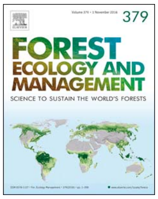
Forest Ecology and Management xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco



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

William H. Livingston[a,*], Laura S. Kenefic[b]

[a] University of Maine, 5755 Nutting Hall, Orono, ME 04469, USA
[b] USDA Forest Service, Northern Research Station, 54 Government Road, Bradley, ME 04411, USA

ARTICLE INFO

Keywords:
Pinus strobus
Predisposing factors
Forest health
Silviculture
Thinning
Drought
Tree decline

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). Trampling by pastured animals can compact soil structure and increase

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* Corresponding author.
E-mail addresses: WilliamL@maine.edu (W.H. Livingston), lkenefic@fs.fed.us (L.S. Kenefic).

https://doi.org/10.1016/j.foreco.2017.12.047
Received 31 October 2017; Received in revised form 29 December 2017; Accepted 29 December 2017
0378-1127/

Please cite this article as: Livingston, W.H., Forest Ecology and Management (2018), https://doi.org/10.1016/j.foreco.2017.12.047

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.

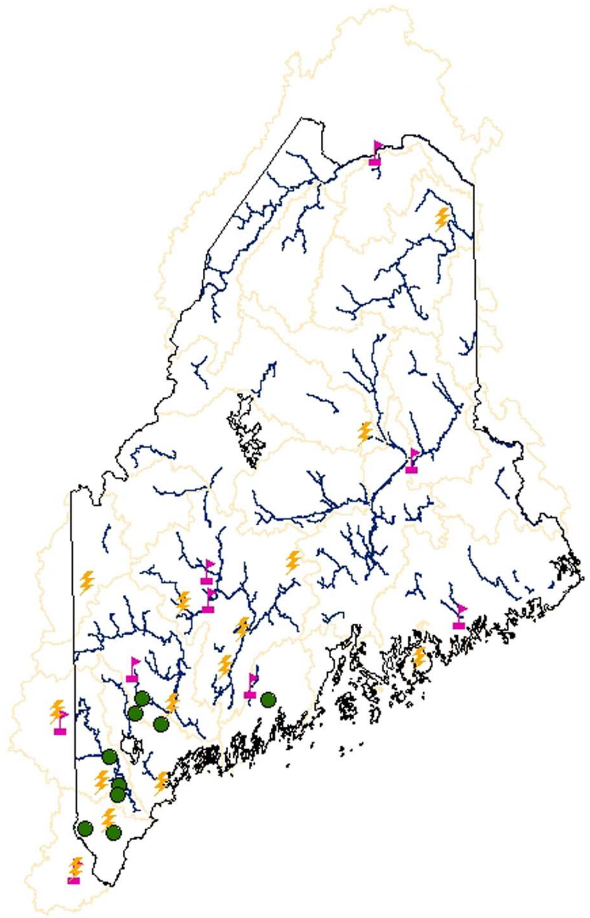

Fig. 1. Locations of paired sites ●, stream gauge stations ⚑, weather stations ⚡, major rivers (blue lines), and watersheds (yellow lines). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

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