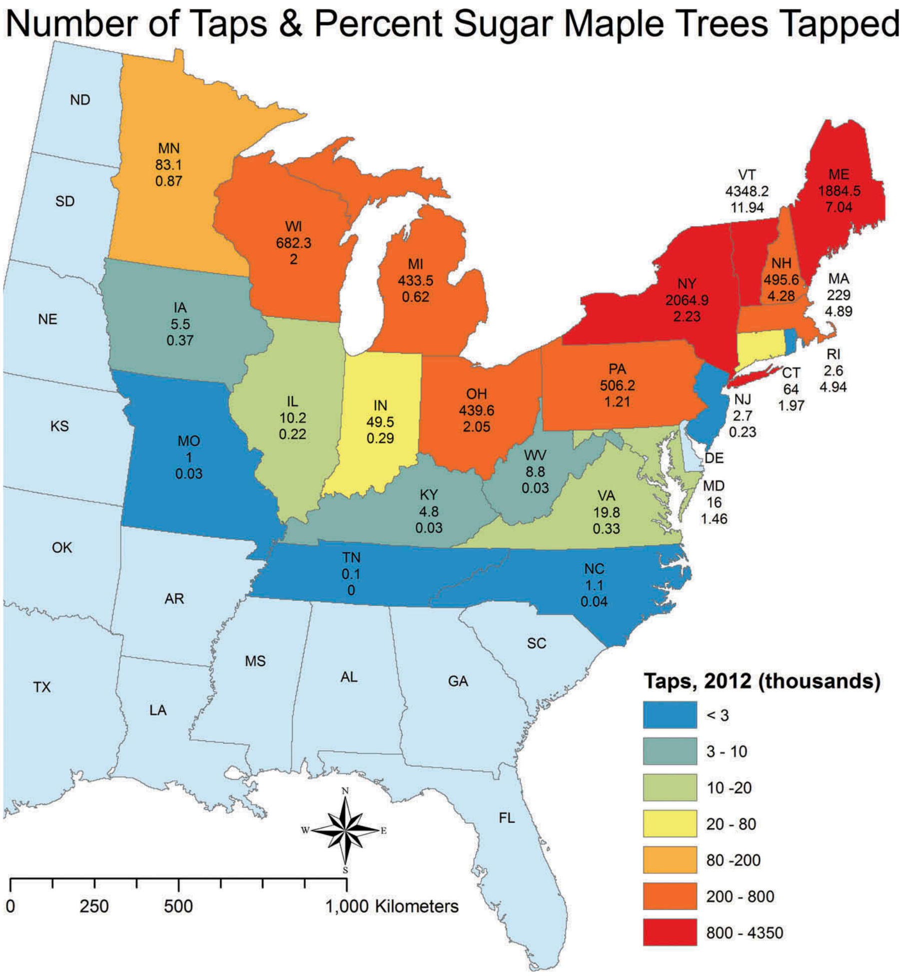

Figure 2. The number of taps (×1000) in 2012 for each state (NASS data, https://quickstats.nass.usda.gov/), with the corresponding percent of sugar maple trees suitable for tapping according to FIA (www.fs.fed.us/fia).

Iowa, Minnesota, Illinois, Indiana, Ohio) benefiting from PCM-B1 (Figure 3). Minnesota and Maine even show slight benefits for sugar maple habitat under the harsh GFDL-A1Fi scenario, at least until about 2070 (Figure 3). The risk matrix, exemplified for three states, shows that this trend varies widely by location, scenario, and date (Figure 4). For example, Minnesota, in the far north central, shows an increase in habitat in all scenarios and dates except a small decrease by 2100 in the most severe scenario (Figure 4). On the other hand, Kentucky, at the southern portion of sugar maple range, shows a severe decline, starting early and increasing in severity, under the GFDL-A1Fi scenario. Vermont loses nearly half its habitat under GFDL-A1Fi, but remains fairly stable under PCM-B1 (Figure 4, Supplementary Table 1).

