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Relationships between Rooting Restrictions, Radial Growth, and Drought Stress with White Pine (Pinus strobus) Decline in Southern Maine

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RELATIONSHIPS BETWEEN ROOTING RESTRICTIONS, RADIAL GROWTH, AND DROUGHT STRESS WITH WHITE PINE (*PINUS STROBUS*) DECLINE IN SOUTHERN MAINE

By

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B.S. State University of New York at Buffalo, 1999

A THESIS

Submitted in Partial Fulfillment of the

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(in Forestry)

The Graduate School

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August, 2002

Advisory Committee:

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By Megan L. Fries

Thesis Advisor: Dr. William H. Livingston

An Abstract of the Thesis Presented
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Throughout southern Maine there was a noticeable decline and mortality of white pine (*Pinus strobus*) from 1997 through 2000 in dense pole-size stands. The decline was widespread, scattered, and happened simultaneously indicating that it was incited by an abiotic stress. Because only isolated stands showed decline and mortality, site factors likely predisposed trees to injury.

Site factors are likely related to the widespread field abandonment that took place throughout southern and central Maine, and led to establishment of pure white pine stands in many areas. Although white pine can regenerate on many sites, some locations

will have soil limitations, such as plow plans and lithological discontinuities that cause white pine roots to spread more horizontally. A shallow root system would result in less water being available to a tree during a drought.

The first hypothesis is that soil rooting restrictions predisposed the white pine to water stress inciting decline and mortality. The second hypothesis follows that the drought event occurred prior to 1997-2000, the period of white pine mortality.

Paired sites, consisting of one high and one low mortality site, were evaluated in nine locations in Maine south of 45° N latitude in the towns of Wells, Lebanon, Hollis, Limington, Casco, Nobleboro, Massabesic, New Gloucester and Oxford. Tree species, crown class, crown condition, and diameter at breast height (DBH) were recorded at each stand. Two cores were removed from each dominant and codominant white pine, including dead trees, for dendrochronological analysis. Crossdating of cores was used to calculate the percentage of dead trees with the last growth ring in a given calendar year. Average annual increments between dead and surviving trees were compared on each high mortality site using mean ring widths. Potential rooting depth was measured in each site.

Stream flow, precipitation, temperature, and Palmer Drought Severity Index (PDSI) were used with the program PRECON to look at long term relationships between climate and growth.

Paired t-tests were used to evaluate differences in basal area, stems/ha, and potential rooting depth on high and low mortality sites. Standard t-tests were calculated by location for differences in DBH, age, and number of years of decline of white pine between high and low mortality sites and between dead and surviving white pine on high mortality sites.

High mortality sites had restrictive soil layers (ranging from 19.0 cm to 26.5 cm) that were significantly shallower than low mortality (ranging from 39 cm to >50 cm) sites at all nine locations. White pines on high mortality sites were significantly younger (49 yr) than those on low mortality sites (78 yr). High mortality sites also had significantly higher density of white pine (495 stems/ha) than low mortality sites (273 stems/ha). Trees that died had smaller DBH (20.8 cm) than those that survived (26.5 cm). I conclude that shallow rooting depth and high stem density predisposed trees to mortality induced by drought stress. Climate data suggest that a drought in 1995 was the inciting factor for the decline. Most predisposed trees died from 1995 to 1998 with peak mortalities in 1996 (30 %) and 1997 (34 %).

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CHAPTER 1: INTRODUCTION

Throughout southern Maine there was a noticeable decline and mortality of white pine (*Pinus strobus*) from 1997-2000 in dense pole-size stands. The symptoms included crown thinning, yellowing of needles, and mortality of dominant and codominant trees. The decline and mortality were scattered, widespread, and happened simultaneously, indicating that the inciting stress occurred simultaneously across the region.

Declines typically involve multiple factors, not just the inciting stress (Sinclair 1965, Manion 1991). Manion (1991) describes forest decline as a disease complex consisting of predisposing, inciting, and contributing factors. Predisposition to decline is hypothesized to arise gradually due to an adverse microenvironment, increasing competition from neighboring trees, or as one or more growth shocks due to physical damage (McClenahen 1995), all of which can impede a tree's ability to endure stress. Pedersen (1998), in investigating oak (*Quercus* spp. L.) overstory mortality, described predisposing factors as the long-term stresses that predisposed oak to injury by short term, inciting factors.

Inciting factors are those that can substantially reduce tree vigor by impeding physiological processes (McClenahen 1995). In some cases severe predisposing and/or inciting factors can lead to a tree's inability to regain full vigor, or even mortality. However, if a tree does not recover from an inciting stress, mortality is often a result of contributing factors such as weak pathogens (Manion 1991).

This study investigated likely predisposing and inciting factors causing mortality of white pine decline in southern Maine. Because forest decline can often be traced to historical land use patterns (Christensen 1989), it was imperative to understand how historical land use in and around the study areas could influence long-term sites characteristics as predisposing factors to decline. One key site factor known to adversely affect white pine growth is rooting depth (Wendel and Smith 1990, Steve Howell, personal communication 2001). White pine is especially sensitive to physical problems in the soil such as poor drainage, hardpans, and high plasticity (Balmer and Williston 1983) because these changes in soil physical structure can impose rooting restrictions (Stevens 1931, Lutz et al. 1937, Horton 1960).

Historical Land-Use

Much of the current widespread distribution of white pine is due to abandonment of agricultural fields. The number of farms in Maine peaked in 1880, covering more than 6.5 million acres (Ahn et al. 2002), yet by 1940 the total number of farms in Maine had declined by 80% (Moore and Witham 1996). The abandonment of farms was especially pronounced in southern and central Maine. In York and Cumberland counties, which encompass seven of the nine study sites, the amount of land in farms decreased by 60% from 1850 to 1944 (Ahn et al. 2002). This extreme decline in farms was due to a combination of factors. The early Maine farmers faced many challenges including stony land that often took many generations to clear, and unpredictable weather. These hardships, along with the economic hardships, and the promise of fertile land were enough to entice many farmers to abandoned their land and move west (Hart 1968, Whitney and Davis 1986, Foster et al. 1992, Moore and Witham 1996). In addition, the industrial revolution allowed for non-farm sources of income, which led some farmers to abandon farming altogether (Ahn et al. 2002). As farmers left, the surrounding forests quickly reclaimed the abandoned land. Because of the cold weather and rocky landscape of New England, much of the farmland was pasture and hayfields rather than tilled land. The abandonment of these pasture and hayfields resulted in fields of sod, grass, and litter, all of which offer suitable seedbeds for white pine establishment (Glitzenstein et al. 1990, Wendel and Smith1990, Foster 1992, Whitney 1994, Foster 1995). In addition, the grazing of animals assisted white pine establishment if it reduced hardwood competition (Foster 1995). The fields and pasturelands were often surrounded by woodlots or fencerows with many white pine seed trees (Foster 1995), which provided white pine with abundant and reliable seed sources. White pine seeds are wind dispersed and can travel up to 700 feet in the open, easily reaching surrounding fields. The ability of white pine to take advantage of the changed landscape allowed for the establishment of pure white pine stands in many areas.

