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Low densities in white pine stands reduce risk of drought-incited decline☆

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ABSTRACT

White pine (*Pinus strobus*) is commonly found in naturally regenerated even-aged stands on former agricultural lands throughout its range. These stands can be managed for rapid production of high-quality sawtimber, and are thus a valuable timber resource. Yet, periodic growth decline and mortality events have occurred, such as that observed in the late 1990s in southern Maine, USA. The present study uses increment measurements from white pine tree cores collected in the early 2000s to compare increment chronologies in high- and low-mortality stands in southern Maine. Periods and severity of decline were quantified, revealing a growth decline and mortality event that began in 1996 following a late-summer drought in 1995. Further, the sites on which mortality was most pronounced were observed to have soil restrictions resulting in shallow rooting depth, ranging from 19 cm to 32 cm deep. Restrictions included bedrock, lithological discontinuity (loamy cap overlaying sand), and plow pans. Stand stocking was also a predisposing factor; on average, stands that experienced greater mortality during the decline event had higher stocking than those that experienced less mortality. As a consequence, stand densities in declining stands were reduced through mortality to levels more common in nearby non-decline stands; those densities correspond to recommendations for low-density management of white pine (i.e., 330–540 trees ha^{-1} and 17–25 $m^2 ha^{-1}$ of basal area at 20–30 cm DBH). The smaller diameters of the affected trees indicate the need to give priority to retention of large-diameter trees when thinning pole- and small sawtimber-sized (20–30 cm DBH) white pine stands. This and other studies demonstrate the need for low-density management of pole-size white pine stands to not only maximize growth and value but also reduce the risk of drought-incited decline and mortality on sites with rooting restrictions.

1. Introduction

White pine (*Pinus strobus*) is an ecologically and economically important tree species in the northeastern and Great Lakes regions of the U.S. and adjacent portions of Canada. In Maine, white pine is the third most abundant tree species by growing stock volume with 87 million m^3, primarily in the southern portion of the state (Huff and McWilliams, 2016). Between 1997 and 2000 there was noticeable decline and mortality of white pine in dense pole-size stands in southern Maine (Dearborn and Granger, 2001, 1999). The decline and mortality were scattered across southern Maine and appeared simultaneously, indicating that the inciting stress or stresses occurred simultaneously across the region. Symptoms included crown thinning, yellowing of needles, and mortality of dominant and codominant trees. Twenty years later, similar symptoms of decline and mortality are affecting pole-size white pine across a larger region (Costanza et al., 2018).

Declines typically involve multiple factors, not just the inciting stress. Manion (Manion, 1991) described forest decline as a disease complex consisting of predisposing, inciting, and contributing factors. Potential factors in the decline of white pine include, among others, land use history and stand density (predisposing factors), and drought (inciting factor).

Prior to European settlement white pine was a well distributed, but relatively small component of New England forests (Abrams, 2001; Cogbill, 2000; Whitney, 1994). Many white pine stands in that region today originated after agricultural abandonment. In Maine, agricultural land covered more than 2.6 million hectares in 1880 (Ahn et al., 2002), but the number of farms in the state declined by 60–80% by 1940 and nearly 50% of farmland was lost by 1944 (Ahn et al., 2002; Moore and Witham, 1996). Abandonment of these agricultural lands resulted in fields of sod, grass, and litter, all of which offer suitable seedbeds for white pine establishment (Foster, 1992; Glitzenstein et al., 1990; Wendel and Smith, 1990; Whitney, 1994).

The use of plows and grazing of animals on agricultural lands can result in long-lasting changes in soil properties (Foster, 1995).

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Trampling by pastured animals can compact soil structure and increase resistance to soil penetration (Bryant et al., 1972), while the use of plows can create dense zones immediately below the plowed layer, called plow pans (Brady and Weil, 2008). These changes in soil structure reduce soil moisture or oxygen and increase mechanical impedance to root penetration (Bennie, 1991; Nambiar and Sands, 1992; Phillips and Kirkham, 1962). In addition, lithological discontinuity, defined here as fine textured material (loam) over a layer of coarse textured material (sand), can affect white pine rooting (Brown et al., 1961; Horton, 1960). White pine is especially sensitive to these soil problems (Balmer and Williston, 1983), because soil physical structure can impose rooting restrictions (Horton, 1960; Lutz et al., 1937; Stevens, 1931).

Stand density might also play a role in white pine decline. Competition in dense stands reduces water availability, and negatively impacts tree vigor by preventing the development of large crowns (Hunt and Mader, 1970). White pine growing in dense stands and on soils with rooting restrictions are likely predisposed to damage by drought. Drought was present in southern Maine just prior to the observed 1997–2000 decline (Lombard, 2004).

Predisposing factors of historical land use patterns (Christensen, 1989; Foster, 1992), subsequent changes to soil properties affecting rooting depth (Wendel and Smith, 1990), and stand density (Leak and Yamasaki, 2013) may have acted as a disease complex with the inciting factor of drought to cause the observed 1997–2000 white pine decline in Maine. Analysis of tree ring increments can be used to test these hypotheses. Fritts (1974), working with conifers in western North America, found that increases in water stress were followed by reduced net photosynthesis, low accumulation of food reserves, reduced rates of cambial activity, and ultimately the formation of narrow growth rings. In essence, wide and narrow rings – when occurring in the absence of damaging agents such as disease or defoliating insects – can be interpreted as favorable and unfavorable climate variations throughout a tree's life (Fritts, 1976; Glock, 1955).

Specifically, we hypothesized that (i) drought stress occurred just prior to the start of the 1997–2000 decline of white pine across the affected area, and (ii) severity of decline and mortality were highest in dense stands on sites with rooting restriction. The intent of this work is to inform white pine management decisions in both the study area and other regions with similar land use histories and stand characteristics.

2. Methods

2.1. Site and stand data

The study area is located in southern Maine, USA. Because of the localized nature of the decline, sample sites were placed in areas of known high mortality (Dearborn and Granger, 1999). For each high-mortality site, a low-mortality site was established nearby in a mature stand exhibiting few or no dead trees. The paired sites were evaluated in eight locations, all south of 45° N latitude. The site locations occurred in four counties including York (Lebanon, Hollis, Limington, and Massabesic); Cumberland (Casco and New Gloucester); Lincoln (Nobleboro); and Oxford (town of Oxford) (Fig. 1). The stands were predominantly white pine (Table 1). A modified Forest Inventory and Analysis (USDA, Forest Service) sample design consisting of four adjacent circles, each 14.6 m in diameter, was used (Anonymous, 2001). This design created sites with four sub-plots with a total area of 0.07 ha.