The impact on maple syrup production services in light of climate change can be glimpsed by transferring these habitat ratios onto syrup production (Table 1). Considering the amount of habitat as a driver of potential sugar maple availability, there is a projected increase in the number of taps needed to maintain current production by the end of the century, but the magnitude varies greatly with emission scenario (Table 1). For example, the additional taps required to meet the 2012 production levels show that, under the harsh scenario (GFDL-A1Fi), an additional 4.9 million taps would be needed to make up for the projected loss of syrup across the eastern US (Table 1). By state, Vermont would require 1.5 million, New York 0.6 million, and Ohio 0.3 million additional taps under this scenario (Table 2). In fact, for the most part, all states show a requirement of additional taps needed by end of century, especially under the harsh scenario and especially for the states near the southern range boundary (Table 2). For example, Tennessee, Indiana, Illinois, and Ohio would need to increase their tapping by 101, 81, 75, and 69 percent, respectively (Table 2). Though of these, only Ohio has a sizable syrup industry at present (355k liters syrup in Ohio vs. Indiana with 47k liters in 2015 (USDA-NASS 2015)). These trends indicate the potential for the industry to move further northward over time.

Additional evidence as to the potential impact of maple syrup production is demonstrated by the projected change in GDD75 by state. The current gradient of Julian date to reach GDD75 reflects the increasing length of maple syrup season moving

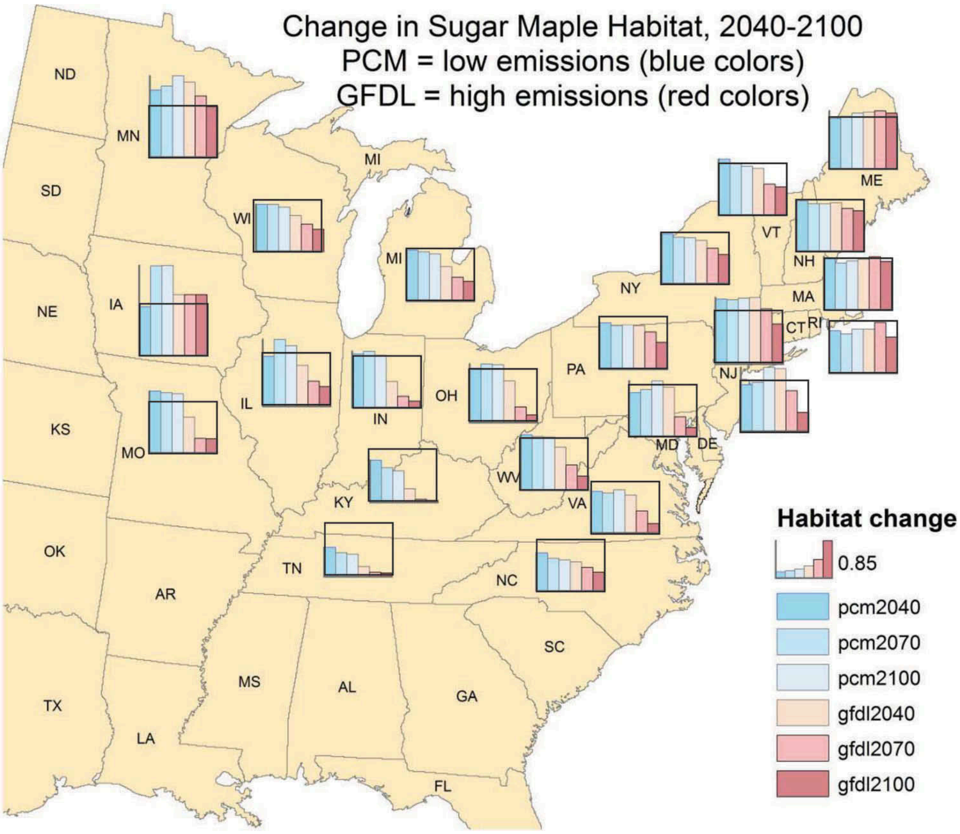

Figure 3. Projected change in sugar maple habitat under PCM-B1 (low emissions) and GFDL-A1Fi (high emissions) at three time points (2040,2070,2100) from 20 × 20 km species distribution models. For each state, a ratio of future IV to current modeled IV are presented such that a value <1 indicates a decrease in habitat while a value >1 indicates an increase. The horizontal line identifies a ratio of one and makes the distinction between gaining or losing habitat for the state.

