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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.

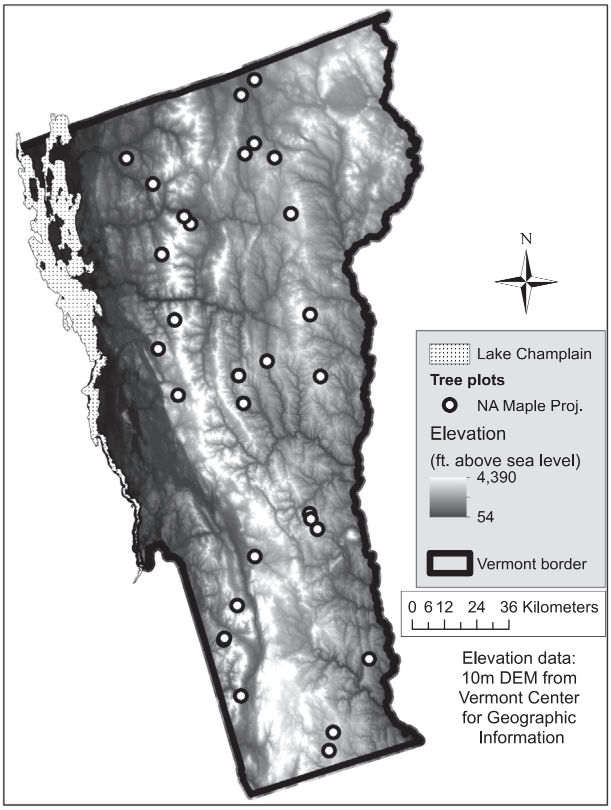

Fig. 1. Digital elevation map of Vermont showing the locations of long-term sugar maple monitoring plots from the North American Maple Project (NAMP) monitoring network.

Specifically, this involved the normalization of each canopy condition metric using a standardized z-score based on the 25 years of sugar maple measurements at each plot, such that more positive values represented higher stress symptoms than average and negative values represented healthier conditions than average. This normalization was conducted independently for each plot in order to remove any variability in sugar maple condition *among* plots due to site-based (e.g., elevation, slope, soil texture and nutrition, drainage, etc.) influences on crown health, and instead capture year-to-year variability due to climate at a given location. Following normalization, forest health metrics for individual trees were averaged to produce a yearly, plot-averaged FSI value for all sugar maple at that location. For the remainder of this text, it is important to note that this is a stress index, such that higher values indicate less favorable canopy condition.

2.3. Climate metrics

Climate data used in conjunction with ecological observations commonly originate from local meteorological stations or gridded observational products, which are generally more accurate and meaningful when the spatial scales better match the target. For example, gridded products of 50–200 km^2 resolutions will poorly capture the growing season length in specific high elevation locations because the scale is too broad to isolate montane conditions. For this reason, observational climate data products with fine resolutions and/or downscaled climate projections (i.e., 10–20 km^2) are preferable for use in regions of complex topography.

In order to obtain observational climate data products with resolutions as fine as possible, daily climate time series were extracted from an 800 m gridded climate data product. This 800 m product was downscaled from 4 km PRISM AN81d data (1981–2012) of daily maximum temperature, minimum temperature, and precipitation totals (Daly et al., 2008, http://www.prism.oregonstate.edu) via the commonly used "delta method" (also known as "change factors" or "spatial disaggregation") (Hijmans et al., 2005, Wood et al., 2004, Ahmed et al., 2013). This method uses highly resolved patterns of climatological normals to spatially disaggregate lower-resolution grids. In this instance, the Norm81m mean values of the daily meteorological variables for the 1981–2012 time frame (Daly et al., 2008, http://www.prism.oregonstate.edu) were used to downscale the daily 4 km gridded time series to 800 m resolution.

It must be noted that downscaling introduces uncertainty into time series estimated at most specific locations (Bishop and Beier, 2013). This, in turn, systematically reduces the strength of statistical relationships between climate metrics (potential drivers) and tree health metrics (responses). This is also true for the usage of gridded products over local measurement stations – if available. However, since we had neither on-site measurement stations nor reason to believe this uncertainty would bias the identification of healthy or stressed sites within our statewide analysis, we utilized downscaled data with the recognition of established limitations.

From the 800 m daily climate data, we calculated 141 individual climate metrics for each year. These climate metrics included common climate metrics (e.g., length of the growing season, mean, minimum and maximum monthly temperature, etc.), as well as what we identified as novel and potentially ecologically relevant metrics designed to capture winter thaw events, early frost events, the number of extreme hot or cold days, etc. (Table 1). As with the canopy condition metrics, all climate metrics were normalized by location and scaled according to their historical distribution across all years.

2.4. Disturbances

Acute disturbances such as insect defoliation, ice storm damage, spring frost injury, moisture excess and deficits were observed on the NAMP plots for many years during the 1988–2012 study period. Insect defoliation was directly assessed over the 1988–2012 period and rated using the following NAMP scale: (1) no defoliation, (2) light defoliation, (3) moderate defoliation and (4) heavy defoliation (Cooke et al., 1995).

Table 1
Summary of the 141 climate metrics considered in comparison to yearly sugar maple Forest Stress Index (FSI) values.

