Assessing the Influence of Climate and Pollution on the Growth of Northern Hardwood Trees

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As a result of climate change, temperature and precipitation levels in the northeastern United States have increased in recent decades, and they are projected to continue to do so in the decades ahead (Janowiak et al. 2018). Projected changes include increases in maximum, minimum and average temperatures, with the greatest increases forecast for winter (Janowiak et al. 2018). Precipitation inputs are also expected to generally increase, though inputs may be more intense (leading to greater runoff and less soil infiltration) and episodic - creating intermittent droughts (Janowiak et al. 2018). Combined changes in temperature and precipitation may converge to cause more precipitation to fall as rain versus snow, resulting in reduced depths and durations of snowpack in regional forests (Janowiak et al. 2018). Although for some species there have been reports of improved tree growth with greater moisture availablity (Stern et al. 2020, Stern et al. 2021) and reduced growth with shrinking snowpacks (Comerford et al. 2013), analyses of how changing climate may influence the productivity of trees more generally in the northern hardwood forest have been limited.

In addition to changes in climate, atmospheric inputs of sulfur and nitrogen pollution that cause acid precipitation have decreased following reductions mandated by the 1990 Amendments to the Clean Air Act (Kosiba et al. 2018). These reductions have led to rebounds in the growth of some sensitive tree species like red spruce (*Picea rubens* Sarg.) (Kosiba et al. 2018). However, the influence of reduced pollutant loading on tree growth more broadly is unresolved.

To better understand how climate and pollution inputs influence wood production within the northern forest, we evaluated the radial growth of three tree species characteristic of the northern hardwood forest - sugar maple (*Acer saccharum* Marsh), American beech
(*Fagus grandifolia* Ehrh.), and yellow birch *(Betula alleghaniensis* Britton), and a fourth species, red maple (*Acer rubrum* L.), whose abundance has increased in the region. In particular, we analyzed the association of growth with climate (temperature, precipitation and snow) and pollution data for 690 trees: 203 sugar maple, 137 American beech, 172 yellow birch, and 178 red maple. Trees were distributed among 45 unmanaged northern hardwood forest plots across a broad range of locations within Vermont (Figure 1; Stern et al. 2022). We sampled only dominant and codominant trees in order to limit the influence of competition and suppression that can mask the influence of climate and other environmental factors on growth.

Growth was assessed using xylem increment cores that were collected, processed and measured using standard dendrochronological methods (see Stern et al. 2020, 2021, 2022). Radial growth was standardized to produce basal area increment (BAI) measures for general growth comparisons, and by calculating a Ring Width Index (RWI) used for correlation analyses of growth with climate and pollution data (Stern et al. 2020, 2021, 2022). Patterns of significant ($p \leq 0.05$) correlations were used to identify environmental parameters most associated with greater or lesser growth.

Over the course of the common time period (1945 to 2014) all four species showed a general increase in BAI growth during stand maturation with more plateaued growth during the second half of this timespan (Stern et al. 2022). Recent growth was somewhat higher for red maple (an average of 15.7 cm^2 for the second half of the chronology) as compared to sugar maple (14.2 cm^2) and yellow birch (13.2 cm^2) for the same time period. Year-to-year variations in growth were the greatest for sugar maple – a species that has experienced sporadic declines in health and productivity in the region (Schaberg et al. 2001). In general, growth was more modest (12.7 cm^2 for the second half of the chronology) and less variable for American beech, a species for which beech bark disease (BBD) has been known to constrain growth (Gavin and Peart 1993). We cored trees with little visible BBD in order to limit the effect of this and better isolate the influence of climate and pollution inputs on growth (Stern et al. 2022).