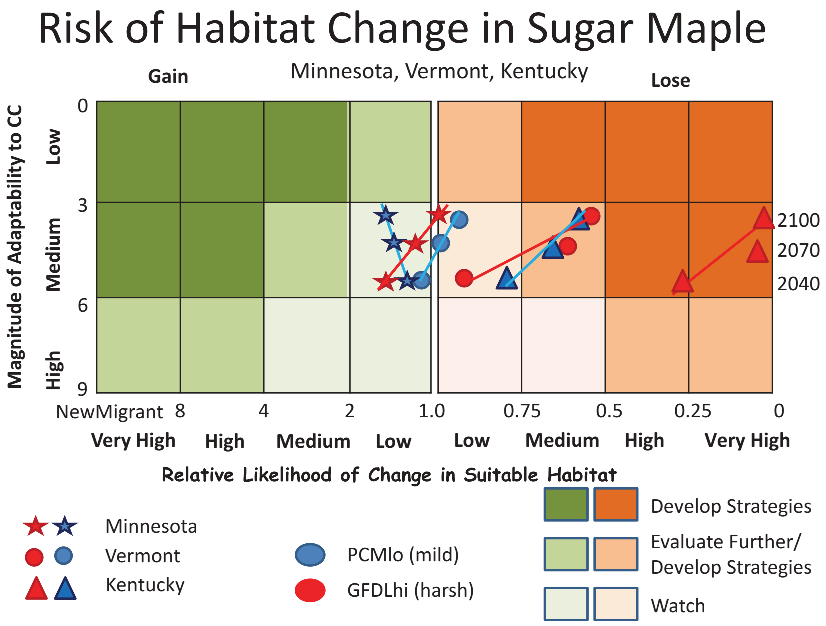

Figure 4. Risk matrix illustrating climate change vulnerability for Acer saccharum (sugar maple) in Minnesota, Vermont and Kentucky through time and under PCM-B1 and GFDL-A1fi climate models and emission scenarios.

south to north (Figure 5). This pattern is further modulated by the difference in continental vs. coastal climate. The projected reduction in days to reach GDD75 intensifies toward mid-century with the mean reduction by 2070 of 9.5 to 14.1 days under PCM-B1 and GFDL-A1Fi, respectively. The reduction continues under GFDL-A1Fi reaching a mean of 22.1 days reduction in GDD75 across all states while it remains relatively stable at 9.5 days under the milder scenario (Figure 5). Consistent

Table 1. Maple syrup production in 2012 and projected into future according to two scenarios (PCM-B1 and GFDL-A1Fi) and three time periods (2040, 2070, 2100), assuming that change in habitat corresponds to shifting syrup opportunity.

	Liters (x1000)	ΔLiters (x1000)	New Taps (x1000)
2012	8691		
PCM2040	8698	+8	-
PCM2070	8366	−326	313
PCM2100	8256	−435	407
GFDL2040	7824	−867	2340
GFDL2070	6136	−2555	2957
GFDL2100	5488	−3202	4896

Also presented is the change and the number of new taps required to fulfill the 2012 production based on 2015 extraction levels (USDA-NASS 2015).

with our results from above, the reduction in season length are projected to be greatest along the southern tier of current maple syrup production and while the absolute loss of days may appear less, the ratio of change is far greater than other northern states under both GCM scenarios (Figure 6). In fact, though the metrics are different, there is a strong association (Pearson's-$r = 0.75$, $p < 0.01$) of potential reduction in maple syrup production days to potential habitat loss by the end of the century on the GFDL-A1Fi scenario. This pattern indicates the loss of habitat as well as novel spring climate conditions could greatly reduce the maple sugaring season, especially in the southern tier.