800 m downscaled climate indices	
Temperature (°C)	**Temperature extremes**
Monthly minimum temperature (T_{min})	Monthly # days w T_{max} > 1 stdev
Monthly maximum temperature (T_{max})	Monthly # days w T_{max} > 2 stdev
Monthly mean temperature (T_{mean})	Monthly # days w T_{min} < 1 stdev
Annual T_{min}	Monthly # days w T_{min} < 2 stdev
Annual T_{max}	
Annual T_{mean}	
Growing Season Summaries	**Seasonal Freeze/Thaw Events**
Growing degree days (4 °C threshold)	Monthly #days T_{min} > 0 °C
Modified growing degree days (4 °C–30 °C window)	Monthly #consecutive days T_{min} > 0 °C
Growing season length	Monthly #days w > 5 °C increase and T_{mean} > −5 °C
#days T_{min} above 0 °C	Monthly #days w > 5 °C decrease and T_{mean} < 5 °C
#days T_{mean} above 5 °C	#days T_{mean} > 0 °C in Jan, Feb
Cooling degree days (18 °C threshold)	#days T_{max} > 10 °C in Jan, Feb
Heating degree days (18 °C threshold)	#days T_{min} < −5 °C in Oct, Nov
	#days after the first frost is first T_{max} < = 0 °C
Precipitation (mm)	
Monthly total snowfall	
Monthly total precipitation	
Monthly Max daily precipitation	
Monthly longest period of no precipitation	
T_{max}: previous 10-day precipitation	

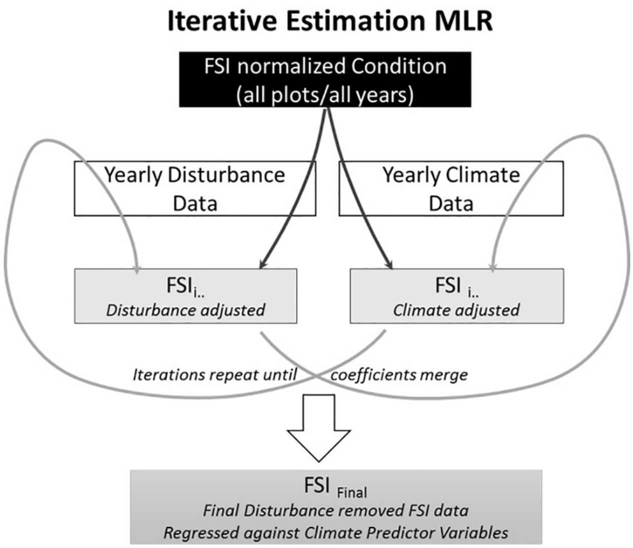

Fig. 2. The iterative estimation partition regression model for the Forest Stress Index.

Similar to crown condition metrics, defoliation observations were normalized to a z-score at the plot level for inclusion as a covariate in analyses. Another major disturbance was the January 1998 ice storm that affected over 260,000 ha of forests in Vermont (Dupigny-Giroux, 2000). During the summer of 1998, plots were evaluated for ice-related crown damage, expressed as binary (damage/no damage) value, which was also included as a covariate in this analysis.

2.5. Data analysis

In order to develop a statistical model to estimate FSI values based on climate metrics, while minimizing the influence of acute disturbance events such as insects and storm events, we used an "iterative estimation partition regression" analysis (Fiebig, 1995). This technique allowed for the simultaneous fitting of both a climate and disturbance model to predict FSI, refining each model through iterative, residual adjusted regressions in order to isolate the influence of each model on FSI while also allowing for objective predictor-variable selection. All data were analyzed, as well as statistical models developed and executed, with Matlab (version R2014) software. The iterative estimation method (Fig. 2) was run on the pooled data (in total, 718 plot-year observations) beginning with a multiple linear regression between disturbance predictors and FSI values. The resulting disturbance-adjusted residual values were then used in a forward stepwise multiple linear regression between climate predictors and FSI values. Climate-adjusted residuals from the resulting climate-based regression model were subsequently used to fit a new disturbance model. With each iteration, variability due to either climate or disturbance variables was removed from the response variable, so that the influences of acute disturbance could be identified and isolated from the impact of climate on the FSI response. This process of using iteratively refined residuals continued until the coefficients for both models converged, such that the selected predictors and their corresponding regression coefficients did not vary by more than 0.00001 from one given iteration to the next. For each iteration, predictors were selected using an unusually high confidence level (99.9%) in order to minimize the complexity of the model, ensure predictor strength and account for inter-correlation.

The performance of the statistical models was quantified using four error measurements: (1) the significance of individual variables, (2) the percent variance explained (R^2), (3) the root mean squared error (RMSE) and (4) the median absolute difference (MAD).

2.6. Spatial modeling of FSI

In order to better understand the spatial patterns of climate impacts on FSI, the final climate FSI empirical model was executed using 4 km climate rasters (i.e., not downscaled) for each year during the 1981–2012 period. The 4 km rasters were opted for over 800 m rasters because the downscaling method did not produce subgrid (800 m) variability on a year-to-year basis (e.g., each time step had the same bias removed via downscaling based on a common climate normals raster).