Stand measurements for trees included species, crown class (Oliver and Larson, 1996), diameter at breast height (DBH, 1.4 m from the base on the high side), and crown condition (live, red needles, few red needles, no needles) for all trees > 2.5 cm DBH. Basal area (BA) $(3.1415 * ((\mathrm{DBH} * 10^{-2})/2)^2)$ per hectare and stand density (trees ha^{-1}) were calculated for trees > 11.4 cm DBH. Subsets of trees were harvested prior to coring: 16 in Oxford (high-mortality), 18 in Oxford (low-mortality). Cut trees were dead in the high-mortality sites but were living at the time of harvest in the low-mortality sites. The harvesting prescription is unknown. Each stump's narrowest and widest diameters were measured and averaged. DBH was estimated by formulas presented by Westfall (2010). Four pits were dug at each site and averaged to obtain soil depth. Depth was measured to the restrictive layer of plow pan, bedrock, water table, or lithological discontinuity. If no restriction was encountered the soil was measured to a maximum depth of 50 cm. Soils were characterized in terms of agricultural use and/or restrictive layer.

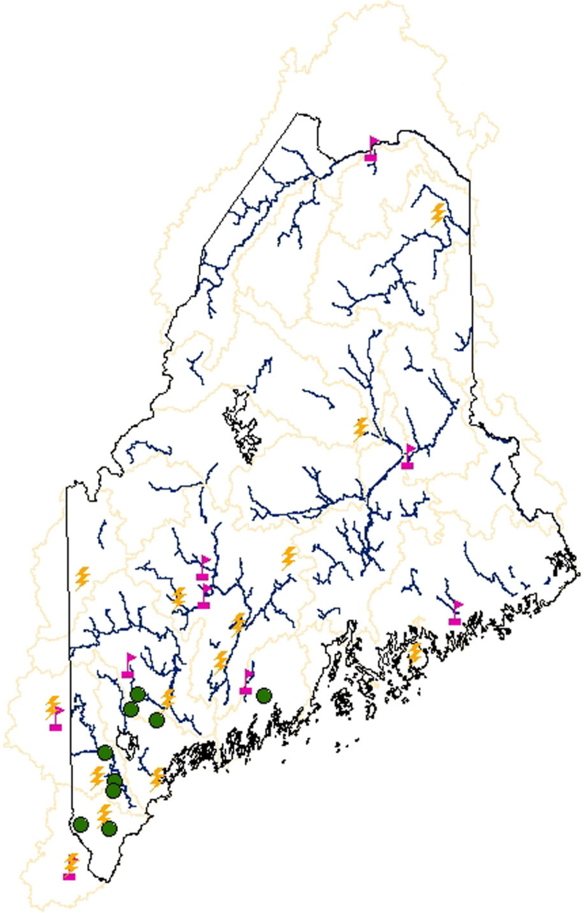

Fig. 1. Locations of paired sites ●, stream gauge stations ⚑, weather stations ⚡, major rivers (blue lines), and watersheds (yellow lines). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2.2. Core data

Along with stand measurements, two increment cores were removed from each living codominant and dominant tree at 90° angles. Dead trees were also cored. Due to the high number of trees at the Massabesic high-mortality site, a subsample of 31 trees was randomly selected from the 46 trees in the sample site for coring. If there were not 12 dominant or codominant white pine within the site, the nearest white pine starting to the north of the site was chosen. This was done for one tree on the low-mortality site in Oxford. The preparation of increment cores was based on the methods described by Stokes and Smiley (1996). Cores were placed in labeled paper straws, allowed to dry at ambient temperature, and mounted on grooved wooden boards so that the tracheids were longitudinal. Cores were then sanded with 100, 250, 350, 400, and 600 grit sandpaper to facilitate counting rings and measuring ring-widths.

Crossdating was used to identify the year in which each ring was formed and assign calendar dates (Fritts, 1976). The outermost ring indicates either the year the sample was taken or, for dead trees, the last

Table 1

Stand data for all trees, > 11.4 cm DBH, and species in high-mortality (H) and low-mortality (L) sites. Standing dead trees are included in the calculations. Mortality is percent of basal area. Standard errors for pooled data are in parentheses under column headings. Paired *t*-tests were calculated for all parameters; means differed (P ≤ .05) for basal area of dead trees and potential rooting depth.

Location	Stand mortality level	Basal area ($m^2 ha^{-1}$) (0.3)	Basal area of white pine (%) (8.5)	Basal area of dead trees (%) (5.1)	Density (stems ha^{-1}) (194)	Potential rooting depth (cm) (2.2)	Soil characteristics
Lebanon (N43°22′ W70°53)	L	26.5	92%	0	400	> 50.0	No evidence of agriculture
	H	30.3	88%	17	771	32.3	Lithological discontinuity
Hollis (N43°38′ W70°38′)	L	37.1	78%	2	563	> 50.0	Possible 1820s plowing
	H	18.4	81%	23	593	23.0	Lithological discontinuity, very old plow layer
Limington (N43°47′ W70°42′)	L	28.2	89%	0	430	39.0	Extra 9″ from flood deposit
	H	40.0	90%	55	815	23.8	Plow pan and lithological discontinuity
Casco (N44°02′ W70°30′)	L	23.3	98%	0	222	39.0	Old plow layer, no pan
	H	25.3	100%	32	563	26.5	Plow layer, no pan, high water table, hard pan, old blueberry field
Nobleboro (N44°07′ W69°27′)	L	37.6	76%	0	370	39.8	Grazing, no pan
	H	20.6	94%	21	415	26.3	Bedrock and grazing
Massabesic (N43°34′ W70°38′)	L	57.2	91%	7	667	42.3	No evidence of plowing or agriculture
	H	43.2	81%	14	1438	24.0	Lithological discontinuity and very old plow layer
New Gloucester (N43°59′ W70°18′)	L	30.6	88%	0	356	> 50	No evidence of plowing or agriculture
	H	34.3	88%	14	667	19.0	Lithological discontinuity
Oxford (N44°07′ W70°27′)	L	37.0	82%	0	474	43.3	No evidence of plowing or agriculture
	H	34.3	85%	43	800	23.3	Plow pan and lithological discontinuity

year of the tree's growth. Rings were measured, and cores were initially crossdated visually using pointer years to identify false or missing rings using Windendro (Regent Instruments, Inc., Quebec, QC, Canada). Dating and homogeneity of the cores were checked with COFECHA (Richard L. Holmes, Laboratory of Tree-Ring Research, University of Arizona, Tucson, Arizona, USA), which calculates cross correlations between individual series and an average chronology (Holmes, 1983). The flagging of a problem area was followed by visual inspection of the core. These processes allowed for the aging of all cores, and determination of year of last growth on dead trees. The stand chronology was based on cores from both live and dead white pine trees (refer to Section 2.4).

