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The complex relationship between climate and sugar maple health: Climate change implications in Vermont for a key northern hardwood species

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ABSTRACT

This study compared 141 ecologically relevant climate metrics to field assessments of sugar maple (*Acer saccharum* Marsh.) canopy condition across Vermont, USA from 1988 to 2012. After removing the influence of disturbance events during this time period to isolate the impact of climate, we identified five climate metrics that were significantly related to sugar maple crown condition. While three of these are monthly summary metrics commonly used in climate analyses (minimum April, August and October temperatures), two are novel metrics designed to capture extreme climate events (periods of unusual warmth in January and August). The proportion of climate-driven variability in canopy condition is comparable to the proportion accounted for by defoliating pests and other disturbance events. This indicates that climate conditions, though rarely included in sugar maple decline studies, may be of equal importance as more traditionally studied stress agents. Modeled across the state, results indicate that changes in historical climatic conditions have negatively impacted sugar maple health over the 25 year study period, and are likely to degrade further over time. Climate projections under a low emissions scenario indicated that by 2071 55% of sugar maple across the state would likely experience moderate to severe climate-driven stress relative to historic baselines, increasing to 84% under a high emissions scenario. However, geographic variability in projected climate impacts indicates that while conditions for sugar maple will likely deteriorate across the state, climate refugia should also be available to maintain sugar maple in spite of changing climatic conditions. Considering the predominant role of sugar maple in Vermont's economy and culture, managing this resource into the future could pose a considerable challenge.

1. Introduction

Sugar maple (*Acer saccharum* Marsh.) occupies a large proportion of northern hardwood forests across the northeastern United States (US) and southeastern Canada. Across the broader northern hardwood forest type, sugar maple is a dominant climax species. Furthermore, current technological advances and market conditions for maple syrup production have expanded this agricultural crop and with it, increased the focus on maintaining this valuable resource. The important ecological and economic role of sugar maple has made it one of the best-studied species in eastern North America. In particular, there has been much interest in understanding the drivers of sugar maple decline, which is characterized by reductions in canopy condition (Horsley et al., 2000) and growth (Duchesne et al., 2002), increases in tree mortality, and shifts in species composition (McWilliams,1996; Pontius et al., 2016).

Sugar maple silvics include a high requirement for soil nutrients and a narrow range of soil moisture requirements (Godman et al., 1990), both of which make this an environmentally-sensitive species. Episodes of sugar maple decline have occurred periodically since at least the early 1900s. Early observations tied declines to numerous factors including insect defoliation, drought, elevated growing season temperatures, winter freezing injury and early fall frosts (Westing, 1966). More recently, sugar maple decline has been witnessed across the northeastern US and eastern Canada (Horsley et al., 2002). Nutrient limitations and metal toxicities, alone or in combination with defoliating events, have been consistently linked with sugar maple decline across the region (Long et al., 1997; Horsley et al., 2000; Bailey et al., 2004; Schaberg et al., 2006; Halman et al., 2013), particularly when these co-occur with exposure to other environmental stressors (Schaberg et al., 2001; St. Clair and Lynch, 2004; St. Clair et al., 2008; Pitel and Yanai,

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2014). A more recent regional assessment of sugar maple growth (Bishop et al., 2015) indicates that trees have exhibited negative growth trends in the last several decades, regardless of age, diameter, or soil fertility. Such growth patterns were unexpected given recent warming and increased moisture availability, as well as reduced inputs of acidic deposition (Bishop et al., 2015).

While it is understood that weather plays a direct role in regulating tree health and productivity, and that extreme weather events can damage vegetation, identifying the relationships among long-term climate records and sugar maple condition have been elusive. This is largely because long-term, continuous datasets of canopy condition are required for multi-decadal comparisons with climate. Further, the resolution of regional climate data is typically coarse, both in terms of the spatial scale (which fails to capture fine-scale topographic variability), temporal frequency and detail of climate metrics. Any historical observations that do exist are generally limited to wide-spread hydroclimatic events such as drought or winter freeze-thaw cycles as potential contributing factors to decline (Cleavitt et al., 2014; Pitel and Yanai, 2014). Despite the unquestioned importance of climate in influencing tree vigor and productivity, an integrated analysis of the influence of broad trends in climate and episodic weather events on sugar maple health has not been conducted for trees across native landscapes.

Nonetheless, many scientists and land managers alike note the likely influence of a changing climate on sugar maple across the region. During the 20th century, annual-mean air temperatures (at 2 m above ground level) in the northeastern region increased at a rate of approximately 0.09 °C per decade (Kunkel et al., 2013). Those temperature increases were greatest during the winter months. Consequently, the mean growing season length has increased by several days per decade since 1960 (Betts, 2011a, 2011b). Annual precipitation totals across the northeastern US have also increased in the 20th century (Kunkel et al., 2013), with a conspicuous increase in the frequency of heavy rainfall events since the late 1950s (Groisman et al., 2005).