To provide future estimations of climate impacts on FSI, we derived key climate metrics from daily climate model projections provided by the third National Climate Assessment (Kunkel et al., 2013) Climate Model Intercomparison Project (CMIP3, http://www.ipcc.ch). Statistical downscaling of these NCA CMIP3 data included 13 km × 9 km projections (Stoner et al., 2013), yielding 171 individual grid cells over Vermont, for four time frames (1981–2000; 2021–2050; 2041–2070 and; 2070–2099), under two emissions scenarios ("A2" high-emissions and "B1" low-emissions). These projections of key climate metrics were used to apply the final FSI empirical model across the landscape in order to estimate forest health in response to projected climate conditions. For interpretation of future climate impacts on FSI, we only considered differences in FSI that exceeded uncertainty in modeled FSI response, quantified as the mean absolute difference between observed and modeled FSI values.

3. Results and discussion

3.1. Iterative partition estimation modeling

The iterative regression model building process converged upon completion of its 14th iteration. The overall effect of removing disturbance impact from observed FSI values was a reduction in observed FSI values proportionate with increasing disturbance severity (Fig. 3), shifting the mean stress index from 0.00 to −0.17. Most plot/year combinations reported no disturbance, and hence received no FSI adjustment (green in Fig. 3b). The largest adjustments for disturbance (dark blue in Fig. 3b) reflect high disturbance years including: 1988 (pear thrips injury), 2005 and 2006 (forest tent caterpillar defoliation) and 1998 (an ice storm that damaged tree crowns in nearly 20% of Vermont's forested area and exactly 20% of our plots). The differences between Fig. 3a (Observed FSI) and Fig. 3b (Disturbance Severity) resulted in the "Disturbance Adjusted FSI" (Fig. 3c), which allowed us to examine the yearly climate contribution to sugar maple crown condition absent the influence of non-climate disturbance events.

3.2. Modeling climate drivers

Seven of the 141 climate metrics (Table 1) considered were static through time at one or more plot locations and were removed from the modeling process. This resulted in 134 climate metrics for comparison to sugar maple health. The final "climate model" included five climate metrics (Table 2) and accounted for approximately 19% of the total variation in sugar maple FSI ($R^2 = 0.185$, $P < 0.001$, RMSE = 0.541, PRESS RMSE = 0.546, MAD = 0.32). For comparison, the full FSI model, including both disturbance and climate terms, explained 31% of the variability in the observed FSI values ($R^2 = 0.309$, $P < 0.001$, RMSE = 0.541, PRESS RMSE = 0.546, MAD = 0.317).

It is important to note that the additional variation captured in the full model (with the addition of disturbance events) includes one climate-related event (1998 ice storm) for which data were available for the NAMP plots. As such, the 19% of the variation in FSI attributable to the five combined climate variables (Table 2) is likely a conservative estimate of the overall importance of climate in modulating sugar maple health. If this extreme climate event had been included in our climate model, overall variability in FSI would be much higher.

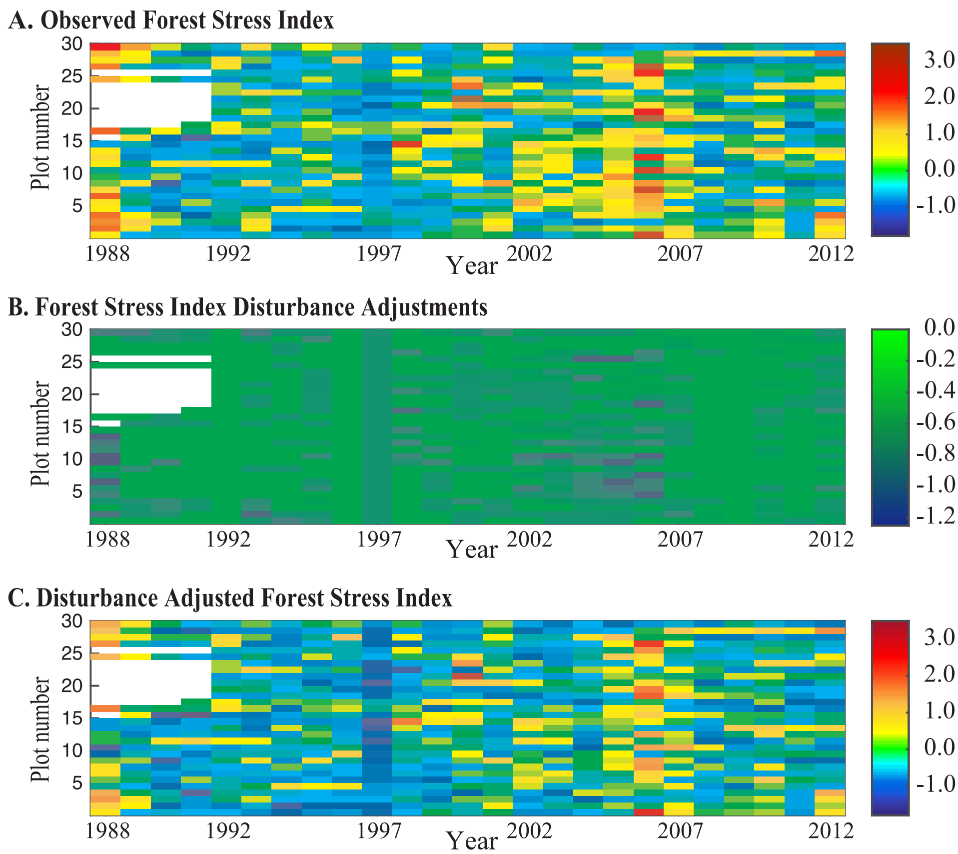

Fig. 3. (A) Field observed FSI values, (B) Disturbance adjustments to quantify disturbance severity (more negative indicates more severe disturbance), and (C) the final Disturbance Adjusted FSI, calculated as the difference between panels (A) and (B). Higher Observed FSI and Adjusted FSI values indicate higher stress.

