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TREE-RING ANALYSIS OF RED SPRUCE TIMBERS FROM THE MOOSILAUKE RAVINE LODGE, WHITE MOUNTAINS, NEW HAMPSHIRE

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ABSTRACT

Historic harvesting and mortality from air pollution drastically reduced the abundance of red spruce *(Picea rubens)*, a late-successional dominant of cool-temperate forests of the northeastern U.S. and southeastern Canada, leaving few opportunities to understand the natural growth and disturbance responses of this species. Timbers salvaged from the Moosilauke Ravine Lodge, a structure built from trees harvested in the late 1930s, provided an opportunity to reconstruct radial growth patterns and dynamics of a former old-growth red spruce stand located in Jobildunc Ravine on Mount Moosilauke in the White Mountains of New Hampshire. Ravine Lodge tree-ring series were compared with data from a 255-year-old red spruce found living in Jobildunc Ravine, from the Nancy Brook site in the White Mountains, and from other dendroecological studies across the region. Ring counts provide minimum tree ages of 187–286 years for timbers from Jobildunc Ravine, suggesting they established between the mid-Seventeenth and mid-Eighteenth Centuries. Dendroecological analyses identified early decades of suppression in the understory followed by 2–5 growth releases and 2–4 growth declines for each sample, indicating occasional, small-scale disturbances of the canopy before the 1930s. A growth decline in 1834–1835 coincides with an outbreak of spruce budworm (*Choristoneura fumiferana*) in eastern Canada, perhaps reflecting a regional defoliation event that occurred as far south as Mount Moosilauke. This study illustrates the insights that can be gained from wood from historic structures on the dynamics of now-scarce old-growth red spruce forests.

Keywords: tree rings, dendroecology, *Picea rubens*, red spruce, old growth, spruce budworm, White Mountains.

INTRODUCTION

Red spruce (*Picea rubens* Sarg.) has the smallest range of the three *Picea* species found in eastern North America, with populations limited to southeastern Canada and the northeastern U.S., extending south along the Appalachian Mountains at high elevations (*e.g.* White and Cogbill 1992). After expanding across this region during the late Holocene (*e.g.* Spear *et al.* 1994; Lindbladh *et al.* 2003), red spruce was historically common in various ecological settings, from coastal to montane, occurring with a variety of other species, including eastern hemlock (*Tsuga canadensis* (L.) Carr.), red maple (*Acer rubrum* L.), sugar maple (*Acer saccharum* Marsh.), yellow birch (*Betula alleghaniensis* Britt.), paper birch (*Betula papyrifera* Marsh.), American beech (*Fagus grandifolia* (Ehrh.) Little), northern white cedar (*Thuja occidentalis* L.), and balsam fir (*Abies balsamea* (L.) Mill) (White and Cogbill 1992;

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Nowacki *et al.* 2010). Because of its value for construction, pulp, and specialized uses such as aircraft, shipbuilding, and musical instruments (*e.g.* Blum 1990), large-scale timber harvesting in the 19th and early 20th Centuries greatly reduced the prevalence of red spruce across its range (Johnson *et al.* 1995; Cogbill *et al.* 2002; Nowacki *et al.* 2010; Thompson *et al.* 2013). Climate change following the Little Ice Age, particularly an increase in winter freeze-thaw cycles, is also suspected to have negatively impacted red spruce populations (Hamburg and Cogbill 1988; Houle *et al.* 2012). Later, acid deposition induced widespread mortality of remnant red spruce in the second half of the 20th Century (*e.g.* Battles and Fahey 1996; DeHayes *et al.* 1999; Kosiba *et al.* 2018; Wason *et al.* 2020). In the northeastern U.S., mature red spruce is largely restricted to scattered locations at higher elevations (*e.g.* Cogbill 1996). Although red spruce can reach 400 years of age or older, the long history of harvesting and pollution-driven mortality has left few extant old-growth stands available for sampling to characterize natural growth and disturbance dynamics, and thus historic structures provide an important opportunity for generating new tree-ring chronologies. Studies of remnant stands and analyses of timbers in historic structures suggest that, prior to its loss to logging and acid deposition, red spruce occurred in uneven-aged stands that experienced regular disturbance by wind, ice, disease, and insects (*e.g.* Blais 1965, 1983; Morin *et al.* 1993; Cogbill 1996; Krause 1997; Boulanger and Arseneault 2004; Fraver and White 2005a; Fraver *et al.* 2007; Boulanger *et al.* 2012). In this study we examined timbers from the Moosilauke Ravine Lodge in the White Mountains of New Hampshire, which was built from locally harvested red spruce in the 1930s. Our results provide insights into the history of this species on Mount Moosilauke and surrounding areas.