The proliferation of pure white pine stands exemplified the changes in New England's forest following land abandonment. Prior to European settlement white pine was a well distributed, but relatively small component of the New England forests (Whitney 1994, Abrams 2001, Cogbill 2000). White pine is disturbance dependent and often recognized as a pioneer species, although it can be a climax species on the drier, sandier soils or a long-lived successional species (Wendel and Smith 1990, Foster 1995, Abrams 2001). It generally becomes established after large-scale disturbances such as fire and blow downs or after smaller, gap creating, disturbances (Abrams 2001). White pine was sparse in the presettlement forests of New England (Cogbill 2000), especially in the north. Compositional percentages ranged from a low of 0-1% in western and northeastern Maine to a maximum of 22% in north-central Massachusetts (Cogbill 2000, Whitney 1994). The low compositional percentages suggest that the frequency of fire in New England during presettlement times was relatively low, but increased from north to south. New England's presettlement white pine usually occurred as a scattered emergent in old growth stands and not in the pure even aged stands that can be found today. This suggests that gaps created by individual tree death and/or windstorms were the primary natural generators of suitable habitats for white pine during this time. Foster (1992) noted that modern forests have been strongly controlled by land use at the landscape level. However, at the regional level, post and presettlement forests are similar except for structural changes and the loss of a few species. It is important to recognize, however, that changes in stand structure and compositional can be significant to a forest ecosystem.

This is typified by changes in root competition that can take place when a stand is transformed from mixed species, such as those prior to European settlement, to a single species stand, such as white pine stands on old fields. In single-species stands, roots tend to occupy the same layer of soil and develop at the same rate, increasing severity of root competition, which directly affects tree health, rate of growth, and size of individuals (Stevens 1931). Balmer and Williston (1983), however, suggest that pure stands of white pine seldom stagnate because of inherent variations in vigor. However, they emphasize that variation in vigor is more pronounced on better sites where there is likely to be more available rooting area in addition to ample water and nutrients (Balmer and Williston 1983).

Agricultural land use can have detrimental long-term impacts on forest soils in terms of structure, nutrient composition, and function. The use of plows and grazing of animals can result in long lasting changes in soil properties (Foster 1995), including plow pans and soil compaction. The trampling of pastured animals can change soil structure in a way that often results in an increase of resistance to soil penetration (Bryant et al. 1972, Bezkorowajnyj et al. 1993), while the use of plows can create dense zones immediately below the plowed layer forming plow pan (Brady and Weil 1999). These changes in soil structure reduce soil moisture or oxygen and increase mechanical impedance to root penetration (Phillips and Kirkham 1962, Bennie 1991, Nambiar and Sands 1992). Water stress can be inflicted on plant growth in two opposing ways due to soil compaction. First, the hard layers can impede deeper root penetration making soil water less available. Second, compaction can reduce infiltration of water to deeper parts of the soil leaving deeper soils dry and/or roots sitting in water, both of which can impede plant growth (Barnes et al. 1971).

I hypothesize that any species of the New England forest growing in a setting that has changed so dramatically from its original habitat is likely to be more predisposed to stresses during its lifetime. As the following section demonstrates, white pine's rooting system makes this species especially sensitive on sites that have shallow rooting restrictions.

Rooting

White pine lacks a tap-root and instead utilizes central and lateral sinkers. The lateral roots and fine roots are generally only a few cenimeters below ground surface in the A and B horizon (Horton 1960). Smaller vertical roots and sinkers extend from the lateral roots and can penetrate the soil to a depth of 4.6 meters (Horton 1960, Brown and Lacate 1961). Although white pine is considered a shallow rooted species (Wendel and Smith 1990), the depth of these vertical roots enables white pine to compete well with hardwoods, especially on dry sites. Root grafting begins early in white pine stand development, yet competition between individuals is still more important. Substances in the phloem are easily shared between trees because they can move laterally from tree to tree. Xylem, however, and the water and minerals it transports, tends to follow the grain of the wood and therefore will not be diverted from one healthy tree to another (Bormann 1966). Therefore, in times of water stress there can be pronounced competition between individuals for the resource.

Changes in soil structure can be disadvantageous to white pine. The vertical roots of white pine are not able to penetrate or go around soil compaction, high water table, bedrock, plow pan, or lithological discontinuity (defined here as fine textured material over a layer of coarse textured materials) and instead spread out laterally forming a plate-like rooting system (Figure 1) (Horton 1960, Brown and Lacate 1961). Other species, such as red pine, are able to avoid obstacles by circumventing rocks or breaking through tough soil with a taproot (Horton 1960). Rooting restrictions reduce white pine productivity (Horton 1960) and may predispose it to other stresses, such as water stress (Stevens 1931, Lutz et al. 1937, Bennie 1991, Nambiar and Sands 1992).

Figure 1. White pine roots growing on soil with shallow rooting depth potential due to shallow bedrock.

(Photo by Howell, SH. 2001)

Water Stress

Water is imperative for normal tree functions involving high water content and turgor, such as cell expansion (Kramer and Kozlowski 1979). The first visible effects of water stress are closure of stomata, wilting of leaves and young stems, and cessation of growth. These responses are followed by premature senescence and shedding of leaves, suppressed shoot growth, restricted bud formation and elongation, and leaf expansion (Kramer and Kozlowski 1979).

Water stress also influences the cambium, indirectly by inhibiting synthesis and downward translocation of growth regulators and directly because low turgor pressure inhibits cell expansion (Kramer and Kozlowski 1979). Zahner and Donnelly (1967) concluded that 68% of variation in ring widths of young red pine (*Pinus resinosa*) in Michigan was associated with moisture conditions of the current season. Fritts (1974), working with conifers in western North America, found that increases in water stress were followed by reduced net photosynthesis and low accumulation of food reserves, resulting in reduced rates of cambial activity and ultimately the formation of narrow growth rings.

In the southwestern United States, changes in the width of tree rings represent the net effect of climatic factors on processes that influence growth. In essence, wide and narrow rings can be interpreted as favorable and unfavorable climate variations throughout the tree's life (Glock 1955, Fritts 1976). The climatic variations that form a ring in one year influence the tree's response to climate in following years. For example, Zahner (1968) notes that drought one year may result in reduced food storage for utilization in growth the following year. This "lag effect" is well recognized and can be measured (Fritts 1966). However, in northeastern North America, where climate is believed to be less limiting to growth, radial growth of trees has been reported to be less sensitive to climate changes (Fritts 1976; Phipps 1982; Tardif et al. 2001). For example, in the Great Lakes region Graumlich (1993) concluded that influences of climate on tree growth are not mediated through changes in mean climate conditions, but through the influence of a small number of years of extreme climate.