A scatterplot of the actual and climate modeled FSI values (Fig. 4) indicates that predictions were most accurate when FSI values were in the healthy to normal condition range ($-1 < \text{FSI} < 0.5$). However, when trees were more severely stressed ($\text{FSI} > 1$) the climate model tended to under-predict climate-driven impacts. This suggests that climate plays a relatively larger role in creating *favorable* conditions, but that factors not considered here likely play a more pronounced role to create *unfavorable* conditions (e.g., trees weakened by climate stress are more susceptible to secondary stress agents such as pests and pathogens). Similarly, the tendency of the model to underestimate adverse climate impacts implies that future projections may also be underestimated in this study.

While three of the final climate model terms correspond to common, month-based climate summaries, (e.g., monthly minimum temperature), two indices correspond to cumulative, extreme climate conditions (e.g., the number of extremely hot days in a given month) (Table 2). This suggests that it may not simply be the severity of individual, extreme climatic conditions that impact sugar maple health, but also the timing, coincidence and/or consecutive nature of such events. It is important to note that the iterative partition regression model identified general relationships (i.e., across plots and over time) between canopy condition and climate variables.

Monthly minimum temperature for three different months (April, August and October) were significant predictors of FSI. Higher minimum temperatures in both April and October were associated with more severe reductions in sugar maple canopy condition (higher FSI). It is possible that higher minimum temperatures in April provoked earlier budbreak, which then increased tree vulnerability to spring frost injury. Such injury events result in reduced leaf photosynthetic surface area (if injured leaves persist) or depleted carbon (C) reserves and a reduced functional growing season (if emerging leaves were killed and a second flush of leaves was triggered). Field studies confirm that elevated spring

Table 2
Final Disturbance Adjusted FSI climate metrics and possible physiological connections to sugar maple condition. Note that a positive coefficient indicates higher stress condition with higher climate metric values. All terms significant at $P < 0.01$.

Climate metrics	Coefficient[a]	Hypothesized implication
April minimum temperature	+0.15	Warmer minimums could foster earlier spring budbreak and increase the risk of frost injury
Preceding August minimum temperature	−0.10	Warmer minimums could delay foliar senescence, which could increase net carbohydrate production providing more resources for growth and protection
Preceding October minimum temperature	+0.13	Warmer minimums could increase foliar respiration relative to waning photosynthesis, reducing net C storage that supports tree growth and crown vigor
No. of January days w/Tmax > 2 SD	+0.08	Warm winter thaws result in lower snowpacks, soil freezing and associated root damage. Thaws may also lead to tissue dehardening – increasing the risk of later freezing injury
No. of preceding August days w/ Tmax > 2 SD	+0.19	High August temperatures increase foliar respiration rates and cause reductions in net photosynthesis

Y-intercept for the final climate FSI model was −0.17.
[a] Positive coefficients indicate that an increase in the climate metric was associated with declining crown condition.

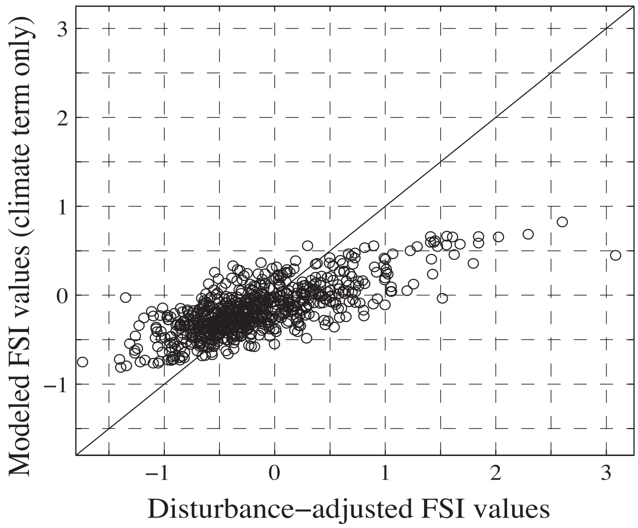

Fig. 4. Relationship between Actual Disturbance Adjusted FSI values (x-axis) vs. climate predicted FSI values (y-axis). The 1:1 relationship is plotted for comparison.

temperatures are associated with earlier budbreak (Richardson et al., 2006; Groffman et al., 2012), with maximum response to warming occurring in late winter and early spring (Clark et al., 2014). Sugar maple is the first tree species to break bud within regional forests (Richardson et al., 2006), so it would be particularly vulnerable to injury from spring frosts (e.g., Halman et al., 2013).

In October, the delay of lower temperatures, which speed leaf senescence (Heide and Prestrud, 2005), would result in trees retaining leaves with higher rates of respiration relative to photosynthesis. Respiration is highly temperature sensitive, whereas, autumnal photosynthesis would likely be limited by reduced light capture as chlorophyll seasonally catabolizes (Thomas et al., 2001) and day lengths recede. Elevated respiratory losses would deplete carbohydrate reserves that are typically translocated into shoots and used to support leaf production and crown health in the following spring. Also warmer minimum October temperatures would likely decrease anthocyanin production – resulting in less leaf protection, and reduced sugar and nitrogen resorption from senescing leaves that support later growth and crown vigor (Schaberg et al., 2008).