2.3. Climate data

Drought is a plausible mechanism for the decline, but consistencies need to be established between decline symptoms and the abiotic stress over the region and time (Johnson et al., 1992). To determine if there were consistencies between high mortality of white pine and drought, we looked at a number of climate parameters including stream flow and precipitation.

Stream flow data from U.S. Geological Survey were used as indicators of water status in the watersheds (Coakley et al., 2001; Lombard, 2004; Stewart et al., 2000). Stream flow is effective because it is affected by all inputs (rain, snow, melt) and outputs (evaporation, transpiration). Monitoring of stations was kept to rivers that are not largely regulated by dams. River data used included measurements from the St. John, Mattawamkeag, Narraguagus, Saco, Carrabassett, Sandy, Little Androscoggin, Sheepscot, and Oyster rivers (Fig. 1). To identify years of extremely low stream flows, stream flows were log transformed to normalize the data, and standard deviations from the daily means for the period of record of stream flows were calculated for 1990–2000. Values were used from the three closest stations to the study area: Little Androscoggin, Oyster, and Sheepscot. The minimum value of each month was used as an indicator of severity of drought stress. Additional watersheds were then evaluated to see if dry conditions for that year extended beyond the region of white pine decline.

The National Centers for Environmental Information (NCEI) (https://www.ncei.noaa.gov/) provided precipitation and temperature data from weather stations throughout Maine and the New Hampshire border including Caribou, Millinocket, Corinna, Middle Dam, Farmington, Acadia National Park, Waterville, North Conway, Augusta, Lewiston, Portland, Buxton, Sanford, and Durham (Fig. 1). Precipitation amounts during the growing season (May to October) were obtained for Lewiston, Portland, and Sanford for 1990–2000 to identify the driest year during the study period. Additional stations were then evaluated to see if dry conditions for that year extended beyond the region of white pine decline. To identify years of extremely low precipitation, the number of standard deviations that observed values differed from the monthly mean for the period of record were calculated.

2.4. Analyses

The two raw core chronologies from each tree were averaged by tree, and the averaged increments were used in additional analyses. Basal area increments (BAI) were calculated by first calculating total BA using the estimated diameter inside bark at DBH (DBH ∗ 0.934) (Dixon and Keyser, 2013). Next, the first increment was subtracted from r (= DBH/2), the smaller BA was calculated and subtracted from the first. BAI values were calculated in this manner for all increments on the tree cores.

To detect the start of declining white pine growth, defined as periods of reduced BAI, the D-score was used, a recently developed metric used to quantify the magnitude of BAI change within a chronology while also accounting for variability (Livingston et al., 2017). The D-score uses the same formula as an independent two-sample *t*-test based on the three-year average BAI before and after each sample year. Dividing by the standard error results in lower values for portions of the chronology that were highly variable and likely did not result from stress-induced decline trends. The relatively short three-year averages allow us to detect shorter trends that develop rapidly. Moreover, this metric is unlikely to detect slower declines resulting from low-level, chronic stress. As such, this approach filters out low-level stress and allows us to better identify stress events or agents that are likely to have more dramatic impacts on tree growth.

The longest chronology from each sample tree was used for assigning tree age at DBH. Paired *t*-tests ($\alpha = 0.05$) were used to compare the depth of soil restrictions between high- and low-mortality sites. Some sites had no soil restrictions to a depth of 50 cm, the maximum depth excavated. Paired *t*-tests ($\alpha = 0.05$) were also calculated to compare basal area and number of stems ha^{-1} between high- and low-mortality sites for all species and for dominant and codominant white pine. For parameters having a variance within a site (DBH, age), paired *t*-tests ($\alpha = 0.05$) were calculated by location. Comparisons of age and DBH for dead and surviving white pine were based on estimated values for 1995.

3. Results and discussion

3.1. Comparison of high- and low-mortality sites

The high-mortality sites had shallow soil restrictions (< 33 cm) at all eight locations. The paired *t*-test indicated that the rooting depth potential of the high-mortality sites (ranging from 19.0 to 32.3 cm, mean = 24.8) was significantly less than that of the low-mortality sites (ranging from 39.0 to > 50 cm, mean = 44.2, $P < .05$) (Table 1). The causes of rooting restrictions on high-mortality sites include plow layers from earlier agricultural use (two locations), high water table (one location), shallow bedrock (one location), or lithological discontinuities (five locations). Overall, soils were well drained, sandy loams except for gravelly sandy loams in Oxford and sandy loam with outcrops at the high-mortality site in Nobleboro. Because these study sites were dominated by a cohort of mature white pine of approximately 40–50 years old (Table 1) and without the presence of large stumps, it was assumed that the land had been cleared for agricultural use such as blueberry fields, grazing, or cultivation prior to the establishment of these stands.

The low-mortality sites also had evidence of soil change due to agriculture within the last 100 years (four locations), but all low-mortality sites had rooting restrictions that were at or deeper than 39 cm (Table 1). The implications of these historical activities mean that white pine stands were sometimes established on sites to which the species is not well adapted, i.e., sites with soil restrictions (high-mortality sites in the present study). In other cases, although the agricultural use allowed for establishment of white pine, it was not on areas of soil restrictions and therefore trees were not predisposed to drought stress (low-mortality sites).

Although dead white pine stems were found on low-mortality sites, the numbers were significantly less than the number of dead white pine found on high-mortality sites ($P < .05$) (Table 1). This evidence supports the hypothesis that shallow rooting depth, to which white pine is sensitive (Brown et al., 1961; Horton, 1960), predisposed the species to other stresses.