STUDY AREA

Mount Moosilauke is a 1464-m-high peak located in the western White Mountains of northern New Hampshire, USA (Figure 1). Weather observations recorded at Glencliff, New Hampshire (CLIMAP 2021), located at 503 m a.s.l. elevation, 7 km southwest of the Moosilauke summit, show the highly seasonal climate of the study area (Figure 2). Summers are warm and wet (mean July temperature and precipitation are 19°C and 105 mm, respectively), whereas winters are cold and drier (mean January temperature and precipitation are −9°C and 54 mm, respectively), with most winter precipitation falling as snow. Forest composition changes with elevation: northern hardwoods occur below 750 m a.s.l., spruce-fir at 750–1200 m, balsam fir at 1200–1400 m, and alpine tundra above 1400 m (Reiners and Lang 1979). The southern and southeastern flanks of Mount Moosilauke currently are owned by Dartmouth College; the rest of the mountain is part of the White Mountain National Forest.

Jobildunc (also spelled Jobildunk) Ravine is a southeast-facing glacial cirque on the east side of Mount Moosilauke, bounded by the Moosilauke main summit to the west, Mount Blue to the north, and Mount Jim to the northeast; it is drained by the Baker River (Figure 1). The cirque floor, at 1100 m elevation, is surrounded by 250-m-high headwalls. A forested peatland occupies the center of the ravine, and at present the peatland and surrounding uplands are dominated by early successional forest featuring red spruce, balsam fir, paper birch, yellow birch, and mountain ash (*Sorbus americana* Marsh.). The east slopes of Mount Moosilauke experienced heavy timber harvesting during 1896–1923, but Jobildunc Ravine was not logged at that time, perhaps because the trees suffered from a fungal disease that limited their value for pulp (Brown 1958).

The Moosilauke Ravine Lodge was built from red spruce logs cut in Jobildunc Ravine in the winter of 1937–1938 (Figure 3). At the time the land was owned by the Parker-Young timber company, but Dartmouth College was allowed to remove logs “from the fringes” of the stand per a special clause in the College’s deed to the adjacent Gorge Brook tract (Brown 1958). Logs were pulled to the Lodge site by horse teams via a since-abandoned logging path known as the Go-Back Trail. Dozens of red spruce were cut, but a visitor to the harvest site remarked: “Our logging operation leaves untouched a major portion of the lumber company’s virgin spruce in the upper wilderness of Jobildunk Ravine” (Brown 1989). Nearly all the trees remaining after the Dartmouth harvest were blown down by a hurricane in September 1938, and much of Jobildunc Ravine was salvage logged during 1943-1947 (Brown 1958).