In contrast, higher (warmer) minimum temperatures in August were associated with improved sugar maple crown condition (lower FSI). Across Vermont, fall starts relatively early, with many cool August nights that help propel leaf senescence. Higher minimum temperatures during this critical time could delay foliar senescence (Thomas and Stoddard, 1980), and support full leaf function when day lengths are still long and maximum increases in carbohydrate production and transport are possible. These critical C resources are needed to support later growth, protection and overall crown health.

The final two climate metrics associated with reduced crown health (higher FSI) were increased occurrences of extremely warm days (more than two standard deviations above the historic norm) in August and January. On average across the state, this equates to temperatures in August above 24.5 °C and over −3.4 °C in January. This relationship was particularly strong in August, when it is likely that extreme heat could increase foliar respiration rates and reduce net photosynthesis (though Drake et al. (2015) suggest that trees can better acclimate photosynthetic capacity to elevated temperature than once thought). Because precipitation data were not related to crown condition, we propose that any negative effects of August heat on crown health were not associated with secondary water stress. However, it is possible that our use of precipitation, as opposed to direct measurements of soil moisture variables, limits our ability to directly detect water limitations and subsequent stress.

While extremely warm days in January may be beneficial to temperate conifers that have the capacity to become photosynthetically active and capture C during thaws (e.g., Schaberg et al., 2000), leafless hardwoods are more likely to be negatively impacted. Warm winter thaws result in lower snowpacks and greater risk of soil freezing and associated root damage in sensitive, shallow-rooted species such as sugar maple (Tierney et al., 2001; Comerford et al., 2013). Because roots are needed to support crown health, freezing-induced root damage is associated with reduced crown growth (Comerford et al., 2013). Warm January thaws may also lead to tissue dehardening that increases the risk of shoot freezing injury (that would further degrade crown condition) when more seasonable cold temperatures return.

Interestingly, no growing season or seasonal freeze/thaw event metrics were retained in the final climate-driven FSI model. Also of note was the absence of any precipitation metrics in the final climate FSI model. Rather than indicating a lack of sugar maple sensitivity to water stress, there may be several overlapping reasons for the absence of significant correlates between water inputs and canopy condition. The first is the period of record under analysis (1988–2012). While this time frame does capture droughts in the 1998–1999 and 2001–2002 timeframes, these events were not on the order of magnitude of the prolonged droughts of the mid-1960s. Secondly, drought in Vermont is typically a localized phenomenon, and it is possible that the sampling reflected in the NAMP plots may not have coincided with sufficient pockets of moisture deficit across the state to influence the statistical modeling. Droughts in a humid climate like Vermont's do not typically manifest themselves in severe decline and tree mortality common in other climate regimes. Such extreme droughts have not been observed in the northeastern US since the 1700s and 1800s (Dupigny-Giroux, 2002; Dupigny-Giroux and Mock, 2009, Pederson et al., 2013). Finally, it is likely that our use of precipitation metrics do not fully capture water availability across our range of sites. Other factors such as soil depth and texture, water holding capacity, water table depth, etc. may be better suited to directly test the impact of water stress across our sites. Future modeling efforts could incorporate water availability and capacity metrics to better understand how changes in precipitation might influence sugar maple condition.

3.3. Spatial modeling of historical sugar maple FSI

In order to understand how the relationships established at the plot level may play out across the state, we applied the FSI climate model to yearly climate metrics on a landscape scale. Analysis of these spatially continuous (4km) FSI estimates demonstrated that the influence of climate on FSI varied tremendously in both space and time (Figs. 5 and 6). FSI varied from year to year, with a slight, but insignificant trend towards greater decline symptoms over the 32-year climate record (Fig. 5). The healthiest (low FSI) modeled historical year occurred in 1997, with a mean FSI of −0.62 (Fig. 6). The highest predicted stress (high FSI) year occurred in 1988 with mean FSI of +0.39 (Fig. 6). This coincides with field health metrics collected across the NAMP plot network, which show 1997 to have the lowest percent dieback (mean dieback = 6.6%) and canopy transparency (mean transparency = 13%) on record. Similarly, 1988 and 2006, the two highest statewide modeled FSI years, had the highest reported percent dieback (mean dieback > 9.4%) and two of the top three highest canopy transparency years (mean transparency > 21%).

The temporal variability across all years (standard deviation across yearly means = 0.24) was almost three times higher than the spatial variability within years (mean yearly standard deviation = 0.09), indicating that while spatial patterns were apparent, temporal variability was the primary driver of differences in FSI.