Discussion

Considering the current importance of sugar maple and its role in providing multiple ecosystem services across its range, understanding how the species might be impacted by climate change in the coming decades signifies the complex realities of managing our natural resources within the Anthropocene (Wolkovich et al. 2014). The current economic and cultural importance of the maple syrup industry in North America brings together many threads of how we develop and sustain ecosystem services across a species range, highlighting the variation in opportunity and in investment (e.g., Quebec and Vermont showing maple sugar industry far surpassing other political entities). Our analysis shows that the expected climate change pressure for sugar maple habitat over this century will present novel conditions for the species. Changes in the intensity of suitable habitat (projected IV ranging from 0, loss of habitat to 100 most suitable) will influence the extent of suitable growing conditions for the species. Loss of habitat projected along a broad southern front of the sugar maple range will impact not only maple syrup production but other ecosystem services provided by the species. At the same time, understanding the temporal habitat dynamics toward the middle and northern portion of the species range may illuminate opportunities to encourage existing and growing resources of the species. One key feature of determining the potential for increases in production will be the density of appropriately sized sugar maple trees within stands, as this will signify opportunities for greater intensification and hence profitability (Farrell 2013). The converse of this situation is also apparent in areas projected to decline in habitat that are currently highly productive. Brown et al. (2015), via a GIS habitat

Table 2. Number of taps per state in 2012 and corresponding number of additional taps needed to maintain similar levels of production under GFDL-A1Fi by the end of the century.

State	St	Taps 2012 (×1000)	Taps Needed GFDL-A1Fi 2100 (×1000)	% Tapped 2100 under GFDL-A1Fi	Sugar Maple size class 22–33 cm (×1000)	% Tapped by 2100 of 22–33 cm cohort
Vermont	VT	4348.2	1483	16.01	46.3	7.05
New York	NY	2064.9	620.7	2.9	122.1	1.25
Maine	ME	1884.5	−88.9	6.71	41.4	2.63
Wisconsin	WI	682.3	135.5	2.39	73.3	0.76
Pennsylvania	PA	506.2	177.3	1.63	53.1	0.72
New Hampshire	NH	495.6	69.1	4.88	20.2	1.78
Ohio	OH	439.6	306.6	3.47	27.8	1.52
Michigan	MI	433.5	158.5	0.85	127.1	0.3
Massachusetts	MA	229	13.9	5.19	5.3	2.44
Minnesota	MN	83.1	1.6	0.89	19.3	0.29
Connecticut	CT	64	11.2	2.31	2.5	1.3
Indiana	IN	49.5	40.3	0.52	19.3	0.24
Virginia	VA	19.8	5.5	0.42	7.9	0.18
Maryland	MD	16	7.5	2.13	1.5	0.9
Illinois	IL	10.2	7.7	0.39	5.2	0.18
West Virginia	WV	8.8	3.6	0.05	41.1	0.02
Iowa	IA	5.5	−0.5	0.34	1.6	0.16
Kentucky	KT	4.8	1.9	0.04	33.9	0.01
New Jersey	NJ	2.7	1	0.32	1.9	0.12
Rhode Island	RI	2.6	0.3	5.51	0.1	2.14
North Carolina	NC	1.1	0.5	0.06	2.5	0.03
Missouri	MO	1	0.4	0.04	9.1	0.01
Tennessee	TN	0.1	0.1	0.00	18.3	0
TOTAL		**11,353**	**2957**	–	**680.3**	–

The additional taps would require an increase in the proportion of trees tapped over that presented in Figure 2. Because the next cohort of trees will be maturing into tappable range, we provide a conservative estimate of how these new trees might provide opportunity to achieve new taps.