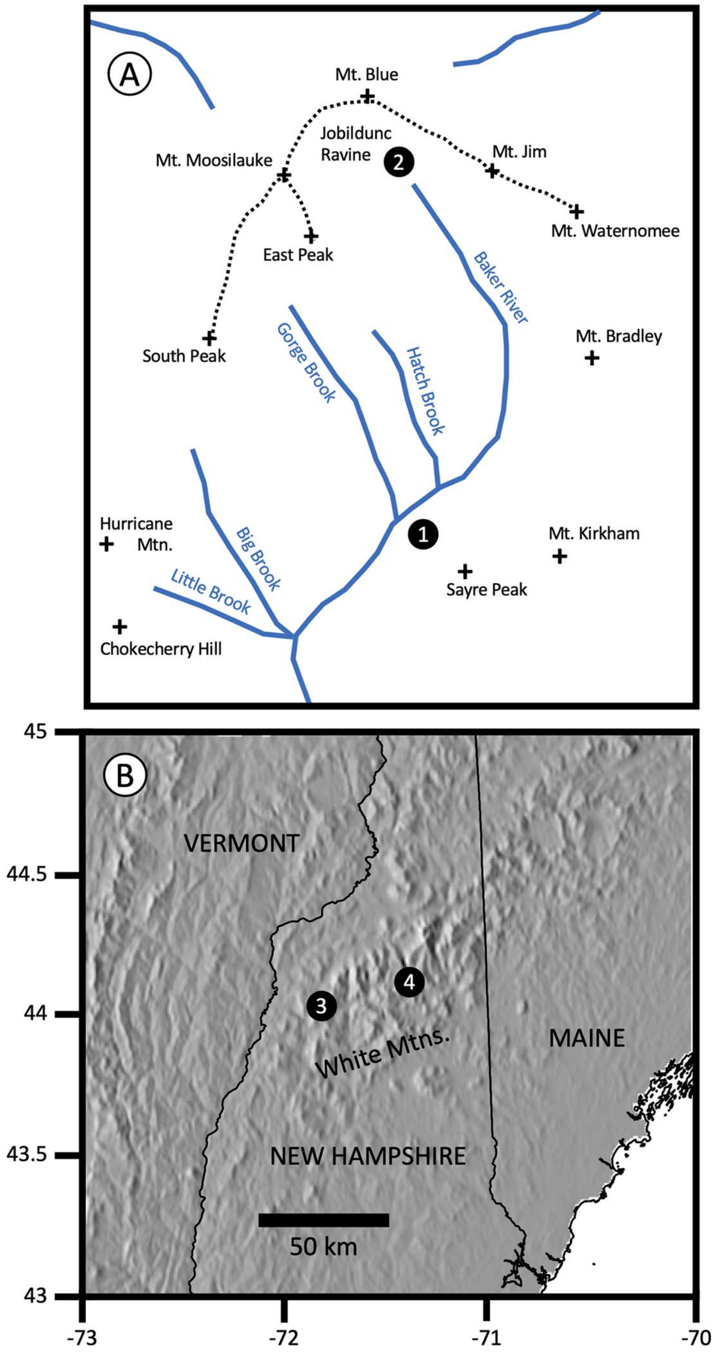

Figure 1. (A) Map of Mount Moosilauke highlighting the locations of Jobildunc Ravine, the Moosilauke Ravine Lodge (1), and the living tree cored for Jobildunc sample C1 (2); plus (+) symbols are peaks, dotted line is ridgeline. (B) Regional map with locations of the Mount Moosilauke (3) and Nancy Brook (4) study sites in the White Mountains, NH.

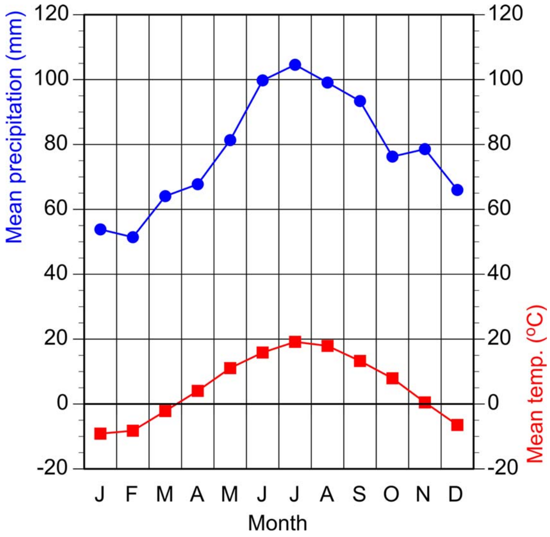

Figure 2. Monthly mean precipitation (blue line) and temperature (red line) data from Glencliff, NH (CLIMAP 2021).