Spatial patterns in historical modeled FSI were apparent, but differed from one year to the next, with few regularly occurring features (Fig. 6). This indicates that locations of favorable or unfavorable

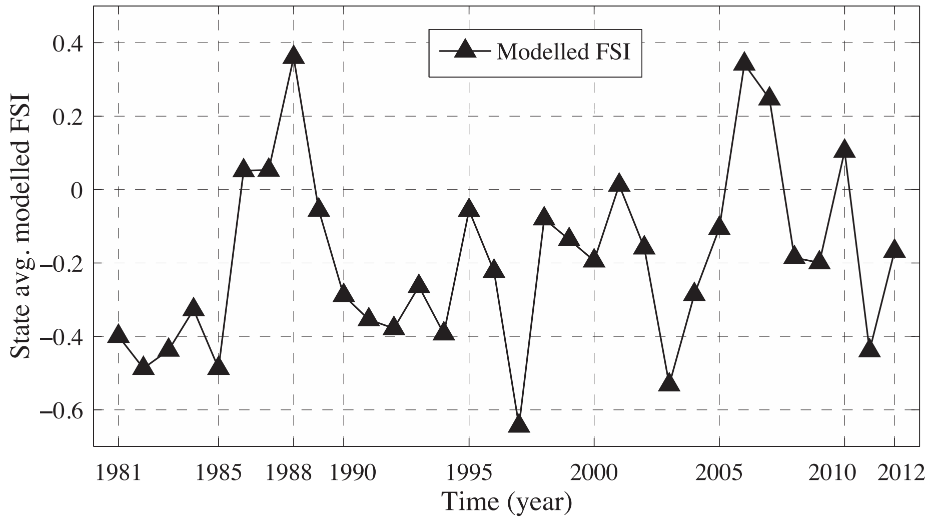

Fig. 5. Statewide average for the 4 km scale FSI model output using historical climate observations over the 1981–2012 period.

climate conditions are not consistently located in the historical data set. This has important implications for interpreting historical climate-based FSI means and future projections. For example, while the empirical relationship between the five climate metrics and FSI are strong, how those climate metrics vary spatially is likely to be highly variable over time. Thus, any spatially projected climate metrics should be considered as estimates of typical climate conditions across the landscape, with the expectation that conditions may vary widely from year to year.

In order to identify locations across the state where climate conditions have typically been favorable or unfavorable for sugar maple over the historic record, we applied the NAMP plot derived FSI climate model to historical climate metric "normals" on a landscape scale. The resulting map indicates that the northeastern-most region of Vermont (locally referred to as the Northeast Kingdom) was typically the most adversely affected by climate over the historical record (Fig. 7), while the southeastern region was the most favorably affected under projected climate normals (see Fig. 8).

3.4. Future climate FSI-impacts

In order to estimate the impact that changes in climate conditions will have on future sugar maple FSI, the final climate-driven FSI plot-level model was used in conjunction with future climate landscape projections (13 km) of the five relevant climate metrics. Projected FSI values relative to the 1981–2010 historical mean showed significant

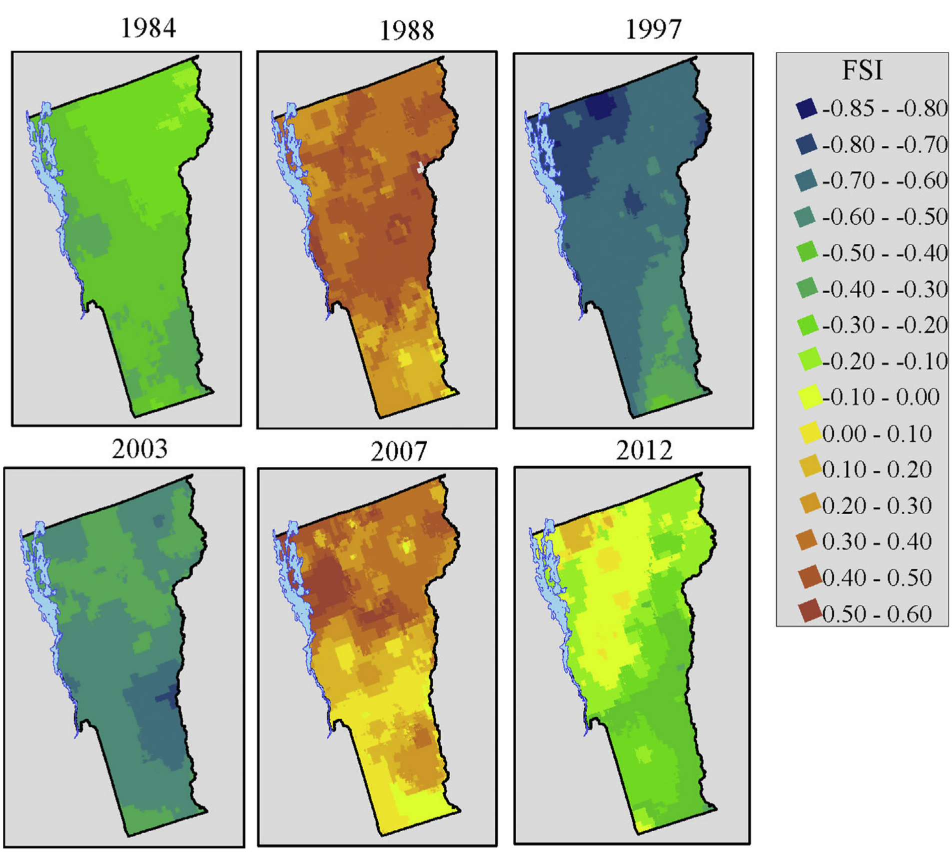

Fig. 6. Estimates of FSI produced from 4 km spatially continuous historical climate observations and the climate based FSI regression model for six individual years (1984, 1988, 1997, 2003, 2007, 2012) demonstrate the high degree of both temporal and spatial variability in climate adjusted FSI. Larger positive values indicate more severe stress.