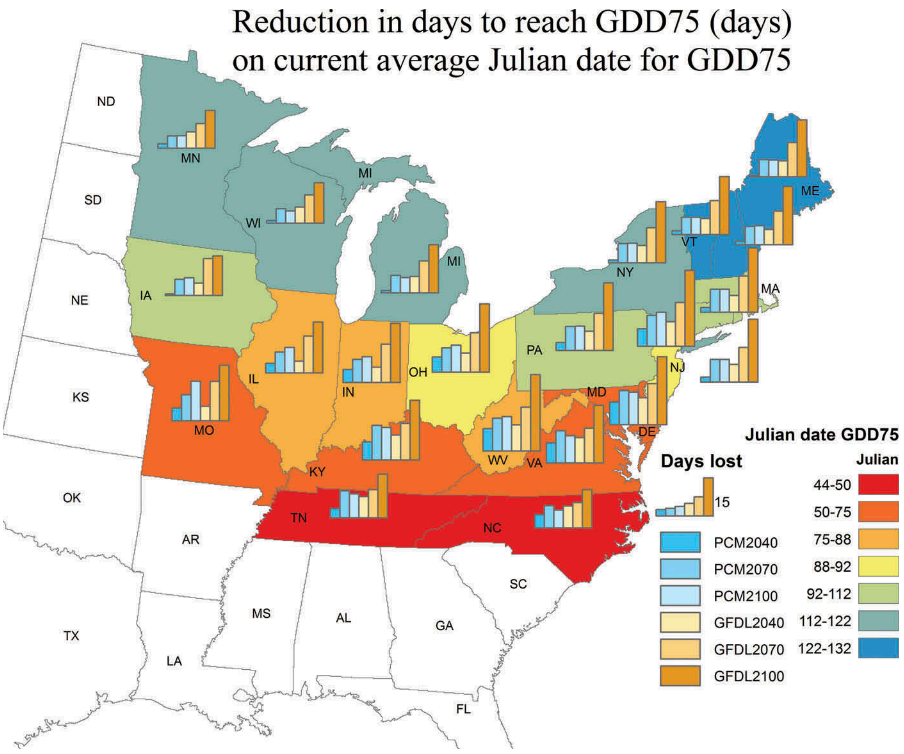

Figure 5. Current distribution (1980–2009) mean of Julian date at which Growing Degree Days reaches 75, and corresponding reduction in the number of days to reach GDD75 under PCM-B1 (low emissions) and GFDL-A1Fi (high emissions) at three time points (2040, 2070, 2100).

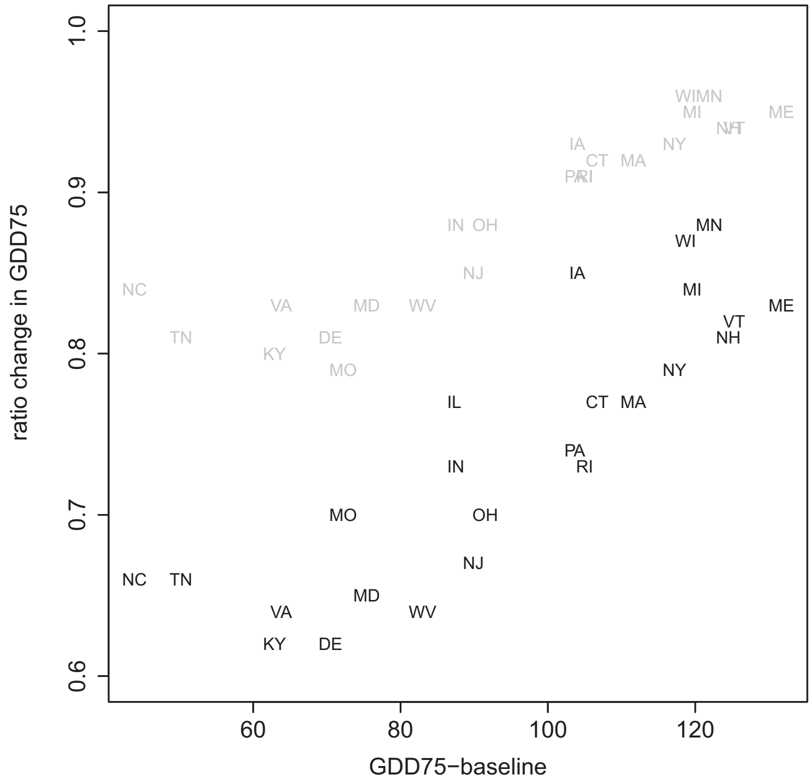

Figure 6. The projected current mean Julian to reach Growing Degree Days of 75 (GDD75) by the ratio change in GDD75 under GFDL-A1Fi (Black) and PCM-B1 (Gray) for each state in our study (see Table 2 for state abbreviation names).

mapping approach similar to ours, shows that within southern Ontario, some of the highest occurrences of sugar maple stands also show the strongest potential to decline under climate change. Understanding the likelihood of increases or decreases in habitat conditions will provide bounds of uncertainty around the potential for sugar maple habitat, and potentially maple syrup production, to be maintained.