Differences between the high- and low-mortality stands became more apparent in statistical tests conducted exclusively on dominant and codominant white pine. The basal area per hectare for dominant and codominant white pine was not significantly different between the two types of stands; however, the low-mortality stands had significantly fewer dominant and codominant stems per hectare ($P < .05$) with significantly larger diameters ($P < .05$) (Table 2).

There are several explanations for these structural differences in the white pine of the high- and low-mortality stands. Primarily, the age of the high-mortality sites was significantly younger ($P < .05$) (43–61 years at DBH) than that of low-mortality sites (48–114 years) (Table 2). The age difference may mean that the high-mortality stands are growing on more recently abandoned farmland which could imply that the land was farmed longer, leaving a longer legacy of use resulting in more soil compaction or plow pans. Another implication of the difference in ages may be that the older stands have already gone through a process of competition-induced self-thinning as indicated by their lower number of stems per hectare.

The intense competition for soil resources in the high-mortality sites is made more acute due to rooting depth restrictions. The high number of stems, along with the restricted rooting depth, predispose the stands to decline and mortality.

Densities of the stands were compared with New England white pine stocking guides (Leak and Lamson, 1999). The A-line represents 100 percent stocking, the B-line represents recommended stocking for full site utilization, and the C-line indicates the lower density limit at which crown closure can still be attained (Seymour and Smith, 1987). The lower densities of the C-lines are recommended for crop-tree management of white pine (Leak and Yamasaki, 2013; Seymour, 2007). The lower C-line limit for an unmanaged white pine stand with a 20 cm average DBH, for example, is about 530 trees ha^{-1}, while the lower B-line limit is about 680 trees ha^{-1} (Leak and Lamson, 1999). In our study, high-mortality plots were more heavily stocked on average than low-mortality plots before the decline (Table 3). However, after reducing stand densities to those of surviving trees, stocking in seven of eight high-mortality plots fell below the B-line. Overall, decline-induced mortality in the high-mortality sites reduced stand densities to levels more common in the less densely stocked low-mortality sites.

3.2. Comparison of surviving and dead white pine on high-mortality sites

The mean difference in increments between dead and surviving white pine trees indicated that high-mortality sites had periods of 25 or 26 years during which dead trees had smaller BAI than surviving trees (Table 4, Fig. 2). The more conservative test using differences greater than two standard errors resulted in five sites having more than ten years of significant growth separation and three sites having between two and four years significant growth separation. The average DBH of the dead trees at each site was less than that of the surviving trees (Table 4). The ages of the dead and surviving trees were not significantly different, indicating that trees that died during the suspected decline period were not younger but growing slower.

The data are consistent with natural thinning processes in which trees that have been able to acquire adequate rooting space and/or intercept adequate amounts of light can put more energy toward growth and compete better than trees that are limited by available resources (Long and Smith, 1984). This competition, as available growing space becomes fully occupied, often leads to accelerated size differentiation. This is because subordinate trees manufacture less gross photosynthate than more vigorous trees and put less toward growth, therefore declining in growth (Oliver and Larson, 1996). During the stem exclusion stage, the trees of pure stands compete fiercely with each other mainly because they all have crowns in the same stratum (Smith, 1997).

3.3. Comparison of mortality, growth, and drought

Drought stress can lead to growth decline, dieback and mortality in white pine (Vose and Swank, 1994), leading to the second hypothesis that drought incited the decline of white pine in southern Maine. Analysis for drought conditions focused on the growing season of white pine, which is approximately May to October.

The timing of a drought is important because as temperatures increase, evapotranspiration losses increase making available water even more limiting to tree growth (Clinton et al., 1997). Stream flow data

Table 2

Dominant and codominant white pine, > 11.4 cm DBH, on low- (L) and high-mortality (H) sites. Standing dead trees are included in basal area, DBH, stem density and age. Age and DBH are estimated for 1995, based on increment cores. Numbers of living and dead stems represent the number of stems found within the sampling site. Numbers in parentheses in the "cores" column indicate number of trees cored outside the sample site; these measurements are only included in the calculations of D-scores (Fig. 4). Standard errors for *t*-tests (DBH, age) are in parentheses next to the mean values; asterisks indicate significant differences between low- and high-mortality sites ($P \le .05$). Standard errors for pooled data (basal area, density) are next to the headings; only density differed ($P \le .05$) between low- and high-mortality sites.

Location	Stand	Basal area (m^{2} ha^{-1}) (0.3)	DBH (cm)	Density (stems ha^{-1}) (60)	Living trees		Dead trees		Age
					# of stems	# of cores	# of stems	# of cores	
Lebanon	L	24.3	34.6* (5.5)	252	17	17	0	0	77* (2)
	H	26.6	23.6* (6.6)	563	27	22	11	8	51* (1)
Hollis	L	29.1	41.3* (8.0)	207	13	13	1	0	96* (2)
	H	14.8	22.5* (4.1)	356	15	13	9	7	47* (1)
Limington	L	25.0	31.6* (8.2)	296	20	20	0	0	48 (1)
	H	36.1	26.0* (5.2)	652	15	13	29	29	46 (1)
Casco	L	22.8	37.0* (5.2)	207	14	14	0	0	62* (1)
	H	25.3	23.3* (4.7)	563	22	17	16	14	46* (1)
Nobleboro	L	28.63	43.2* (11.6)	192	13	13	0	0	64* (2)
	H	19.4	23.9* (8.2)	370	18	18	7	6	51* (2)
Massabesic	L	51.9	37.5* (5.7)	459	28	26	3	3	114* (1)
	H	34.9	21.9* (4.6)	874	46	31	13	8	43* (0)
New Gloucester	L	26.9	41.5* (7.4)	193	13	12	0	0	84* (1)
	H	30.2	28.4* (7.4)	445	22	22	8	8	61* (1)
Oxford	L	30.2	28.1* (5.6)	282	19	12(1)	0	0	76* (2)
	H	29.2	21.6* (6.0)	577	21	20	18	8	46* (1)

collected from 1990–2001 on the Little Androscoggin, Oyster, and Sheepscot rivers, which most closely surround the study area, show that consecutive and extremely low stream flows in August and September were unique to 1995, relative to the 12-year period (Table 5). In addition, the flow of the Little Androscoggin River during years of drought (1965, 1987, and 1995) (Lombard, 2004) shows 1995 was the most extreme case of low stream flow (Fig. 3). The data indicate that for the entire period of record, stream flows of 1995 in the Little Androscoggin from mid-August to mid-September were indicative of unprecedented drought conditions.