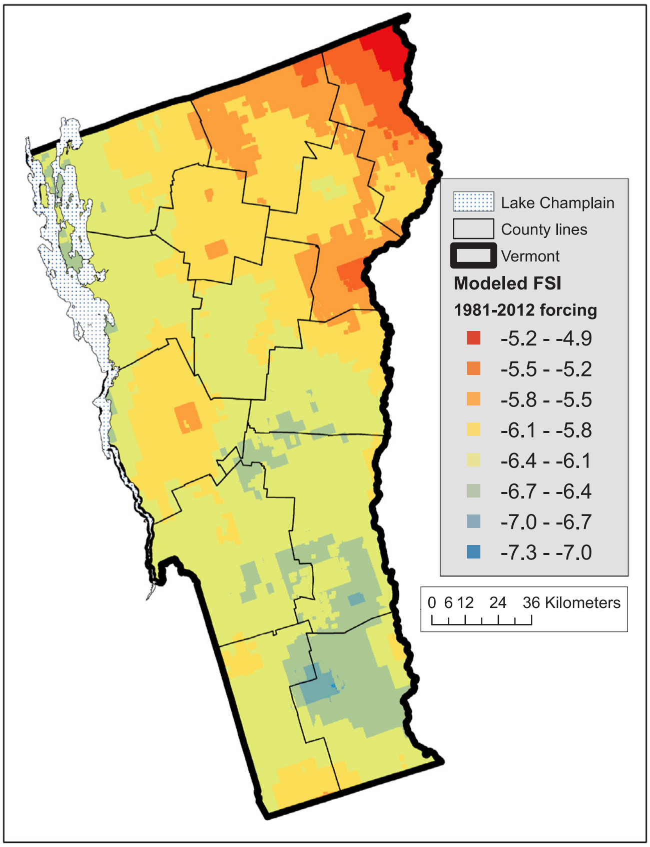

Fig. 7. Spatial patterns of cumulative modeled FSI using historical climate observations between 1981 and 2012. More negative values indicate more climate-favorable conditions were experienced over the 32-year period.

Table 3
Changes in the statewide average FSI values by time period and emission scenario.

Quantity/period	Emissions scenario	
	B1	A2
Uncertainty	0.071	0.070
1981–2010	−0.125	−0.125
2021–2050	0.107	0.146
2041–2070	0.290	0.620
2070–2099	0.624	1.502

increases in the severity of climate-driven sugar maple stress under both high and low emission scenarios (Table 3). This was true for all future periods – including the not-so-distant 2021–2051 period. The projected stress is more severe under the A2 high emissions scenario, enough so that the FSI increase by the 2041–2070 period in the A2 scenario is comparable to the 2070–2099 period in the B1 low emissions scenario. These projected differences in FSI values far exceeded the uncertainty of the models (Table 3).

Considering that FSI is a population distribution-based value, shifts in the mean allow us to quantify the proportion of sugar maple across the state that can be expected to experience moderate (FSI > 0.5) to severe (FSI > 1.5) climate-driven stress. Under the low emissions scenario, the shift from the historical (−0.125) to the projected 2021–2050 (0.107) mean indicates that sugar maple across the state could experience moderate to severe reductions in crown condition 35% of the time. By 2071, changing climate conditions are projected to shift an additional 20% of the sugar maple population into moderate to severe stress. Under the high emissions scenario, this proportion of sugar maple with reduced crown condition is reached by 2051 (20 years sooner), with over 84% of the population projected to be in moderate to severe climate-driven stress by 2071. Differences in future estimates between the two emissions scenarios are stark, with 30% more sugar maple potentially impacted by climate change under the high emissions