A number of studies have used tree ring data to reconstruct past rainfall and drought (Cook and Jacoby 1977, Stahle et al. 1985, Cook et al. 1999), but few have looked specifically at the effects of drought on white pine growth. The conclusions of those who have (e.g., Vose and Swank 1993, Clinton et al. 1997) find evidence supportive of Graumlich's (1993) argument that climate [drought stress] can result in a decrease in white pine increment growth, but consistencies with white pine growth increments and normal variations in climate are often not detected. For example, Vose and Swank (1993) studied the effect of precipitation deficits on the basal area growth of 33-year-old white pine in North Carolina. Although they could observe differences in tree growth with extreme climate variations, between a growing season with precipitation that was 54% below average and one with precipitation that was 63% above average, they found it hard to discern relationships between growth rate patterns and the precipitation. Similarly, Clinton et al. (1997) found that on relatively xeric sites drought limited radial growth, but once precipitation returned to normal or average levels, radial growth patterns suggested that resources other than precipitation were more limiting.

Hypothesis

The forests of today consist of species found in presettlement forests. However, due to agricultural land use and abandonment, white pine stands became established and are developing under conditions different from those to which they are adapted. It is possible that the abandoned fields over large areas of central and southern Maine have allowed for establishment of white pine on sites with rooting restrictions. Therefore, the first hypothesis states that soil restrictions associated with shallow rooting depth of white pine predisposed the species to water stress, and that only white pine on these drought sensitive sites suffered mortality. The second hypothesis follows that the inciting factor was drought which preceded mortality of the white pine during 1997-2000.

CHAPTER 2: METHODS

Site Data

The study areas are located in southern Maine. Because of the localized nature of the decline, sample sites were placed in areas of known high mortality. For each high mortality site, a low mortality site was established nearby in a mature stand exhibiting little or no dead trees. The paired sites were evaluated in nine locations, all south of 45° N latitude. The site locations encompass four counties including York with sites in Wells, Lebanon, Hollis, Limington, and Waterboro; Cumberland with sites in Casco and New Gloucester; Lincoln with sites in Nobleboro; and Oxford with sites in the town of Oxford (Figure 2). The stands are dominantly white pine, except for the high mortality site at Wells, which is predominantly red maple (*Acer rubrum*) and red oak (*Quercus rubra*) (Table 1). The sites in Hollis, Massabesic, and Nobleboro also had noticeable amounts of these species.

A modified Forest Health Monitoring site design consisting of four adjacent circles, each 14.6 m in diameter was used (Anonymous 2001). This design created sites with 4 sub-plots with a total area of .07 ha.

Figure 2. Locations of paired sites, stream gauge stations, and weather stations.

Stream Gauge Stations: St. John (1), Mattawamkeag (2), Narraguagus (3), Saco (4), Carrabassett (5), Sandy (6), Little Androscoggin (7), Sheepscot (8), Oyster (9). Weather Stations: Caribou (10), Millinocket (11), Corinna (12), Middle Dam (13), Farmington (14), Acadia Nat'l Park (15), Waterville (16), N. Conway (17), Augusta (18), Lewiston (19), Portland (20), Buxton (21), Sanford (22), Durham (23).

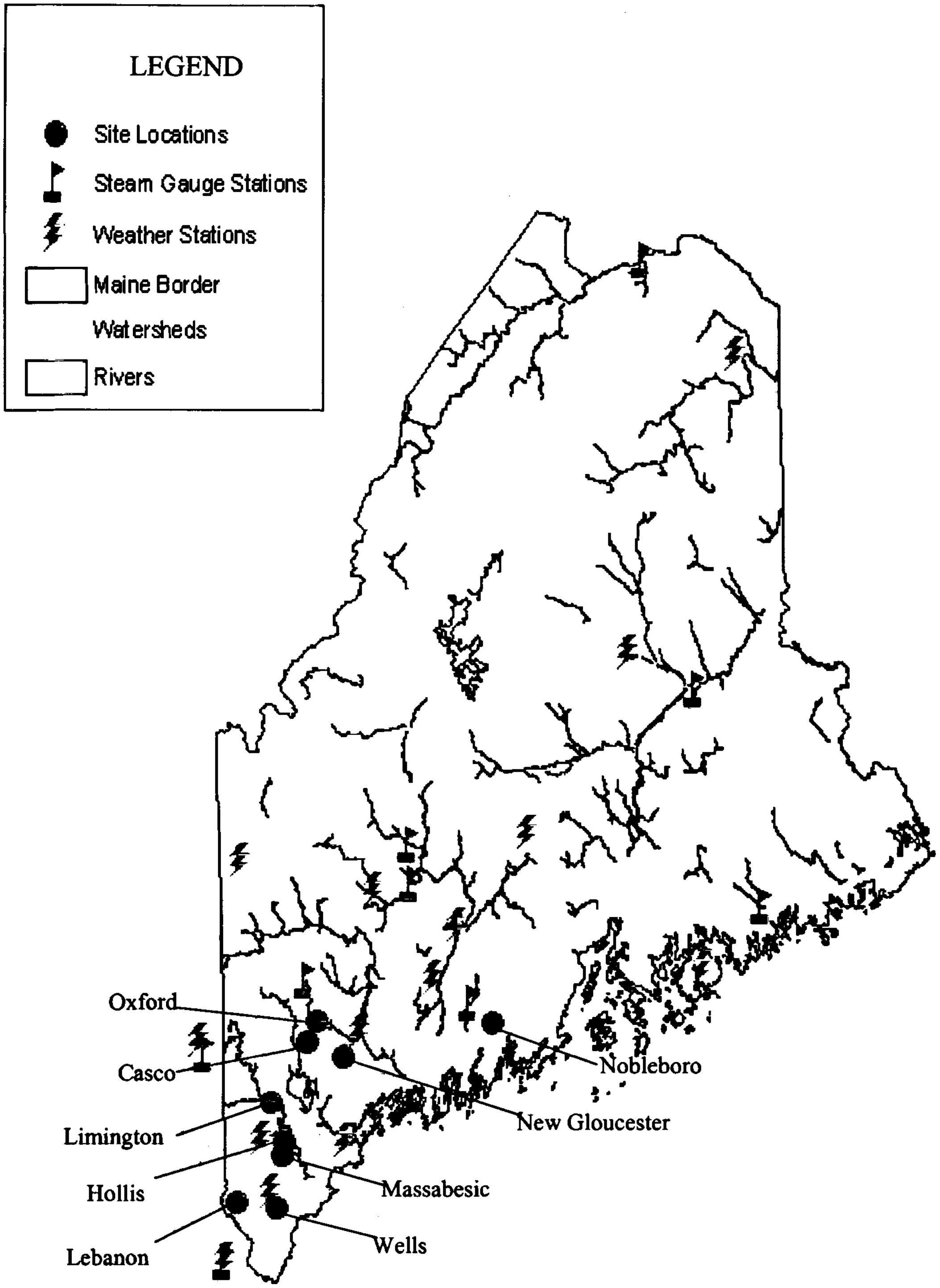
LEGEND
Site Locations
Steam Gauge Stations
Weather Stations
Maine Border
Watersheds
Rivers
Oxford
Casco
Limington
Hollis
Lebanon
Nobleboro
New Gloucester
Massabesic
Wells

Table 1. Percentage of total basal area in each site comprised of white pine

Low mortality plots are represented by "L" and high mortality plots are represented by "H".