The rate of change in many climate variables for the northeastern US is expected to continue and intensify. Increases in annual temperatures between the historical (1979–1999) and near future (2041–2070) periods are expected to be 2.7 °C for the high CO_2 emissions scenario (the A2 special report on emissions scenario; IPCC SRES, 2000) and 2.0 °C under a low emissions scenario (Kunkel et al., 2013). Over the same time periods, annual precipitation totals are also likely to increase. The majority of that gain is projected for the winter months, with an anticipated decrease in precipitation in the summer months (Kunkel et al., 2013).

Several efforts have examined how ongoing changes in climate might impact forest tree species. Bishop et al.'s (2015) examination of regional sugar maple growth included precipitation- and temperature-based climate metrics but found weaker relationships than expected. The United States Forest Service Climate Tree Atlas (Landscape Change Research Group, 2014) uses maps of existing species abundance, climate, and site characteristics to model current and projected species relative importance across the landscape. Their sugar maple model indicates that seven of the top ten predictors of sugar maple importance across its range are related to soil characteristics (Iverson et al., 2008). This lack of significant climate relationships may be influenced by the inclusion of only monthly-level climate metrics, coarse spatial resolution (20 × 20 km) or the lack of climate data over sufficient time periods to fully capture the variability in climate conditions.

In order to better understand which climate characteristics influence sugar maple condition, we compared annual sugar maple crown condition metrics from over two decades of long-term forest health field monitoring to a suite of ecologically relevant climate metrics derived from high-resolution climate data. Our analyses were unique in that they used an integrated crown health index that was normalized to baseline conditions that were standardized at the plot level to remove site-based (e.g., elevation, slope, soil texture and nutrition, drainage, etc.) influences on crown health. In addition, our analyses statistically removed the influence of disturbance events (e.g., insect defoliation and ice storm damage) to better isolate the influence of climate.

Our overarching objectives were to:

1. Identify the key climate metrics that are associated with the historical variability in sugar maple canopy condition.
2. Quantify these relationships between climate and canopy condition across the landscape to characterize spatial and temporal variability.
3. Apply climate projections for these key climate metrics to sugar maple health models to quantify the potential impact of climate change on sugar maple condition and identify potential locations of climate refugia.

This type of information is essential to understand how a changing climate will influence sugar maple's competitive success and distribution across its current range. Appropriate forest adaptation strategies can be targeted to areas where a positive outcome is most likely. In the coming decades, this spatial information will be essential for managing the sugar maple resource in the face of changing environmental conditions.

2. Methods

2.1. Study area

We compiled over two decades of field-based sugar maple health data for comparison to downscaled climate data for Vermont, USA. The density of long-term sugar maple monitoring sites across the state provided a rich archive of forest health metrics for comparison with downscaled climate estimates. In contrast to regional assessments of sugar maple decline that are focused on sites experiencing stress symptoms (e.g., Horsley et al., 2002), sugar maple in Vermont tend to be located on high quality sites, within relatively healthy stands. By focusing our data analysis in Vermont, we were better able to identify and isolate the role of climate on sugar maple conditions, while minimizing variability found across the larger region that has been linked to acid deposition and nutrient deficiencies. Further, the topographic diversity (e.g., Champlain and Connecticut River Valleys versus the Green Mountains) and lake effect (Lake Champlain) on temperatures and precipitation across the state provide a broad range of climate conditions for comparison across the field network.

2.2. Field data

Field data were collected from the Vermont subset of the North American Maple Project (NAMP) regional network of long-term sugar maple monitoring plots (Cooke et al., 1995). As a part of this project, sugar maple-dominated forests at 30 locations across the state (Fig. 1) were visited annually from 1988 to 2012, to evaluate tree health and symptoms of current or recent stress impacts following published NAMP protocols (Millers et al., 1991). Measurements included crown dieback (recent twig mortality) and foliage transparency (a measure of foliage density), defoliation and weather-related tree damage. While these metrics were recorded for individual trees, plot-level averages were required to match the resolution of downscaled climate data. In order to better isolate canopy characteristics related to concurrent stress conditions over and above "baseline" levels, we also calculated the proportion of trees with high dieback (> 15% dieback) and high foliar transparency (> 25% transparent) for each year.

In order to reduce these four canopy condition metrics into one response variable for comparison to climate, a summary stress index (Forest Stress Index: FSI) was calculated using distribution-normalized variables (Pontius and Hallett, 2014). This approach allows for the consideration of all stress symptoms simultaneously and presents a more integrated and comprehensive assessment of overall crown condition relative to normal characteristics for the larger population.