METHODS

The Ravine Lodge was dismantled in 2016 so that a modern building could be constructed in its place. As part of the demolition work, five ca. 8–15-cm-thick cross-sections of timbers were salvaged for this project (hereafter samples MRL 1–5); the samples came from roof beams and exterior corner columns. We also used an increment borer to obtain two cores from a 49-cm-diameter live red spruce (sample C1) in Jobildunc Ravine (44.02452°N, 71.81651°W; 1090 m a.s.l. elevation), the only large red spruce encountered on a traverse through the ravine in August 2019. For MRL 1–5, the cross-sections were sanded to reveal a flat surface. Annual rings were counted with a light microscope and ring widths were measured to the nearest 0.001 mm using a Velmex measuring stage (Velmex Inc, Bloomfield, NY) coupled to MeasureJ2X software (VoorTech Consulting, Holderness, NH). For each of the MRL sections, a single radius from the pith to the outer ring was measured. For Jobildunc C1, cores were glued to reading mounts and sanded to reveal a flat surface. Annual rings were counted using a light microscope and ring widths were measured to the nearest 0.001 mm using Tellervo software at the Cornell Tree-Ring Lab. The ring-width measurements from the two C1 cores were averaged to create a single series.

Figure 3. (A) Photo of the construction of the Moosilauke Ravine Lodge in 1938 (Bouchard 2015). (B) Photo of the Moosilauke Ravine Lodge in 1939 (Anonymous 1939).

We used the dplR package in R (Bunn 2010) to crossdate the MRL samples and Jobildunc C1 with a red spruce standardized tree-ring-width chronology from the Nancy Brook old-growth stand (Cook 2002), located in the White Mountains ca. 35 km ENE of Mount Moosilauke (Supplemental Figures 1–6). Prior to calculating correlation coefficients, the crossdating process first detrends all ring-width series using a 39-year Hanning filter followed by pre-whitening the time series (Bunn 2010). Annual basal area increment (BAI, $cm^2\ yr^{-1}$) was calculated based on raw ring-widths from each of the cross-sections using the “proportional method” of Bakker (2005), which accommodates pith offset (*i.e.* different locations of geometrical and chronological centers of the tree). In this method, the tree diameter at a past year of interest is calculated as the current diameter (calculated from the measured circumference) multiplied by the proportion of radial growth on the measured radii occurring before that year of

Table 1. Tree-ring data from Mount Moosilauke, White Mountains, New Hampshire.

Sample	Diameter (cm)	Number of rings	Inner ring	Outer ring	Release years	Decline years
MRL 1	47.9	162	1818*	1980*	–	–
MRL 5	48.3	161	1819*	1980*	–	–
MRL 2	47.1	286	1651	1936	1776, 1820, 1876	1682, 1789, 1834
MRL 3	49.4	187	1751	1937	1760, 1777, 1816, 1875, 1924	1787, 1829
MRL 4	45.1	241	1696	1937	1737, 1811, 1890	1705, 1790, 1835, 1861
Jobildunc C1	49.0	255	1765	2019	1898, 1945	1862, 1959, 1972

*Provisional assignments for the years of the inner and outer rings for MRL 1 and 5. Given the uncertain provenance of those samples, release and decline years were not determined.

interest. For the Jobildunc tree, BAI was calculated for each core and then averaged.

The disturbance history of the Jobildunc Ravine red spruce stand was reconstructed by analyzing changes in radial growth. Growth releases, interpreted as increased growth of subcanopy trees in response to canopy damage, were identified using the absolute-increase method of Fraver and White (2005b), with a 10-year window for both pre- and post-event. Following Fraver and White (2005b), we set the threshold for identifying a release event at 1.25 times the standard deviation of absolute increases. This value was 0.36, 0.39, and 0.39 mm for MRL 2–4, respectively, so we decided to use a threshold of 0.39 mm. As Fraver and White (2005b) found to be the case, this threshold value is similar to the 90th percentile of the absolute-increase series for MRL 2–4: 0.28, 0.40, and 0.43 mm. We also experimented with the species-specific threshold of 0.58 mm that Fraver and White (2005b) found for red spruce. As would be expected, the lower threshold value of 0.39 mm identifies more releases per tree (3–5 releases; Table 1) than a threshold of 0.58 mm (1–2 releases; data not shown).

Growth declines, interpreted as nonfatal foliar damage to the tree (*e.g.* by insects or ice), were identified using a percent-decrease approach. We defined a decline as a 30% drop in mean growth rate (also using a 10-year window), as that threshold identified common events between samples MRL 2–4.