Location	Stand	Total basal area/ha (m^2/ha)	White pine basal area(m^2/ha)	% of total basal area in white pine
Wells	L	41.2	40.3	98%
	H	29.0	6.2	21%
Lebanon	L	26.7	23.4	88%
	H	30.2	25.6	85%
Hollis	L	36.3	28.1	77%
	H	20.4	14.3	70%
Limington	L	29.3	24.1	82%
	H	39.3	34.8	89%
Casco	L	22.9	21.9	96%
	H	24.4	24.4	100%
Nobleboro	L	39.3	26.8	70%
	H	27.4	18.7	68%
Massabesic	L	58.0	50.0	86%
	H	48.3	33.6	70%
New Gloucester	L	30.9	26.0	84%
	H	34.5	29.1	84%
Oxford	L	41.4	37.6	91%
	H	38.0	31.7	83%

Stand measurements for trees included species, crown class (Oliver and Larson 1996), diameter at breast height (DBH), and crown condition (live, red needles, few needles, no needles) for all trees >2.5 cm DBH. Some of the dead trees had been cut out of the Wells high mortality site and in both of the Oxford sites. Each stump's narrowest and widest diameters were measured and then averaged. DBH was estimated by subtracting 2.5 cm from the average. 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 historical use and/or restrictive layer.

Core Data

Along with stand measurements, two cores were removed from each codominant and dominant tree at 90° angles. This included dead trees. If there were not twelve 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 11 white pine on the high mortality site in Wells and 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 and allowed to dry at ambient temperature. Once dry, the cores were mounted on grooved wooden boards so that the trachieds were longitudinal. Cores were then sanded with 100, 250, 350, 400, and 600 grit sandpaper to facilitate the counting of rings and measurement of ring-widths.

Crossdating is used to identify the year in which each ring was formed and then to assign a calendar date to the rings (Fritts 1976). The outermost ring indicates either the year the sample was taken, or the last 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 the dead trees. The stand chronology was based on both live and dead white pine cores (refer to analyses).

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). In order 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 US Geological Survey were used as indicators of water status in the watersheds (Stewart et al. 2000, Coakley et al. 2001). 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 regulated by dams. These included St. John, Mattawamkeag, Narraguagus, Saco, Carrabassett, Sandy, Little Androscoggin, Sheepscot, and Oyster Rivers (Figure 2). 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 Climate Data Center (NCDC) (National Climatic Data Center Federal Building, 151 Patton Avenue, Asheville, NC 28801-500) 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 (Figure 2). Precipitation amounts during the growing season (May to October) were obtained for Lewiston, Portland, and Sanford for 1990 to 2001 to identify the driest year. 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.

Analyses

Relating long-term trends in tree growth with climate requires statistical removal of changes due to tree age, crown position, and mean growth (Fritts et al. 1965). By using the computer program ARSTAN, chronologies from tree-ring measurement series were standardized to remove effects of endogenous stand disturbances (Dr. Edward R. Cook (1985), Tree-Ring Laboratory, Lamont-Doherty Earth Observatory of Columbia

University in Palisades, New York). The ring-width series measured for each core was standardized using "double detrending", meaning that the time series was fit first to either a negative exponential curve or a linear regression line, according to best fit. The resulting series was smoothed using a cubic smoothing spline with 50% frequency response of 32 years. Finally, each series was autoregressively modeled, and then all series were averaged together, using a biweight robust mean (Cook 1985) to obtain a mean site chronology.

Ring width and climate correlations can show great changes from one month to the next, which is expressed as the response function (Fritts 1976). The standardized ARSTAN data were used in PRECON for response function analysis (Garfinkel and Brubaker 1980). PRECON can be used to define the correlation between radial growth and weather. A bootstrapped method was included to estimate the standard error of the response function weight (Fritts et al. 1991), which tests the significance and stability of the regression coefficients. To find how climate variations relate to long-term radial growth variations in the white pine climatic parameters including temperature and precipitation (to account for evapotranspiration) from the Portland station, Palmer Drought Severity Index (PDSI) for region two in Maine, and stream flow data were also used in PRECON. The PDSI takes into account precipitation, temperature, and available water content to provide measurements of moisture conditions. This system separates Maine into three regions, of which region two was used because it encompasses the most study sites.

The two raw core chronologies from each tree were averaged by tree, and the averaged increments were used in additional analyses. The longest chronology from a tree was used for assigning tree age at DBH. Years of decline were calculated by counting the number of years after 1995 in which the current year's increment was less than the previous year's increment. Paired t-test were used to compare the depth of soil restrictions between high and low mortality sites. Some sites had no soil restrictions found to a depth of 50 cm, therefore, 50 cm was used to calculate a minimum average for each site. Paired t-tests were also calculated to compare basal area and number of stems 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, years of decline), paired t-test calculations were followed with calculations of standard t-tests, by location, to compare differences between high and low mortality sites. Comparisons of age and DBH for dead and surviving white pine were based on estimated values for 1995. For DBH this involved subtraction of the mean annual increments of 1996 to the last year of growth (dead trees), or year of coring (surviving trees) from the DBH measurement.

The site chronologies for dead and living trees on high mortality sites were compared by subtracting the increment of dead trees from that of living trees for each calendar year. Number of years in which the average increment for dead trees was lower than that of the surviving trees was summed over 1970-1995, a period that avoids the juvenile growth phase in trees. Number of years in which the difference exceeded two standard errors from each mean was also calculated. The comparisons were performed on eight of the nine sites, because there were no standing dead trees at the Wells site.