Stream flows throughout Maine and New Hampshire in 1995 were analyzed to determine whether the drought was localized or apparent throughout the region. The stream flow data indicated that only one river in northern Maine, the Mattawamkeag River, and two in southern Maine, the Little Androscoggin and Sheepscot rivers, had stream flows that were greater than two standard deviations below normal in both August and September of 1995 (Table 6). Closer inspection of the stream flow data showed that both the Little Androscoggin and the Sheepscot rivers had low stream flows earlier in the season (May) indicating the available water in these areas may have been low before August (Table 6), i.e. low snow melt or earlier snow melt, which would have imposed greater water stress on the surrounding trees. Although the Mattawamkeag River showed similar drought conditions, the absence of white pine decline in that area is likely due to differences in historical land use. There were no reports of extensive field abandonment and establishment of white pine in northern Maine, as was the case in southern and central Maine (Ahn et al., 2002; Hart, 1968; Moore and Witham, 1996).

Precipitation data did not show as clear a pattern for drought as stream flows. Total growing season precipitation was reviewed for Lewiston, Portland, and Sanford. Though precipitation varied, 1995 was one of the driest growing seasons between 1990 and 2001 (Table 7). Precipitation data throughout the region in the 1995 growing season were particularly inconsistent (Table 8). This suggests that although the summer was dry, some areas were receiving more rain than others within the region of white pine decline. Therefore, it is possible that not all susceptible stands with shallow rooting depth potentials were affected by drought.

In accordance with the drought period, crossdating of the tree rings from trees in the study stands shows a high mortality of white pine from 1995 to 1998 with peak mortality in 1996 to 1997 (Table 9). In addition, pooled BAI and D-score comparisons between high-mortality and low-mortality plots indicate that the greatest BAI decline during this period was in 1996 (Fig. 4). There is thus substantial evidence that the

Table 3

Changes in DBH (cm), BA (m^{2} ha^{-1}), and density (stems ha^{-1}) after mortality of white pine (> 11.4 cm DBH) on low- (L) and high-mortality (H) plots. DBH increased on all high-mortality plots while BA and density decreased.

Location	Stand	DBH before	Density before	BA before	Below B-line stocking	DBH after	BA after	Density after	Below B-line stocking
Lebanon	L	26.8	400	26.5	Y	26.8	26.5	400	Y
	H	21.3	771	30.3	N	23.0	25.0	548	Y
Hollis	L	25.4	563	37.1	N	25.6	35.1	519	N
	H	19.0	593	18.4	Y	21.6	12.9	326	Y
Limington	L	27.1	430	28.2	Y	27.1	28.2	430	Y
	H	24.2	815	40.0	N	29.7	16.7	237	Y
Casco	L	35.9	222	23.3	Y	37.0	22.8	207	Y
	H	23.3	563	25.3	Y	25.6	17.3	326	Y
Nobleboro	L	32.1	370	37.6	N	32.1	37.6	371	N
	H	23.8	415	20.6	Y	25.3	16.3	296	Y
Massabesic	L	31.3	667	57.2	N	31.3	53.5	622	N
	H	18.7	1438	43.2	N	20.3	35.0	993	N
New Gloucester	L	30.1	356	30.6	Y	36.0	28.5	252	Y
	H	24.0	667	34.3	N	27.3	28.1	430	Y
Oxford	L	29.8	474	37.0	N	30.6	36.2	445	N
	H	22.3	800	34.3	N	23.6	19.5	415	Y

Table 4

Dominant and codominant white pine on high-mortality sites. Age and DBH are based on estimated values prior to and including 1995, based on increment cores. The first column for the period of growth separation indicates number of years from 1970 to 1995 that the mean basal area increments for white pine that died were smaller than the trees that survived. The second column shows the number of years that differed more than two standard errors from each basal increment mean. Standard *t*-tests were calculated for age and DBH data by location. Standard errors for age and DBH are shown in parentheses; asterisks (*) indicate $P \le .05$.

Location	Surviving stems	Dead stems	Mean 1995 age surviving	Mean 1995 age dead	1995 DBH live (cm)	1995 DBH dead (cm)	Number of stems that died						Period of growth separation (mean)	Period of growth separation (> 2 SE)
							'90–'94	'95	'96	'97	'98	Post '98		
Lebanon	27	11	48 (1)	43 (2)	24.5* (1.4)	17.9* (1.1)		2	3	3			26	15
Hollis	15	9	44 (1)	43 (1)	23.7* (1.0)	18.1* (0.6)		1	2	3	1		25	20
Limington	15	29	44 (1)	43 (1)	29.6* (0.9)	23.6* (0.9)		2	9	11	7		26	17
Casco	22	16	43 (1)	42 (1)	24.6* (1.0)	19.0* (0.9)	1	2	3	6	2		26	4
Nobleboro	18	7	47 (2)	43 (2)	25.1 (1.9)	19.2 (3.1)		2		2	2		26	2
Massabesic	46	13	37 (0)	38 (2)	21.8* (0.8)	16.6* (1.0)				2	2	4	26	17
New Gloucester	22	8	57 (2)	55 (1)	30.4* (1.5)	20.7* (0.9)			3	3	2		26	26
Oxford	21	18	42 (1)	39 (1)	24.1* (1.3)	19.5* (1.7)	1		6		1		26	4

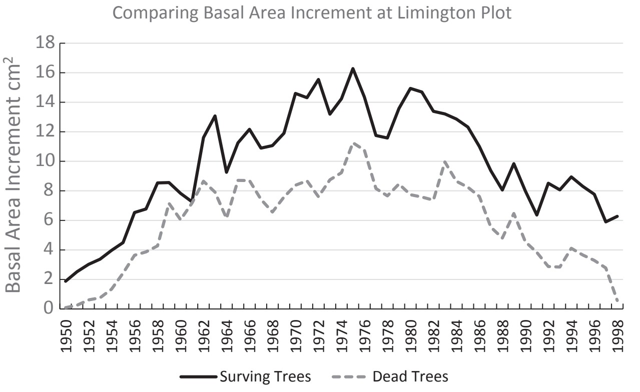

Fig. 2. Average basal area increments of surviving versus dead trees for the Limington high-mortality site.