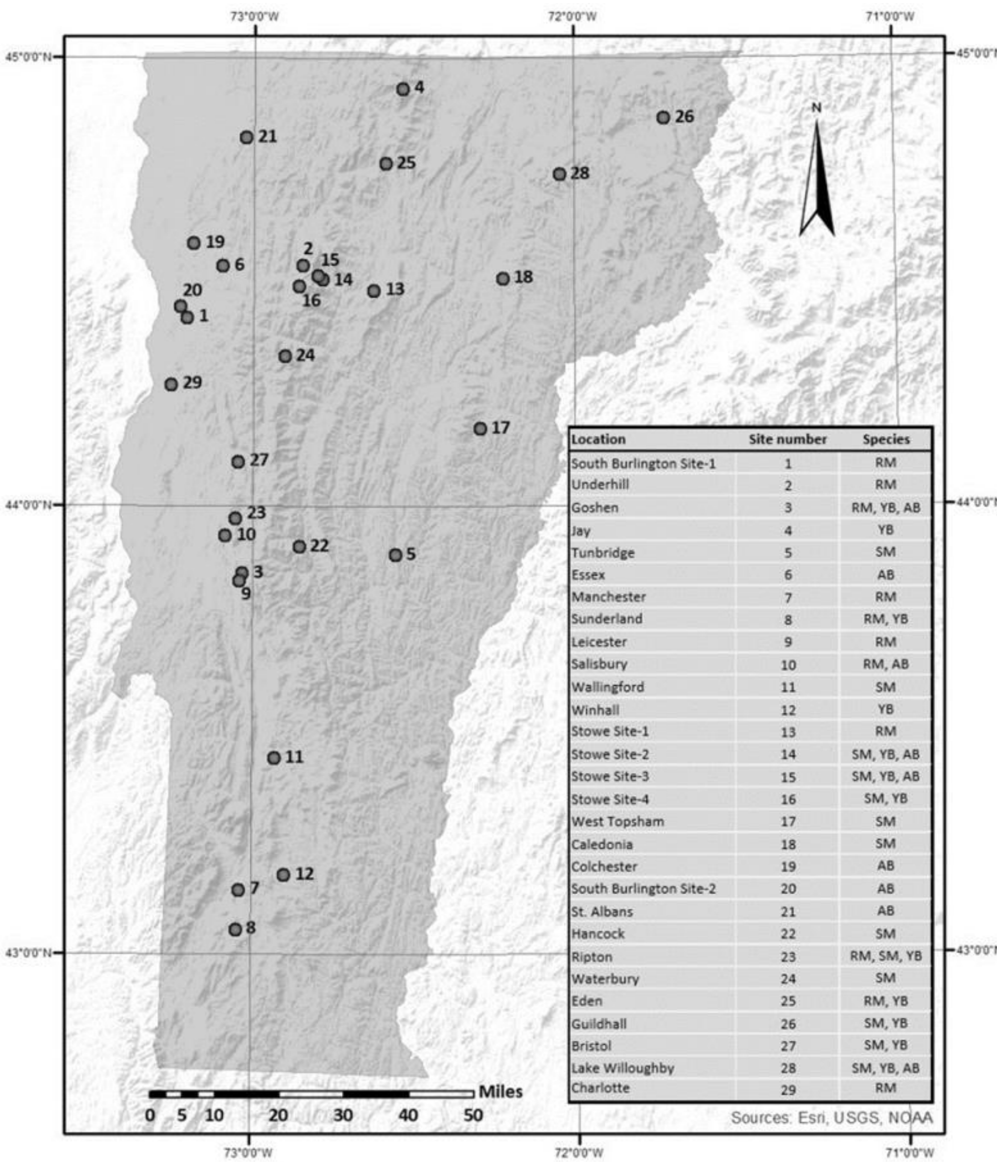
The greatest number of significant correlations with growth involved moisture availability (Table 1). For sugar maple, yellow birch and red maple, this was most evident as positive correlations with summer precipitation (Stern et al. 2022). This suggests that despite growing during a period of generally higher precipitation (Pederson et al. 2013), these hardwoods benefitted from ample water availability during the growing season. However, for the three species most associated with the northern hardwood forest (sugar maple, yellow birch and American beech) positive correlations between winter precipitation and growth were also evident. To assess if positive associations with winter precipitation were related to the presence of snow, we also correlated growth to monthly snowfall and snow duration data. For all four species assessed, winter or early spring (March) snow metrics were positively associated with growth. Winter snowpacks can insulate soils from low air temperatures and prevent them from freezing (Hennon et al. 2012). This can protect roots from freezing damage that can later result in reduced aboveground growth (Comerford et al. 2013). The importance of snowpacks in protecting tree roots and promoting radial growth has been well documented for sugar maple trees (Reinmann et al. 2019), but indications of its broader relevance to the growth of many species is novel and warrants further analysis.