CHAPTER 3: RESULTS AND DISCUSSION

Comparison of High and Low Mortality Sites

The high mortality sites had shallow soil restrictions (< 30 cm) at all nine locations. The paired t-test indicated that the rooting depth potential of the high mortality sites (ranging from 19.0 to 26.5 cm, mean = 24.6) was significantly less than those of the low mortality sites (ranging from 39.0 to >50 cm, mean = 44.8, P<0.01) (Table 2). The causes of the rooting restrictions on the high mortality sites are associated with plow layers from earlier agricultural use (two locations), high water table (one locations), shallow bedrock (one location), or lithological discontinuities (five locations). Because the study sites, both high and low mortality, consisted of dominant white pine it was assumed that the land had been cleared for agricultural use such as blueberry fields, grazing, or cultivation within the last 100 years (Table 2). The implications of these historical activities mean that white pine stands were sometimes established in areas to which it is not well adapted to the soil restrictions (high mortality sites). 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). The low mortality sites also had evidence of soil change due to agriculture use within the last 100 years (four locations), but all these sites had rooting restrictions that were deeper than 30 cm (four locations) or not evident (five locations) (Table 2).

Table 2. Stand data for all tree classes 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 under the headings. Paired t-tests were calculated for all parameters. *P<=0.05

Location	Coordinates	Stand	Basal area/ha (m^2/ha) (0.3)	% of Basal area Mortality* (5.1)	Density Stems/ha (194)	Potential rooting depth (cm)* (2.2)	Soil Characterstics
Wells	N43°21' W70°40'	L	41.2	0	529	>50.0	Plow layer, no pan
	N43°21' W70°40'	H	29.0	13	1186	23.8	High water table
Lebanon	N43°22' W70°53'	L	26.7	0	1171	>50.0	No agricultural evidence
	N43°22' W70°53'	H	30.2	18	1057	32.3	Lithological discontinuity
Hollis	N43°38' W70°38'	L	36.3	5	771	>50.0	Possible 1820's plowing
	N43°38' W70°38'	H	20.4	34	1243	23.0	Lithological discontinuity, very old plow layer
Limington	N43°47' W70°42'	L	29.3	0	1914	39.0	Extra 9" from flood deposit
	N43°47' W70°42'	H	39.3	57	1271	23.8	Plow pan and lithological discontinuity
Casco	N44°02' W70.30'	L	22.9	2	443	39.0	Old plow layer, no pan
	N44°02' W70.30'	H	24.4	32	543	26.5	Plow layer, no pan, high water table, hard pan, old blueberry field
Nobleboro	N44°07' W69°27'	L	38.3	0	1329	39.8	Grazing, no pan
	N44°07' W69°27'	H	27.4	35	1400	26.3	Bedrock and grazing
Massabesic	N43°34' W70. °38'	L	58.0	6	1657	42.3	No evidence of plowing or agriculture
	N43°34' W70. °38'	H	48.3	22	2957	24.0	Lithological discontinuity and very old plow layer
New Gloucester	N43°59' W70°18'	L	30.9	6	929	>50	No evidence of plowing or agriculture
	N43°59' W70°18'	H	34.5	18	1014	19.0	Lithological discontinuity
Oxford	N44 °07' W70°27'	L	41.4	2	571	43.3	No evidence of plowing or agriculture
	N44 °07' W70°27'	H	38.0	47	1471	23.3	Plow pan and lithological discontinuity

Depth of soil restrictions and mortality were the only parameters that significantly differed between high and low mortality sites (Table 2). Although dead white pine stems were found on low mortality stands the numbers were significantly less than the number of dead white pine found on high mortality sites ($P<0.01$) (Table 3). This evidence supports the hypothesis that shallow rooting depth, to which white pine is sensitive (Horton 1960, Brown and Lacate 1961), 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 ($P<0.01$) with significantly larger diameters ($P<0.01$) (Table 3).

There are a number of 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 ($P<0.01$) than that of low mortality sites (Table 3). The age difference, and lack of evidence of there being second growth stands, 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 natural thinning as indicated by their lower number of stems per hectare.

Table 3. Dominant and codominant White pine data for low (L) and high mortality(H) sites.

Standing dead trees are included in calculating basal area, DBH, stem density and age. Age and DBH are based on estimated values for 1995, based on increment cores. Wells sites were not included because cores were not available due to cut trees. Numbers of living and dead stems represent the number of stems found within the sampling site. The numbers in parenthesis in the "cores" columns indicate number of trees cored outside the sample site, and these measurements are only included in the calculations for years of declining growth only. The last column represents the number of years of declining growth between 1995 and 2000 for surviving white pine on low and high mortality sites. Standard errors for pooled data (basal area, density) are under the headings and for standard t-tests (DBH, age, years of decline) are in parenthesis next to the mean values. *P<=.05

Location	Stand	Basal area/ha (m^2/ha) (0.32)	DBH (cm)	Density Stems/ha* (60)	Living stems	# of cores	Dead stems	# of cores	Age	Years of declining growth (1995-2000)
Wells	L	40.3	-	286	20	20	0	0	-	1.3* (0.2)
	H	6.2	-	86	2	1(11)	4	0	-	2.8* (0.3)
Lebanon	L	23.4	32.5* (5.5)	243	17	17	0	0	77* (2)	2.1 (0.2)
	H	25.6	22.7* (6.6)	543	27	22	11	8	51* (1)	2.5 (0.3)
Hollis	L	28.1	41.0* (8.0)	200	13	13	1	0	96* (2)	3.0* (0.2)
	H	14.3	21.7* (4.1)	343	15	13	9	7	47* (1)	2.5* (0.2)
Limington	L	24.1	29.9* (8.2)	286	20	20	0	0	48 (1)	2.3 (0.1)
	H	34.8	25.4* (5.2)	629	15	13	29	29	46 (1)	2.5 (0.4)
Casco	L	21.9	35.3* (5.2)	200	14	14	0	0	62* (1)	2.7 (0.2)
	H	24.4	22.1* (4.7)	543	22	17	16	14	46* (1)	3.2 (0.2)
Nobleboro	L	26.8	39.4* (11.6)	186	13	13	0	0	64* (2)	2.2* (0.2)
	H	18.7	23.7* (8.2)	371	19	18	7	6	51* (2)	3.3* (0.2)
Massabesic	L	50.0	36.9* (5.7)	443	28	26	3	3	114* (1)	2.7 (0.2)
	H	33.6	20.7* (4.6)	843	46	31	13	8	43* (0)	2.7 (0.1)
New Gloucester	L	26.0	41.4* (7.4)	186	13	12	0	0	84* (1)	3.0 (0.2)
	H	29.1	27.8* (7.4)	429	22	22	8	8	61* (1)	3.2 (0.1)
Oxford	L	37.6	35.3* (5.6)	429	30	12(1)	0	0	76* (2)	2.4 (0.1)
	H	31.7	22.8* (6.0)	671	21	20	26	8	46* (1)	2.8 (0.2)

In contrast, the high mortality sites are younger and have not yet gone through a natural thinning process, as indicated by their higher 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. Decline and mortality may have hastened the natural thinning process of these stands. Having less competition, these stands could be less susceptible to future stresses.