Table 5

Standard deviations from the daily mean of stream flow (ln(ft^3 min^{-1})) for the period of record (see Table 6) for August and September in years 1990–2001 for Little Androscoggin River, ME, Oyster River, NH, and Sheepscot River, ME. Values shown are the minimum value for the month. Values greater than two standard deviations from the mean are in bold.

Year	Little Androscoggin		Oyster River		Sheepscot	
	August	September	August	September	August	September
1990	−1.4	−0.7	−0.8	−0.2	0.6	0.1
1991	−1.8	−0.5	−0.9	0.6	**−2.1**	0.0
1992	−0.2	−0.6	0.3	−0.5	−0.3	−0.6
1993	−1.5	−1.5	−1.1	−1.5	−0.9	−0.5
1994	−1.3	−1.2	−1.6	−0.8	−0.8	−1.3
1995	**−2.8**	**−2.8**	−1.7	−1.9	**−2.1**	**−2.6**
1996	−0.7	−1.0	−0.7	−0.8	0.0	0.1
1997	−1.1	−0.5	−1.3	−0.6	−0.8	−0.8
1998	−0.6	−1.1	−0.4	−0.8	−0.6	−1.0
1999	−1.3	−1.6	**−3.2**	**−4.6**	−1.6	−1.7
2000	−0.2	−1.4	−0.6	−0.7	−0.5	−0.9
2001	−1.9	**−2.2**	−1.8	−1.4	−1.7	−1.3

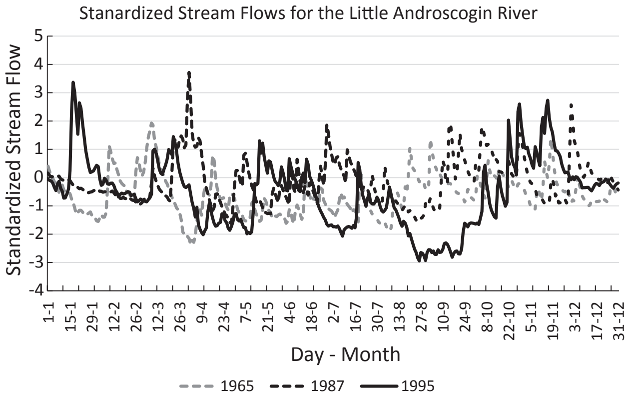

Fig. 3. Standard deviations from the daily mean stream flow (ln(ft^3 min^{-1}) of Little Androscoggin River for growing seasons in 1965, 1987, and 1995 representing periods of drought (Lombard, 2004).

inciting stress was the drought of 1995. The drought happened late in the 1995 growing season. Fritts, Smith, and Stokes (Fritts et al., 1965) suggest that unusually dry and warm conditions in the year prior to growth could affect the following season's growth. Because climatic events during one year can physiologically precondition a tree's potential for growth the next year (Fritts, 1974; Lyon, 1936), a drought late in 1995 would logically result in reduced growth or mortality in 1996 and 1997. The sequence of events in white pine decline were drought in 1995, followed by a last year of growth in 1996 and 1997 on dying trees, and reported appearance of visible symptoms (red needles) beginning in 1997.

The clear relationship between year of drought (1995) and subsequent year of last growth (1996 or 1997) supports the hypothesis that drought incited the observed white pine mortality event. A clear growth decline could not be identified in low-mortality plots, indicating that they were not predisposed to drought injury. Low-mortality plots had relatively consistent levels of BAI, while BAI of trees on high-mortality plots was decreasing (Fig. 4a). This observation indicates that growth and vigor of trees on the latter plots were at lower levels for a couple of decades. Surprisingly, the D-scores were similar between trees in both mortality categories prior to 1993, indicating that trees in both categories were responding to environmental factors in a similar manner. Apparently, after 1993, the higher D-scores on the high-mortality plots indicate trees had reached a stage of development that could no longer be sustained on the sites with rooting restrictions during a severe drought.

Table 6
Minimum standard deviations from the daily mean stream flow ($\ln(\text{ft}^3\,\text{min}^{-1})$) for the period of record for each river throughout the region during the 1995 growing season. Values shown are the minimum value for the month. Values greater than two standard deviations from the mean are in bold.

Station	Period of record (yrs)	May	June	July	August	September	October
St. John	76	−0.8	−1.7	−1.9	−1.6	**−2.0**	−1.7
Mattawamkeag	68	−0.7	−0.8	−1.7	**−2.2**	**−2.3**	**−2.2**
Narraguagus	54	−1.2	−0.7	−0.9	−1.3	−1.3	−1.4
Saco	99	**−2.2**	−1.5	−1.5	−1.4	−1.5	−1.4
Carrabassett	100	**−2.0**	−1.5	−1.3	−1.4	−1.6	−1.3
Sandy	74	**−2.1**	−1.5	−1.3	−1.6	−1.7	−1.4
Little Androscoggin	89	**−2.0**	−1.7	**−2.1**	**−2.8**	**−2.8**	−1.8
Sheepscot	72	**−2.0**	−0.4	−1.1	**−2.1**	**−2.6**	−1.4
Oyster	67	**−2.1**	−1.1	−1.3	−1.7	−1.9	−1.5

Table 7
Total precipitation in cm and standardized values for growing season (May-October) for years 1990–2001 at weather stations in Lewiston, Portland and Sanford. Standardized values represent number of standard deviations of that year's value from the overall mean calculated for the station's period of record.

Year	Total precipitation (cm)			Standardized values		
	Lewiston	Portland	Sanford	Lewiston	Portland	Sanford
1990	54.4	44.7	46.0	1.2	0.4	0.0
1991	58.7	71.9	66.8	1.6	2.9	1.9
1992	34.5	37.8	42.7	−0.8	−0.2	−0.3
1993	29.5	30.7	32.5	−1.2	−0.9	−1.3
1994	46.0	34.0	57.7	0.4	−0.6	1.1
1995	33.0	30.2	36.3	−0.9	−0.9	−0.9
1996	47.2	40.1	44.2	0.5	0.0	−0.2
1997	38.9	30.5	45.0	−0.3	−0.9	−0.1
1998	48.8	57.9	64.8	0.6	1.6	1.7
1999	59.4	45.5	59.7	1.7	0.5	1.2
2000	39.1	34.0	48.5	−0.3	−0.6	0.2
2001	29.3	35.5	40.6	−1.3	−0.4	−0.5

Table 9
Percentage of dead trees with last tree ring in a given year on high- and low-mortality sites. Data were pooled for all locations (Table 4).