RESULTS AND DISCUSSION

MRL 2–4 (Figure 4A) crossdated well with the Nancy Brook chronology (r = 0.32–0.46; Figure 4C) yielding outermost ring years of 1936 (MRL 2) or 1937 (MRL 3–4). For MRL 2, it is likely that the 1937 ring was lost when the log was de-barked in preparation for the construction of the Ravine Lodge or via subsequent wear on the exterior surface of the timber. The Jobildunc tree (C1; Figure 4B) spanned 1765–2019 and crossdated (r = 0.53) with the Nancy Brook chronology. MRL 1 and 5 (162 and 161 years in length, respectively) crossdated poorly with C1 and with the Nancy Brook chronology, but after Hanning filtering they correlated well with each other (r = 0.46). When crossdating these trees by "floating" each tree's detrended ring-width series relative to the Nancy Brook chronology, we found a marginal correlation with an outermost ring set at 1980 (r = 0.18, p = 0.035 for MRL 1 and r = 0.14, p = 0.084 for MRL 5). It is possible that those samples came from timbers used in a kitchen addition and other log replacement work that was done on the Ravine Lodge in the 1980s and 1990s; timbers for the addition were sourced from Dartmouth's Second College Grant in northern NH, 115 km north of Mount Moosilauke (Hooke and Noon 1989; David Hooke, personal communication 29 May 2023). Given the relatively poor crossdating results and uncertain provenance, MRL 1 and 5 were not included in further analyses.

When Jobildunc Ravine was logged in the winter of 1937–1938, the stand of trees featured a number of large and old red spruce. Ross McKenney, supervisor of the construction of the Moosilauke Ravine Lodge, wrote this description: "They were beautiful trees, tall and straight, with very few limbs along their trunks. Some of these trees were thirty-three inches [ca. 84 cm] in diameter at the butts and measured in length to upwards of sixty feet [ca. 18 m]" (McKenney 1989). The three cross-sections from the Ravine Lodge that we analyze here (MRL 2–4), ranged in diameter from ca. 45 to 50 cm, and annual-ring counts ranged from 187 to 286 years

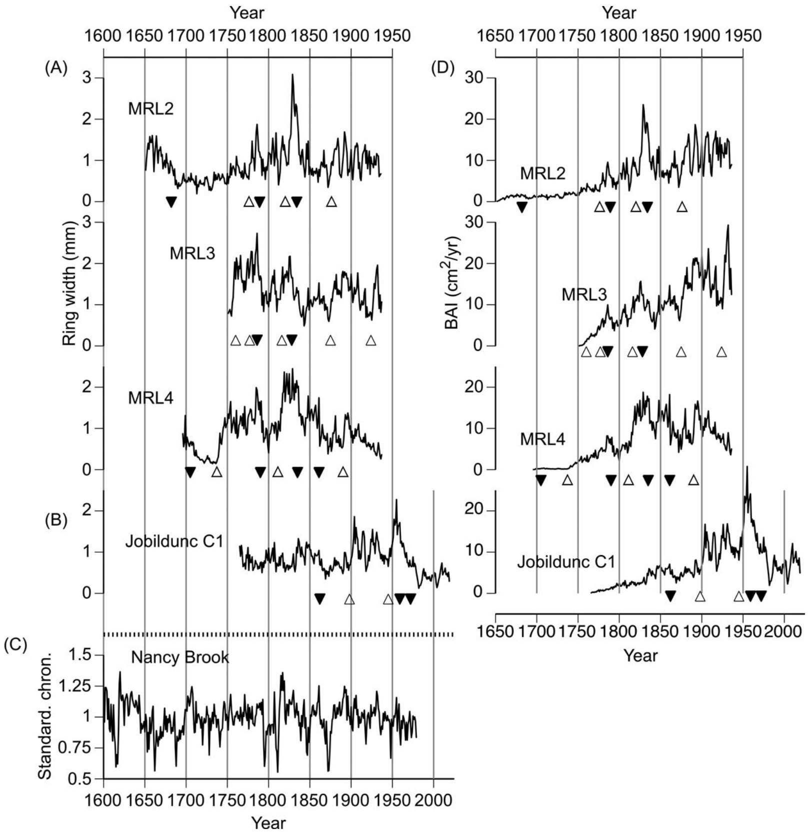

Figure 4. (A) Ring-width measurements for samples MRL 2-4 from the Moosilauke Ravine Lodge; open triangles are growth releases: closed triangles are growth declines; (B) ring-width measurements from sample C1, collected from a live red spruce tree in Jobildunc Ravine in 2019: open triangles are growth releases, filled triangles are growth declines; (C) standardized tree-ring chronology from Nancy Brook, White Mountains, NH (Cook 2002); (D) basal area increment (BAI) estimates for MRL 2-4 and C1, plotted with the growth releases and declines determined from the ring widths.