Additional insights to the dilemma surrounding maple syrup production can be revealed by examining patterns of potential changes in habitat across the species range. In fact, these patterns not only reveal the spatial pattern of changes but also how our society's choices with regard to greenhouse gas emissions will likely impact the maple syrup provisioning services. For example with Ohio, one of the most southern states with a commercial maple syrup industry, the projected changes in habitat range from a loss of 85% to a modest gain depending on emission pathway; this illustrates how future trajectories in greenhouse gasses and the ensuing warming may sway opportunities to grow and sustain the industry at the state level. Further, this highlights that future habitat projections are linked to the climate models and emission scenarios and that sugar maple under alternative projections may have higher persistence of habitat in the southern extent of its distribution. Of course, regardless of scenario explored, refugia or hot spots of capacity will likely persist within states. In Vermont, where massive infrastructure has been established and supported, managers will benefit from understanding that climate change will influence some aspects of maple syrup season and production, but that maintaining or increasing capacity is likely still possible provided wise planning is achieved. Finally, in other regions to the far north within the United States, unique opportunities in Minnesota and Maine show consistency in habitat conditions are projected to remain at present levels or even increase by the end of the century. Across the range of sugar maple, adaptation and planning are necessary to manage sugar maple optimally for the maple sugar industry.

Because the current cohort of sugar maple trees live a long time and a significant portion of them will still be present in 2100, and because over 680 million trees exist in the next smaller cohort not yet optimal for tapping (but many will be in this century (Table 2)), and because technologies to increase sap harvest are improving, it is not unrealistic to assume some increased level of tapping and production can be sustained over the next few decades. However, with the reality that sap flow seasons are likely to be diminished especially in the southern portion of its range (Duchesne & Houle 2014; Skinner et al. 2010), and that sugar maple trees growing in these southern zones face higher climate change risk and pressure, even these new cohorts may provide limited opportunity to increase, or even in some cases, maintain syrup production in these areas. In contrast, in northerly areas where habitat appears to be stable or improving (much more so under the mild scenario of climate change as compared to the harsh scenario), there may be increased opportunities for maple syrup with the new cohort of trees coming up and the remaining large untapped potential of trees (Figure 2, Figure 3).

It is important to point out that this assessment provides insights only to habitat conditions for sugar maple and the many known climate links to ecophysiological processes that sustain and influence sap production and hence this delicious ecosystem service. In fact, our results of projected changes in habitat are strongly associated with the projected reduction of the number of days to reach 75 growing degree days (GDD75). This relationship indicates a consistent pattern of reduction of habitat related to a loss in days to GDD75, a strong predictor of variability in syrup production across the United States and Canada (Duchesne & Houle 2014). Further, changes in GDD75 show greater magnitude of change toward the southern extent of sugar maple where the production season is already constrained by temperature (Figure 6). Shifts in season can affect the opportunity window for maple syrup production (Skinner et al. 2010). Houle et al. (2015) suggest that this can be compensated for by matching this phenological shift by shifting the season up to 19 days earlier in the coming decades, a result consistent with our predicted change in GDD75 under GFDL-A1Fi of 22 days by the end of the century. However, it is also important to consider climatic conditions throughout the year, including not only the growing season conditions, where new growth and hence resources are generated in the tree for future sap production, but also winter conditions which need to be cold enough to support strong carbohydrate concentrations (Duchesne & Houle 2014). In the end, it is both seasonal and year-long processes that are required to produce profitable maple syrup, and uncertainty around how climate conditions may change on a daily and seasonal basis could greatly influence future realities for maple syrup production. Evidence from the latest climate models show a strong tendency for more destabilization of climatic conditions including an increased likelihood of extreme events (Melillo et al. 2014), the reliance on highly specialized phenological events will require a critical evaluation of how adaptable sugar maple and the industry can become.

There are many other factors that influence the occurrence of sugar maple on the landscape that can affect sap production. Even over the last several decades, variation in growth and productivity of sugar maple has been observed across a broad geographic extent (Long et al. 2009). The causes of such impacts and recoveries have been linked to important soil components, atmospheric deposition, and pest outbreaks (Horsley et al. 2002; Long et al. 2009). Indeed, Bishop et al. (2015) detected growth declines for sugar maple in New York's Adirondack Mountains during the 1970–2008 period. In times where declines are documented, these impacts will influence sap production and hence ecosystem services such as maple syrup. In many respects, these variations provide a snapshot of the challenges the producers face, and climate change poses an unprecedented perturbation that will have many cascading influences on forest and forest products. Our results provide a view of how wide ranging and impactful climate change may be on shaping maple syrup production under changing future conditions.