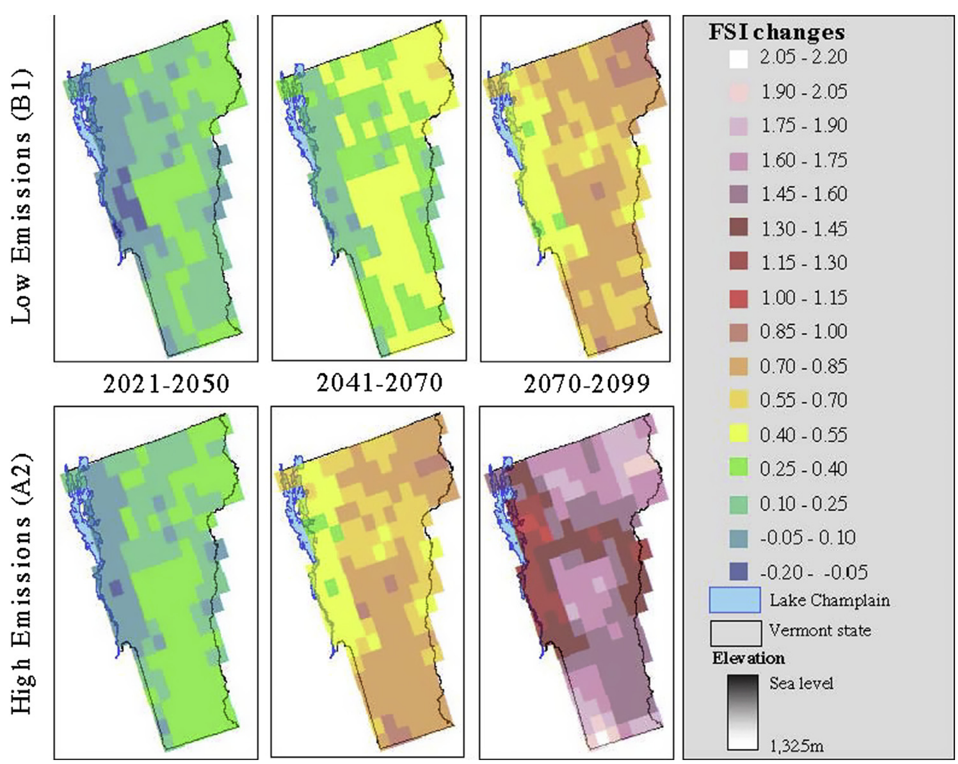

Fig. 8. Changes in FSI values (13 km) from 1981 to 2010 period mean values for three future time periods under low and high emission scenarios. Larger positive values represent more severe projected climate-driven crown decline for sugar maple.

Table 4
Percent of projected total change in FSI accredited to each climate metric over three future time periods.

Time period	Climate period				Climate metric					
	APR T_{min}		AUG T_{min}		OCT T_{min}		JAN hot DAYS		AUG hot DAYS	
	B_1	A_2	B_1	A_2	B_1	A_2	B_1	A_2	B_1	A_2
2021–2050	67.1	61.9	−54.4	−72.5	57.2	68.0	4.1	4.4	26.1	38.2
2041–2070	52.3	36.1	−44.4	−44.0	45.5	38.2	4.8	6.0	41.8	63.7
2070–2099	35.9	24.3	−34.7	−32.8	36.3	28.3	5.7	8.5	56.8	71.8

APR_Tmin denotes changes in the April minimum temperature, AUG_Tmin changes in the August minimum temperature, OCT_Tmin changes in the October minimum temperature, JAN_hotDAYS changes in the number of January days with daily maximum temperatures 2 standard deviations or more above the mean daily maximum; AUG_hotDAYS changes in the number of August days with daily maximum temperatures of 2 standard deviations or more above the mean daily maximum.

scenario. This indicates that there is considerable variability in sugar maple's projected response to climate change depending on the severity of that change.

However, the impact of climate on sugar maple condition is also projected to vary geographically. The spatial differences in projected FSI are highly variable, without obvious patterns beyond a tendency for higher climate-driven stress in the Northeast Kingdom and lower climate-driven stress in the Champlain Valley to the west.

Examining the relative influence of the five climate metrics on projected future sugar maple condition (Table 4), we found that the number of very hot days in January played a very limited role in sugar maple crown condition, and the projected changes in the August minimum temperatures actually worked to counteract climate-driven stress. Instead, projected declines were primarily driven by increasing April and October minimum temperatures, highlighting the increased vulnerability of sugar maple to climate conditions in the shoulder seasons (transition periods between peak winter and summer conditions).

However, the relative contributions of climate metrics also changed over time. The influence of the April, October, and August minimum monthly temperatures were dominant in the earlier time periods but decreased over time, whereas the number of very hot August days was increasingly important in later periods. This indicates that the relative importance of specific climate stress agents are likely to shift over time, with shoulder seasons being particularly important in earlier time periods, followed by extreme summer heat in later periods.

4. Conclusions

These results indicate that there are multiple specific climate metrics that historically have influenced sugar maple health across the state of Vermont. Across our field sites, this climate-driven variability in canopy condition exceeds the variability introduced by defoliation and other acute disturbance events, indicating that climate conditions, although rarely included in sugar maple decline studies, may be of equal importance in modulating species health as are more traditionally studied stress agents. Climate and other factors may also work in conjunction with one another (as predisposing or inciting agents) to contribute to or perpetuate decline (Schaberg et al., 2001).

Significant climate drivers included extreme minimum temperatures in growing season shoulder months and the frequency of extreme warm days in both the hottest and coldest months. The nature of these variables indicates that it is important for assessments of sugar maple response to climate change to include more nuanced and spatially explicit climate characteristics in addition to traditional summary climate metrics.

Applying spatially continuous climate data to the FSI climate model across the Vermont landscape shows that statewide, climate conditions for sugar maple have deteriorated over the 32-year time span of our climate data (1981–2012). Spatial variability in climate impacts on FSI was high, indicating that climate refugia may exist across the study area. However, considerable year to year variability in modeled FSI spatial patterns indicate that no locations are immune to climate-induced stress.

Our projections of how these key climate variables may change over the next 75 years indicate that climate-driven reductions in crown condition will likely increase in severity. However, our sensitivity analysis indicates that the relative influence of each included climate metric may change over time. It is also important to note that this analysis did not consider the potential impact of additional stress agents that may compound the impacts of climate. Therefore, we believe that these estimates of increasing negative impacts to sugar maple health are likely conservative, with long-term sugar maple decline likely higher than projected here.

While our ability to spatially resolve future climate characteristics is limited, our results indicate that the impact of climate change on sugar maple condition varies across the landscape. In order to maximize the sustainability of this critical resource, we suggest that land managers take steps to protect and conserve sugar maple stands, particularly those in areas projected to experience limited climate-driven stress.

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Declarations of interest

None.

Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.foreco.2018.04.014.

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