Year of last ring	High-mortality sites % dead trees n = 88	Low-mortality sites % dead trees n = 3
1990	1%	0%
1991	0%	0%
1992	0%	0%
1993	0%	0%
1994	1%	0%
1995	9%	0%
1996	31%	67%
1997	33%	33%
1998	19%	0%
1999	2%	0%
2000	1%	0%
2001	2%	0%

3.4. Other considerations

Investigations of 88 dead trees on the sites revealed 63.6% had *Cerambycidae*, 60.2% had *Ips* spp., and 56.8% had *Armillaria* spp. The lack of a single pest occurring on most dead and dying trees suggests that these pests were secondary organisms after the trees became stressed by drought.

Recent studies have implicated *Caliciopsis pinea* as an important stem pathogen on declining white pine trees (Costanza et al., 2018). Measurements of symptoms of *Caliciopsis* infections were not made in this study, but factors associated with decline and mortality of white pine in this study are similar to factors associated with *Caliciopsis* infections as observed in recent studies (Costanza et al., 2018). Whether this fungal pathogen was a contributing factor in the 1997–2000 drought-incited decline of white pine in southern Maine is not known.

Along with changes in soil structure, land use can often lead to changes in the nutrient composition of the soil (Paoletti et al., 1993) but were not analyzed in this study. A year with high seed production (Koenig and Knops, 1998), needle cast fungi (McIntire et al., 2018), or a year with defoliation (Mayfield et al., 2005) can reduce BAI, but no high amounts of cone production, needle cast fungi, or defoliation were observed or reported by others during the periods of narrow increments in 1995 and 1996.

Winter thaw-freeze fluctuations have been associated with tree decline in the past. A series of thaw-freeze events has been proposed as an

Table 8
Total monthly precipitation (cm) and standardized values of precipitation during the 1995 growing season in Maine and neighboring stations in New Hampshire. Standardized values represent number of standard deviations of that year's value from the overall mean calculated for the station's period of record.

Station	Total monthly precipitation (cm)							Standardized values						
	May	June	July	Aug.	Sept.	Oct.	Total	May	June	July	Aug.	Sept.	Oct.	Total
Caribou	6.2	3.0	3.8	7.5	4.8	13.0	38.3	−0.5	−1.6	−1.7	−0.5	−0.9	1.3	−2.1
Millinocket	8.9	5.9	8.9	4.0	7.4	17.3	52.4	0.2	−0.7	−0.2	−1.2	−0.4	1.8	−1.1
Corinna	12.0	6.1	5.9	2.5	4.6	15.0	46.1	0.6	−0.7	−0.7	−1.3	−1.0	1.4	−1.2
Middle Dam	9.0	2.1	11.4	4.5	6.1	23.9	57.0	0.2	−1.8	0.4	−1.1	−0.7	3.6	−1.5
Farmington	11.4	3.1	8.2	1.4	4.4	22.4	50.9	0.4	−1.5	−0.3	−1.6	−1.1	2.4	−1.9
Acadia NP	18.7	8.8	9.3	1.4	5.1	12.8	56.1	1.0	−1.0	0.1	−1.1	−0.9	0.2	−0.4
Waterville	9.1	7.9	7.0	0.9	5.7	18.3	48.9	0.1	−0.2	−0.3	−1.7	−0.7	2.0	−1.2
North Conway, NH	6.7	5.0	14.6	5.5	6.0	25.5	63.3	−0.5	−0.9	1.0	−0.9	−0.7	2.2	−1.0
Augusta	8.7	5.5	6.3	1.5	5.7	17.0	44.7	−0.1	−0.7	−0.5	−1.5	−0.5	1.7	−1.5
Lewiston	9.0	5.5	9.1	3.5	5.7	17.5	50.3	0.1	−0.7	0.1	−0.9	−0.6	1.7	−0.9
Portland	8.4	6.6	8.0	1.2	6.1	12.2	42.5	−0.1	−0.3	0.1	−1.1	−0.5	0.3	−0.9
Buxton	8.1	8.4	12.3	4.4	6.4	19.4	59.0	−0.2	−0.1	0.7	−0.8	−0.6	1.5	−0.4
Sanford	8.6	5.2	8.7	5.4	8.6	18.9	55.4	−0.1	−0.7	−0.1	−0.6	−0.2	1.5	−0.9
Durham, NH	7.0	4.7	9.6	6.9	7.1	16.6	51.9	−0.3	−0.7	0.2	−0.3	−0.3	1.4	−0.7