Significant correlations with temperature were less common and were generally limited to negative associations with summer temperature for the three quintessential northern hardwood species (Table 1). In contrast, red maple showed a positive association with temperatures in October and a negative correlation with March temperatures before eventual ring formation. These patterns may suggest that a warmer fall, that allowed for an extended growing season, contributed to growth the following year and that colder March temperatures reduced growth – especially if snow was lacking (Table 1).

Pollution data was negatively associated with growth for sugar maple, yellow birch and red maple (Table 1). We expected that pollution data would be associated with reduced growth for sugar maple – a species known to be sensitive to decline associated with exposure to acid deposition (Schaberg et al. 2001). Furthermore, the lack of sensitivity of American beech to pollution inputs was not surprising and has been shown elsewhere (Halman et al. 2014). However, indications that yellow birch can be negatively impacted by pollution is uncommon (though see Halman et al. 2014), and we are unaware of previous reports of red maple growth being constrained by pollution exposure. Although sensitivities to pollution inputs were sometimes evident, any negative influence on growth should decrease over time as pollution levels decline further.

When associations of growth with climate and pollution data were assessed at finer temporal scales (e.g., monthly temperature and precipitation data), of the four species assessed, red maple had the fewest associations with environmental variables (Stern et al. 2022). This could suggest that red maple is less susceptible to growth reductions as the climate changes. This possibility is consistent with results from the online Climate Change Tree Atlas - a tool that projects a less dramatic change in future habitat suitability for red maple relative to the other species we evaluated (Prasad et al. 2007-ongoing).

Considering the overwhelmingly positive associations of summer precipitation and winter snow on radial growth, changes in the amount, form (rain versus snow), intensity (increased runoff versus greater soil penetration), and periodicity (regular inputs versus intermittent exposures) of precipitation beyond current norms could threaten optimal growth of trees within the northern hardwood forest.



Location	Site number	Species
South Burlington Site-1	1	RM
Underhill	2	RM
Goshen	3	RM, YB, AB
Jay	4	YB
Tunbridge	5	SM
Essex	6	AB
Manchester	7	RM
Sunderland	8	RM, YB
Leicester	9	RM
Salisbury	10	RM, AB
Wallingford	11	SM
Winhall	12	YB
Stowe Site-1	13	RM
Stowe Site-2	14	SM, YB, AB
Stowe Site-3	15	SM, YB, AB
Stowe Site-4	16	SM, YB
West Topsham	17	SM
Caledonia	18	SM
Colchester	19	AB
South Burlington Site-2	20	AB
St. Albans	21	AB
Hancock	22	SM
Ripton	23	RM, SM, YB
Waterbury	24	SM
Eden	25	RM, YB
Guildhall	26	SM, YB
Bristol	27	SM, YB
Lake Willoughby	28	SM, YB, AB
Charlotte	29	RM

Fig. 1. Locations of the study sites throughout Vermont. SM= sugar maple, YB= yellow birch, AB= American beech, RM= red maple. Figure was created using ArcGIS 10. Base map courtesy of Esri, USGS, and NOAA

Species	Season			
	Spring	Summer	Autumn	Winter
Sugar maple	HDD (+) Tmax (-) Snow duration (+)	CDD (-) ca:an (+) SPEI01 (+) SPEI03 (+)	*ns*	SPEI01 (+) SPEI03 (+)
Red maple	Tmax (-) Snow duration (+) SO_4 (-)	SPEI01 (+) SPEI03 (+)	Tmin (+)	
Yellow birch	NO_3 (-) ca:an (+)	CDD (-) HDD (+) Tmax (-) SPEI01 (+) SPEI03 (+)	Tmax (-) SPEI03 (+) ca:an (+)	SPEI03 (+) Snowfall (+) ca:an (+)
American beech	Snow duration (+)	CDD (-) HDD (+) Tmax (-)	*ns*	SPEI01 (+) HDD (+)

Table 1. Significant correlations ($p<0.05$) of growth versus climate and pollution data for each season. Tmax= maximum temperature, Tmin= minimum temperature, CDD= cooling degree days, HDD= heating degree days, SPEI= Standardized Precipitation-Evapotransipiration Index, ca:an=cation to anion ratio, SO_4-=sulfate deposition, NO_3=nitrogen deposition. Snow duration is number of days in a month that snow depth is at least 2.54 cm. Seasons/species with no significant correlations are indicated by *ns*.

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