It is important to note here that chronologies are not available for all of the trees (Table 3). Missing chronologies are due to cut trees (4 in Wells (low mortality), 16 in Oxford (high mortality), 18 in Oxford (low mortality)), decay, and unreadable cores. Cut trees were dead in the high mortality sites but were living at the time of harvest in the low mortality sites. The Oxford site, which had the most missing chronologies, was logged in the winter of 2001. This was done in response to high mortality that was observed from 1997-2001 as in the other sites. Due to the high number of trees at Massabesic (high mortality), a subsample of 31 trees was randomly selected from the 46 trees in the sample site. Despite the missing chronologies in three sites (Wells (low mortality), Oxford (low mortality), and Oxford(high mortality)), the data derived from them were consistent with data on the other sites.

Densities of the stands were compared with New England white pine stocking guides (Philbrook et al. 1979). The A curve represents 80 percent stocking, and stands above it are considered overstocked. The B curve represents minimum stocking for full site utilization, and stands that fall below are considered understocked. Stands between the A and B curves are considered adequately stocked. Where a particular stand might fall in the guide is based on basal area per acre, number of trees per acre, and mean DBH for trees in the main canopy. Plotting the study sites onto the stocking guide indicated that after mortality, four of the eight high mortality stands were understocked (Figure 3). In addition, after mortality densities on high mortality sites were similar to densities found on low mortality sites. This suggests that density may be an additional predisposing factor.

Differences between high and low mortality sites were inconsistent in that the number of years of declining growth on surviving trees, between 1995 and 2000, were not significantly different on six of the nine sites (Table 3). This suggests that the surviving trees on both high and low mortality sites responded to climate similarly in this period.

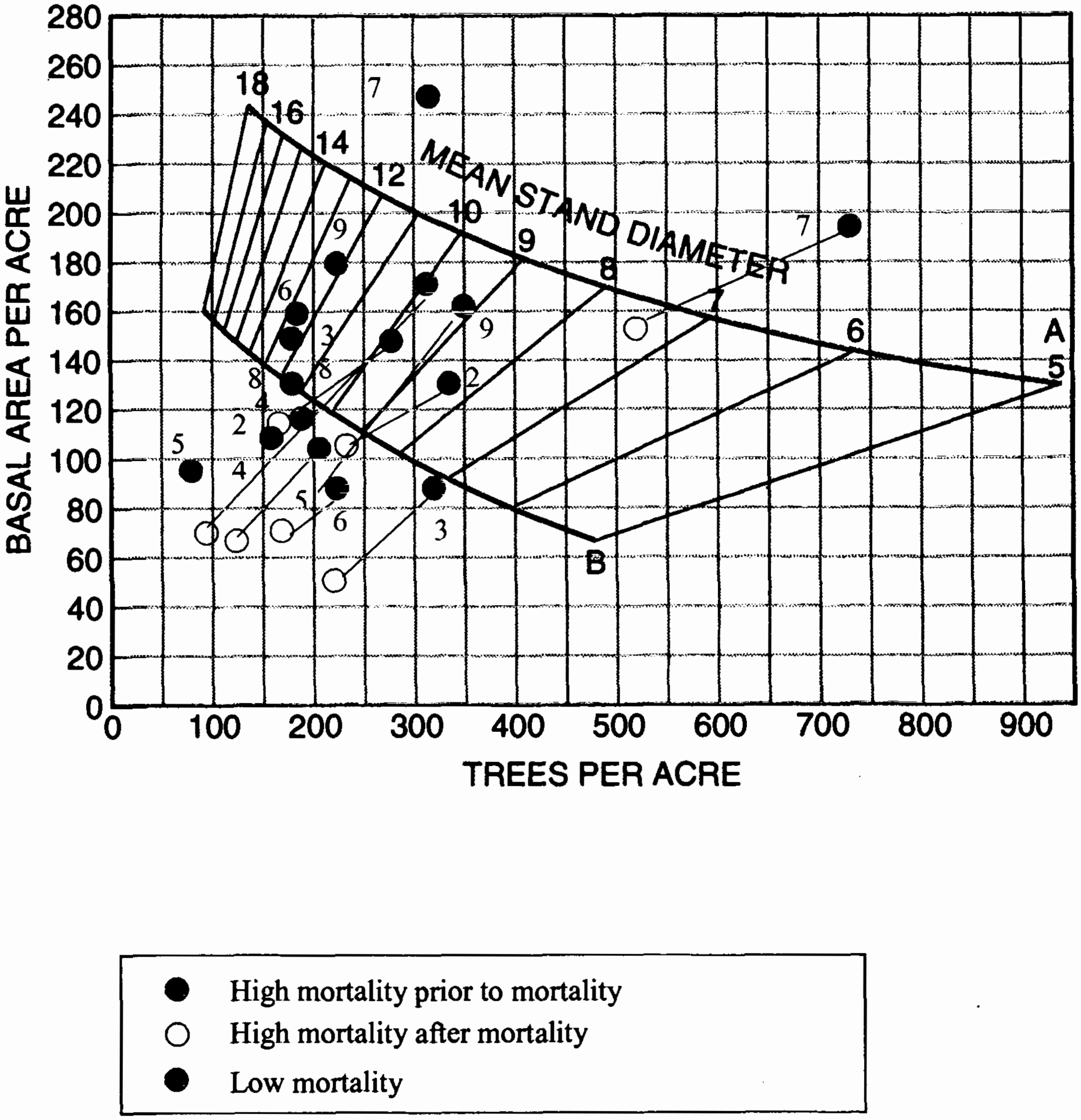

Figure 3. Stocking of study sites compared with New England white pine stocking guide (Philbrook et al 1979).

Wells (Site 1) is not included because of the high component of species other than white pine at these sites.

Comparison of Surviving and Dead White Pine on High Mortality Sites

That the number of years of declining growth in surviving trees on high mortality sites did not significantly differ from surviving trees on low mortality sites indicates a need to investigate possible growth differences between dead and surviving trees. The data showed that on all but one high mortality sites the DBH of dead trees was significantly less than the surviving trees ($P<0.01$) (Table 4). Plotting of the annual increment widths suggested a significant difference in mean annual growth (Figure 4). The mean difference in increment widths between dead and surviving white pine indicated that in seven of the eight high mortality sites there was a period of 24 years or more growth separation between dead and surviving trees (Table 4). The more conservative test using differences greater than two standard errors resulted in three sites having more than ten years of significant growth separation, four sites having between two and five years significant growth separation, and one site having none. It is clear that the mean average growth of the dead trees at each site was less than that of the surviving trees. The ages of the dead and surviving trees was not significantly different indicating that killed trees were not younger, but growing slower.

Table 4. Data for dominant and codominant white pine on high mortality sites.