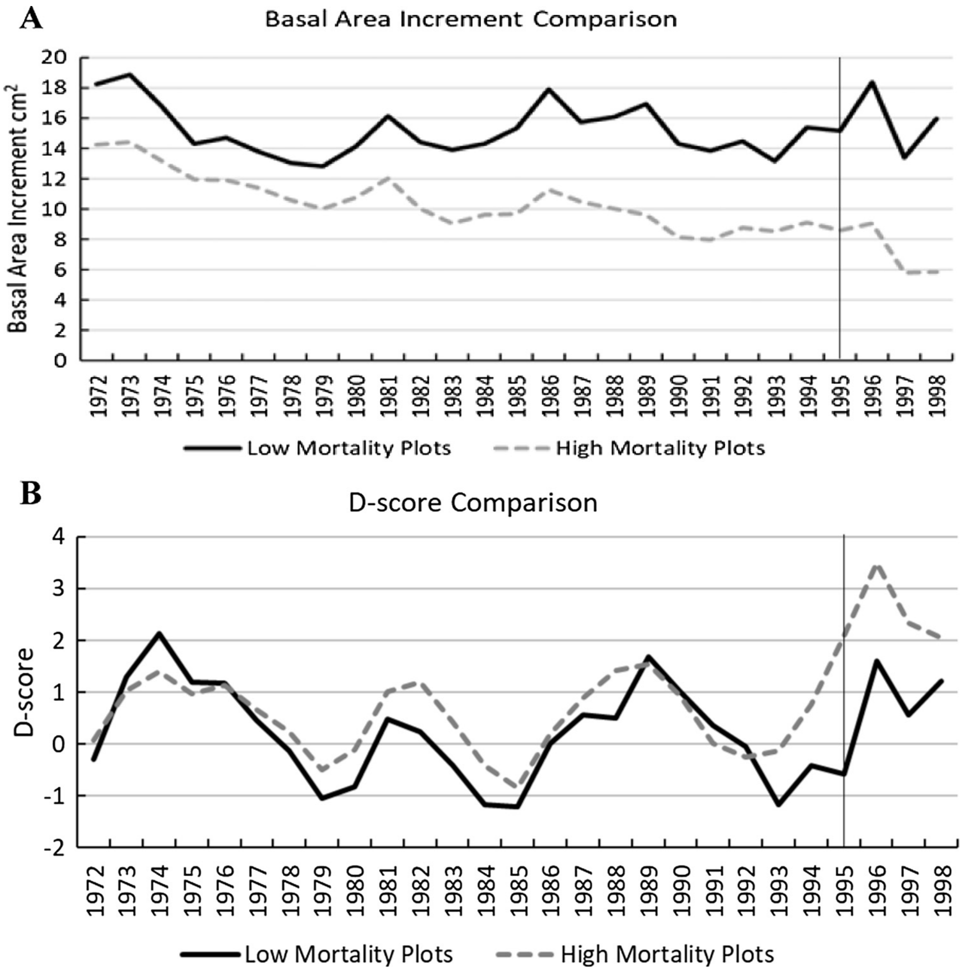

Fig. 4. Comparing basal area increment trends (A) and D-score trends (B) from 1972–1998 between low-mortality and high-mortality plots. Tree data were pooled, and averages calculated for each year. Vertical line indicates 1995, the year of the drought.

inciting stress in the 1935–1936 winter decline ("pole blight") in western white pine (*Pinus monticola*) in British Columbia and the Pacific Northwest (Auclair et al., 1992). The shallow rooting depth of the white pine in our study sites suggests an opportunity for root damage during thaw-freeze events. There is limited literature of the actual temperatures of white pine freezing tolerance, but it has been shown that at least the needles and stems have a minimum cold tolerance of −6 °C to −8 °C in the spring and a maximum of approximately −40 °C to −80 °C in winter (Bigras and Colombo, 2001). There is no actual literature on root hardiness of white pine. However, studies of root hardiness in seedlings of Norway spruce (*Picea abies*) and Scots pine (*Pinus sylvestris*) indicate that root growth capacity declined at temperatures of −6 °C to −11 °C, but there was no cessation of potential growth until soil temperatures reached at least −15 °C to −16 °C (Stattin and Lindström, 1994). Climate data from the NCEI indicate that during the winter of 1995 the lowest air temperatures of −24 °C to −25 °C happened in January and February when conifers are most cold hardy and were accompanied by at least 23 cm of insulating snow cover. In February 1996 Durham had a minimum temperature of −28 °C, accompanied by 15 cm of snow. Conversely Sanford had a minimum recorded temperature of −27 °C that was not accompanied by any snow and therefore rooting damage could have occurred. However, mean temperature for the month of February in Sanford was −4 °C, and it is therefore unlikely that soil temperatures were cold enough to induce root damage. This was a localized event that suggests it would not have influenced the growth of white pine throughout the study area. In addition, the data do not indicate any occurrence of a thaw-freeze event.

Although the stands were predominantly white pine, there were other species present, up to 32% of the BA (Table 1). The most represented species included red maple (*Acer rubrum*) and red oak (*Quercus rubra*), which were found in eight of the 16 sites. There was no visual evidence of decline in the crowns of either species.

3.5. Management implications

Throughout its range, white pine has been effectively regenerated with the shelterwood (uniform or irregular) method, particularly if the establishment cut is timed to coincide with a good seed year (Arseneault et al., 2011; Lancaster and Leak, 1978; Seymour, 1995). The present study suggests that this species will grow better and be less susceptible to drought-induced decline if trees are grown on sites without factors limiting rooting depth, such as bedrock, lithological discontinuities, plow pans, and high-water tables. As white pine stands reach 15 cm DBH, Seymour (2007) and Leak and Yamasaki (2013) recommend low-density management for improved growth, with a target residual density of about 330 stems ha^{-1} and 25 m^2 ha^{-1} of basal area by the time trees reach 30 cm DBH. The present study suggests that another benefit of low-density management is increased resistance to drought-induced decline. Stand densities in declining stands were reduced through mortality to levels more common in nearby non-decline stands; those densities correspond to recommendations for low-density management of previously unmanaged white pine stands (i.e., 330–540 trees ha^{-1} and 17–25 m^2 ha^{-1} of basal area at 20–30 cm

DBH).

In addition to releasing the best trees in upper crown classes (i.e., crop trees), intermediate treatments aimed at improving forest health should include removal of poor-vigor trees from lower crown classes; such smaller trees where the ones killed by the 1995 drought (Table 4). Through this combination of low and crown thinning, white pine stands can be managed both for rapid development of high-value crop trees (Seymour, 2007) and increased resistance to drought-induced growth decline. Where tree quality is an objective, pruning to a height of 5–8 m can be conducted after thinning to increase recovery of clear, high-value butt logs (Seymour, 2007; Smith and Seymour, 1986). It has been shown that the return of clear lumber justifies the cost of intensive white pine management practices such as pruning (Page and Smith, 1994), providing further impetus to manage stands at low densities to reduce drought stress.

4. Conclusion

Historical agricultural use and subsequent land abandonment resulted in the establishment of even-aged, monotypic white pine stands in many parts of its current range. Some of these white pine stands are growing on sites where soil structure impedes rooting depth. The evidence found in this study supports the hypothesis that shallow rooting depth can predispose white pine to other stresses. Our data also suggest that high stand stocking acts as additional predisposing factor on these sites. The high incidence of white pine mortality observed in southern Maine in 1997–2000 correlated well with a 1995 drought that is likely the inciting stress of the decline. Low-density management is recommended to minimize the risk of white pine decline and mortality, and is consistent with silvicultural guidelines for production of high-value white pine sawtimber.

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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.2017.12.047.

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