(Table 1, Figure 4A). Given that the height of the samples on the boles of the trees is not known, these counts represent minimum recruitment dates, ranging from 1651 to 1751. Ring counts by a Dartmouth student at the time of the harvest found that one of the Jobildunc red spruce had recruited in 1617 and was thus 320 years in age (Brown 1989). Ring widths average 0.91–1.34 mm (Figure 4A). The red spruce that we cored in 2019 (sample C1) reached 255 years to the pith and thus recruited ca. 1765; it has an average ring width of 0.82 mm (Figure 4B). At the time of the Dartmouth logging operation in 1937–1938, that tree would have been ca. 30 cm in diameter.

The reconstruction of BAI for the three MRL samples and the Jobildunc red spruce (C1) revealed slow rates of growth when the trees were young (BAI < 2 cm^2 yr^{-1}; Figure 4D). The shade tolerance of red spruce is clearly evident in the growth history of these trees, as the period of suppressed growth lasted for multiple decades (with the exception of MRL 3). MRL 2 had a particularly long period of suppression, with slow growth for about a century. That this tree eventually reached the canopy is remarkable, as a study of the fate of sub-canopy trees (including red spruce) on the west side of Mount Moosilauke found that suppressed saplings rarely attain canopy status (Landis and Peart 2005). Following each tree's initial release, MRL 2 and 3 showed a progressive increase in BAI. For MRL 4 and C1, on the other hand, BAI featured highly variable decadal-scale fluctuations.

The characteristics of the Jobildunc red spruce stand can be compared with data from extant mature stands across the northeastern U.S. (Cogbill 1996). At locations in the Adirondacks and across northern New England, maximum red spruce diameters fall in the range of 42–67 cm, canopy heights range over 12–27 m, and density of stems (>20 cm in diameter) ranges over 210–538 stems per ha. Maximum tree ages are 225–423 years and mean tree age ranges over 146–254 years. Uneven age structures for these stands are interpreted as reflecting periodic recruitment following small disturbances (Cogbill 1996). Thus, the stand that grew in Jobildunc Ravine until the Dartmouth harvest in 1937–1938 appears to have been fairly similar to other red spruce stands in the region in terms of the size and ages of the trees.

Our analysis of radial growth patterns identified 2–5 releases in each of the MRL 2–4 samples and in the C1 core from the live Jobildunc red spruce (Table 1, Figure 4). All trees show different dates of initial release associated with an upward BAI trend, and only two of the release dates appeared to be synchronous between trees (1776–1777 and 1875–1876 in MRL 2 and 3), suggesting occasional, small-scale canopy disturbances by wind, ice, disease, or insects. The Jobildunc C1 core does not exhibit a growth release in response to the 1938 hurricane, even though wind damage in Jobildunc Ravine was reported to have been severe (Brown 1958) and the tree was mature (ca. 173 years in age) and quite large (ca. 30-cm diameter) at the time. Perhaps the pattern of winds during the hurricane spared a stand of trees in that part of Jobildunc Ravine from heavy damage. This interpretation is supported by the occurrence of a growth release in sample C1 in 1945 (Table 1, Figure 4B), likely caused by neighboring canopy trees being cut during the salvage logging operation that took place during 1943–1947 (Brown 1958).