Climate change is not the only ongoing and emerging pressure that sugar maples face. Recent evidence from the widespread loss of ash trees due to emerald ash borer captures how sensitive trees can be to invasive pests (Herms & McCullough 2014), and with the movement of species like Asian long horn beetle, concerns of forest health are warranted for sugar maple as well (Lovett et al. 2016). In the end, being able to capture the potential impact climate change may have on sugar maple is an important first step toward integrating climate change impacts into current forest management decisions. By understanding the vulnerabilities, it may be possible to build more reliable systems that can sustain this delicious ecosystem service. To do this requires both innovation and appreciation for the magnitude of change the forest sector is likely to face under amplified climate change.

Fortunately, there are many positives that the maple syrup industry has going for it. We are currently experiencing a positive trajectory in profits and production of maple syrup within the United States (USDA-NASS 2015). Developments in infrastructure and technology have increased profits and the scale of many operations; for example, new vacuum tubing systems can result in as much as a fivefold increase in sap collection over traditional bucket systems (Farrell & Chabot 2012). Continued advances may also reduce the total number of taps needed to make up for changes in sap flow in the near term. In addition, recent interest and demand for specialized and regional forest products make maple syrup a winner in the local food movement. It is the sugar maple tree that is the iconic species (although red maples are increasing in importance for maple syrup production) which makes this all possible and we are at an important time where future planning is necessary to sustain the species and its ecosystem services. The results from this study clearly show risks and opportunities for sugar maple under accelerated climate change going forward. This example, however, exemplifies but one species in our complex and diverse eastern forest. Within these groups, there will be many independent and dependent responses of tree species to climate change. While trees in general contribute to many important ecosystem services from regulating CO_2 and the water cycle, to mitigating air pollution, and to providing aesthetic values, each species has multiple services they provide to human well-being, and as the climate changes, how these services are preserved requires detailed evaluation to reveal the potential social and economic implications climate change may have on our vital natural resources. The sugar maple is but one tree that exemplifies these multiple ecosystem services and it is important we expand our consideration of potential climate change impacts to other systems where trees are supporting multiple ecosystem services in order to more fully capture the potential impacts on human well-being.

Conclusions

Across eastern North America, sugar maple is a highly valued tree and is most often associated with the unique non-timber product of maple syrup. Suitable climate and growing conditions, along with high carbohydrate concentrations of the species sap, make the extraction and processing of this resource an important ecosystem service all over the 23 states evaluated in this study. While additional fine-scale research is needed to relate how sugar maple trees can most effectively adapt to climate change, this study provides needed insights into how this resource may be impacted by climate change across the United States in the coming decades. It also shows the huge differential of potential impacts, depending on the level of future emissions that human society chooses. From this broad assessment, it appears that the industry should be able to compensate by additional taps and continued development of new technologies. Eventually, however, for some southern regions, the high-value maple trees may become limiting or cost-prohibitive for competitive industry. Further, our results point to regions, especially along the northern tier of the United States where both climate change impacts and currently developing sugar maple cohorts may signify viable opportunities to maintain maple syrup production. In the end, these results illustrate a broader application of considering climate change vulnerabilities of species alongside important ecosystem services, and can facilitate adaptability planning of forest resources in the face of accelerating climate change.

Acknowledgments

Thanks to the Northern Research Station, and the Northern Institute for Applied Climate Science of the US Forest Service for support for this work. We thank Sandra Luque and Christine Fürst for organizing the special session at IUFRO Landscape Ecology meeting in Estonia on the topic. We thank Matthew Duveneck for providing valuable comments to an earlier draft and to the reviewers and editors responsible for improving the manuscript.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This work was supported by USDA Forest Service: Northern Research Station, and the Northern Institute for Applied Climate Science. Specific funding to SNM from Northern Research Station agreement 10-JV-11242302-070.

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