Age and DBH are based on estimated values for prior to and including 1995 based on increment cores. The Wells sites were not included because cores were not available due to cut trees. The first column for the period of growth separation indicates number of years from 1970 to 1995 that the mean 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 2 standard errors from each mean. Standard t-tests were calculated for age and DBH data by location. Standard errors for age and DBH are shown in parentheses. *P<=0.05

							Number of stems that died							
Location	Surviving stems	Dead stems	Mean 1995 age surviving	Mean 1995 age dead	1995 DBH Live (cm)	1995 DBH dead (cm)	'90-'95	'95	'96	'97	'98	Post '98	Pd. of growth separation (mean)	Pd. of growth separation (>2SE)
Lebanon	27	11	48 (1)	43	24.5*	17.9*		2	3	3			25	2
				(2)	(1.4)	(1.1)								
Hollis	15	9	44	43	23.7*	18.1*		1	2	3	1		24	20
			(1)	(1)	(1.0)	(0.6)								
Limington	15	29	44	43	29.6*	23.6*		2	9	11	7		25	17
			(1)	(1)	(0.9)	(0.9)								
Casco	22	16	43	42	24.6*	19.0*	1	2	3	6	2		25	0
			(1)	(1)	(1.0)	(0.9)								
Nobleboro	19	7	47	43	25.1	19.2		2		2	2		25	4
			(2)	(2)	(1.9)	(3.1)								
Massabesic	46	13	37	38	21.8*	16.6*				2	2	4	25	5
			(0)	(2)	(0.8)	(1.0)								
New Gloucester	22	8	57	55	30.4*	20.7*			3	3	2		25	11
			(2)	(1)	(1.5)	(0.9)								
Oxford	21	26	42	39	24.1*	19.5*	1		6		1		15	2
			(1)	(1)	(1.3)	(1.7)								
Total							2	9	26	30	17	4		

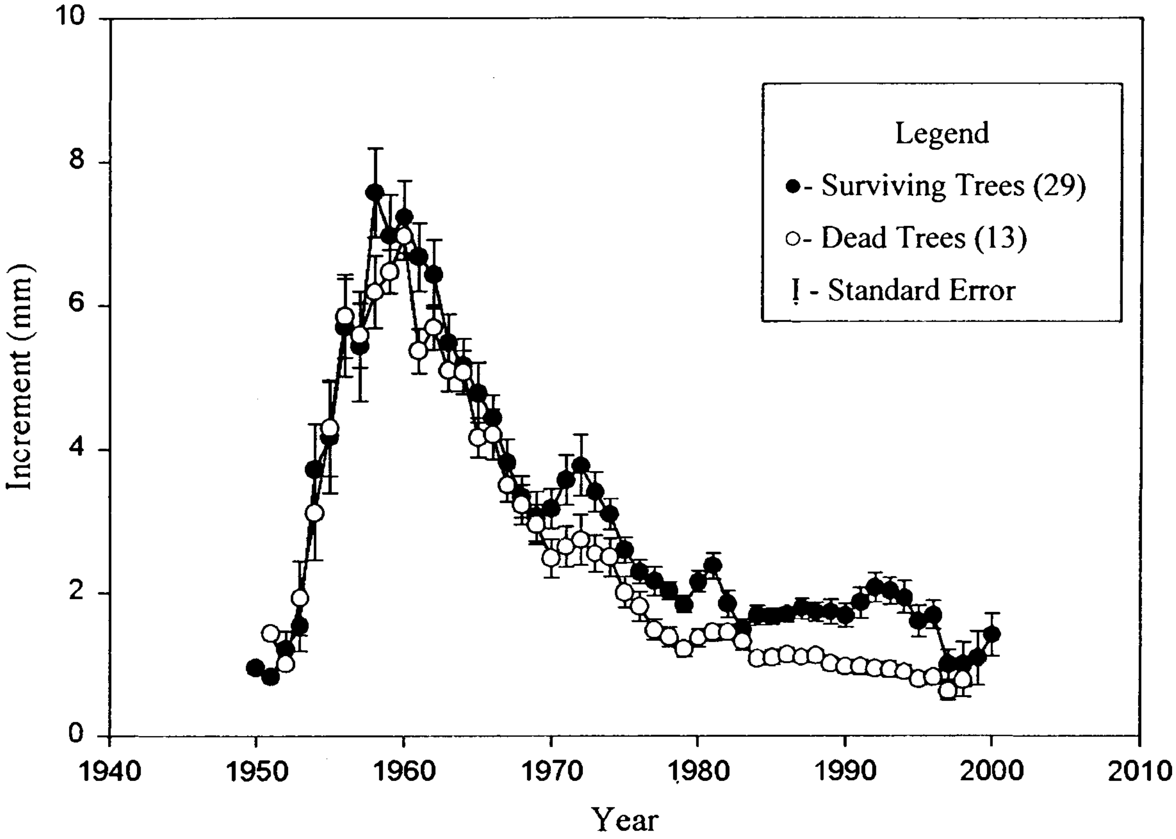

Figure 4. Average annual increment of surviving versus dead trees for the Limington high mortality site.

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 with the trees that are limited by available space (Long and Smith 1984). The increased competition 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 this stem exclusion stage, the trees of pure stands compete fiercely with each other mainly because they all have crowns in the same stratum (Smith et al. 1997).

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. Emphasis was put on drought during 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 radial tree growth (Fritts 1956, Clinton et al. 1977). Stream flow data 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 ten-year period (Table 5). In addition, the Little Androscoggin showed three years (1949, 1978, and 1995) of low stream flow (<2se below normal) of which 1995 was the most extreme case of low stream flow (Figure 5). 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.

Table 5. Minimum standard deviations from the daily mean for the period of record (see Table 6) of stream flows 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 2 standard deviations from the mean are highlighted.