Samples MRL 2–4 and Jobildunc C1 featured 2–4 growth declines, with some coherency among the trees (Table 1, Figure 4). All three samples from the Ravine Lodge featuring declines in 1787–1790, and MRL 2 and 4 had declines in 1834–1835. In this forest type, abrupt growth declines followed by 5–10 years of narrow rings are commonly associated with outbreaks of eastern spruce budworm (*Choristoneura fumiferana*) (*e.g.* Fraver *et al.* 2007). A study of fossil insect remains by Filion *et al.* (2006) demonstrated that spruce budworm has been present historically on Mount Moosilauke. The 1834–1835 decline in MRL 2 and 4 coincides with an outbreak of spruce budworm that took place in eastern Canada during 1832–1845 (*e.g.* Blais 1965; Krause 1997; Boulanger and Arseneault 2004), suggesting a regional defoliation event that reached as far south as Mount Moosilauke. However, the 1830s outbreak was not detected in northern Maine (Fraver *et al.* 2007). The 1787–1790 growth decline in MRL 2–4 was not observed in budworm-outbreak reconstructions from eastern Canada (*e.g.* Blais 1965; Krause 1997; Boulanger and Arseneault 2004; Boulanger *et al.* 2012) or northern Maine (Fraver *et al.* 2007), and thus the decline may represent a localized outbreak or damage to multiple trees by a wind or ice event. Similarly, we found a growth decline in the early 1860s in both MRL 4 (1861) and Jobildunc C1 (1862), but that event is not coincident with spruce budworm outbreaks in other parts of the region (*e.g.* Boulanger and Arseneault 2004; Fraver *et al.* 2007; Boulanger *et al.* 2012). Lastly, the growth decline at 1682 in MRL 2 falls during a budworm outbreak that occurred during 1678–1690 in other parts of the region (Boulanger and Arseneault 2004; Fraver *et al.* 2007; Boulanger *et al.* 2012). However, given that this growth decline appears in only one of the Moosilauke Ravine Lodge samples, it is not clear whether it reflects insect defoliation as opposed to some other type of disturbance.

Although the small sample size of this opportunistic study does not allow us to estimate the return interval of spruce budworm outbreaks and other disturbances, our results are consistent with previous reconstructions of red spruce stand dynamics. Small canopy gaps occurred regularly and were scattered through space and time, whereas larger (*i.e.* gaps of tens of m^2) disturbances by insects and wind occurred every few decades. Stand-replacing disturbances were rare, some trees reached hundreds of years in age, and because of the shade tolerance of red spruce, the composition of these forests remained stable over time (Cogbill 1996; Fraver and White 2005a; Fraver *et al.* 2007).

The Jobildunc C1 tree shows a release at 1945 followed by a reduction in BAI and radial growth through the 1960s–1980s (with two identified decline events; Table 1, Figure 4B). This single tree fits a pattern widely observed in red spruce growth history, in which the 1960s–1980s decline co-occurred with regionally higher mortality and cannot be attributed entirely to succession or stand-dynamic processes, but rather a pattern consistent with winter injury and acid rain (Johnson *et al.* 1995). In more recent decades, decreased pollution and increasing temperature may be driving an increase of growth of the red spruce that survived the 1960s–1980s decline (Gavin *et al.* 2008; Kosiba *et al.* 2018; Wason *et al.* 2020).

Previous work has demonstrated that the growth of red spruce is influenced by temperature (*e.g.* Conkey 1979, 1986). However, we did not observe growth declines in MRL 2–4 and Jobildunc C1 during the cold events that marked the latter part of the Little Ice Age (*e.g.* Timmreck *et al.* 2021), including the cold summer of 1816 that followed the 1815 Tambora eruption (*e.g.* Chenoweth 1996), and that are recorded in tree-ring data from various sites in eastern North America (D'Arrigo *et al.* 2003, 2013), including New England (Pearl *et al.* 2020). Although these red spruce were growing close to their upper elevational limit on Mount Moosilauke, it seems that position in the canopy and other stand dynamics may be more important than interannual variability in climate in controlling growth, perhaps underlining the importance of light limitations to growth in a narrow mountain valley in a region characterized by wet, cloudy summers (Figure 2).

CONCLUSIONS

This opportunistic study provides a glimpse into the structure and stand dynamics of an extinct forest ecosystem—montane red spruce—prior to the extensive logging of the 19th and early 20th Centuries and the pollution-caused mortality of the mid to late 20th Century. Our analyses of a small sample of trees from Mount Moosilauke revealed a stand of large, mature red spruce that experienced occasional, small-scale disturbances of the canopy by wind, ice, disease, or insects. This study highlights the value of analyzing wood from historic structures in regions where there are few old trees available for sampling.

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