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

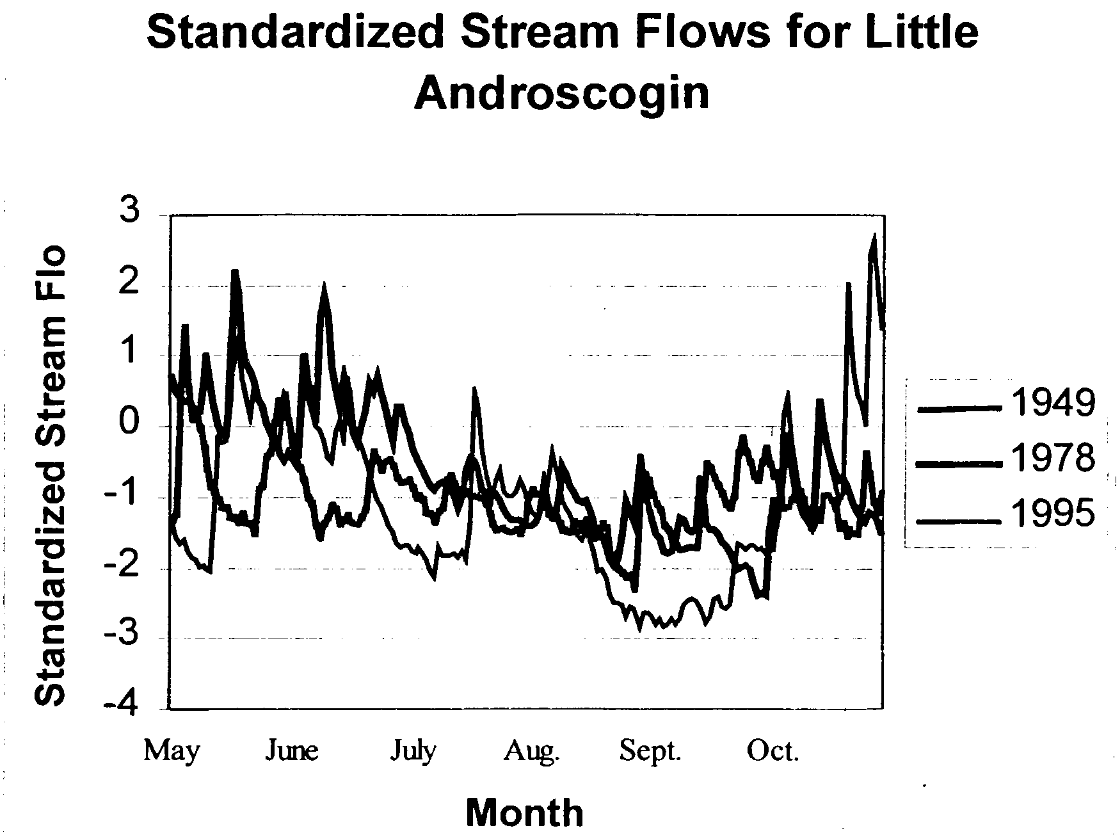

Figure 5. Standard deviations from the daily mean stream flow of Little Androscoggin River for growing seasons in 1949, 1978, and 1995.

Stream flows throughout Maine and New Hampshire in 1995 were analyzed to see if 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 shows 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 the area is likely due to differences in historical land use. There were no reports of northern Maine having as extensive field abandonment and establishment of white pine was the case in southern and central Maine (Hart 1968, Moore and Witham 1996, Ahn et al. 2002).

Table 6. Minimum standard deviations from the daily mean stream flow for the period of record for each river throughout region during the 1995 growing season.

Values shown are the minimum value for the month. Values greater than 2 standard deviations from the mean are highlighted.

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

Precipitation data did not show as clear a pattern for drought as stream flows. Total growing season precipitation was looked at for Lewiston, Portland, and Sanford. The precipitation was inconsistent, but clearly 1995 was one of the driest growing seasons from 1990-2001 (Table 7). The precipitation data throughout the region in the 1995 growing season was 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.

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.

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

									Standardized Values						
Station	May	June	June	July	Aug.	Sept.	Oct.	Total	May	June	July	Aug.	Sept.	Oct.	Total
Caribou	6.2	3.0	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	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	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	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	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	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	7.9	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	6.7	5.0	5.0	14.6	5.5	6.0	25.5	63.3	-0.5	-.09	1.0	-0.9	-0.7	2.2	-1.0
Augusta	8.7	5.5	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	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	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	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	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	7.0	4.7	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

In accordance with the drought period, crossdating of the tree rings show a high mortality of white pine from 1995-1998 with peak mortality in 1996-97 (Table 9). This is substantial evidence that the inciting stress was the drought of 1995. The drought happened late in the 1995 growing season, which would result in reduced growth or mortality appearing in 1996 and 1997 because of a lag effect. In other words, climatic events during one year can physiologically precondition a tree's potential for growth the next year (Lyon 1936, Fritts 1974). In fact, Fritts et al. (1965) suggests that unusually dry and warm conditions in the year prior to growth could affect the following season's growth. The sequence of events in white pine decline were drought in 1995, last year of growth primarily in 1996 and 1997, and reported appearance of visible symptoms (thinning crowns, red needles) beginning in 1997.

The clear relationship between year of last growth following the year of drought supports the hypothesis that drought incited white pine decline. That a clear growth decline could not be identified in surviving trees was indicative that they were not predisposed to drought injury as previously discussed (Table 3).

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.

Year of last ring	% dead trees high mortality n=88	% dead trees low mortality 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%

A response function analysis was performed on all 18 sites with PRECON for the master stand chronologies that were standardized with ARSTAN. In addition, dead trees and surviving trees on high mortality sites were analyzed separately because their growth parameters differed (Table 4). Response function analyses are interpreted as expressing the way in which climate parameters (precipitation and temperature, PDSI, stream flows) during and preceding the current growing season are related to long-term variations in radial growth (Cooke and Jacoby 1977). There were no consistent significant responses between climate and increment variation between master chronologies (results not shown). Apparently, it is difficult to detect climate's influence on long-term limiting increment growth in white pine in southern Maine in contrast to other studies that select sites for precipitation sensitivity at the forest-desert border in semiarid southwestern regions (Fritts 1976). Bartholomay et al. (1997), in Acadian National Park, also were not able to detect strong associations between climate and tree rings in white pine. They found that ozone levels and site factors, such as shallow bedrock, had more influence on tree-ring indices than climate. In temperate regions like the northeastern United States, climate can be less limiting than site factors (Fritts 1974, 1976, Phipps, 1982, Graumlich 1993). PRECON looks for linear relationships in climate and annual increments. That these relationships are hard to find in the northeast may indicate that the climate/growth increment relationship are not linear and therefore the response function technique may be inadequate for modeling the relationship between growth and climate.

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 (W.H. Livingston, personal communication 2001). The lack of a single pest occurring on most dead and dying trees suggests that these pests were secondary organisms.

Along with changes in soil structure, land use can often lead to changes in the nutrient composition of the soil (Paoletti et al. 1993). Studies of the soil nutrient concentration in high and low mortality sites between the sites in terms of soil nutrient concentration were inconclusive (W.H. Livingston, personal communication 2001).

Winter thaw-freeze fluctuations have been associated with decline of forests in the past. In the winter of 1935-1936 a series of thaw-freeze events has been proposed as an inciting stress with 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 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 et al. 2001). There is no actual literature on root hardiness of white pine. However, extensive studies of root hardiness in seedlings of Norway spruce (*Picea abies* (L.) Karst.) and Scots pine (*Pinus sylvestris* L.) 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 (Lindström and Stattin 1994). Climate data from the NCDC indicates 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 snow cover that insulated soils from the cold. In February 1996 Durham had a minimum temperature of –28°C, which was 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 potential rooting damage could have occurred. However, the 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 tree 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 that did not show decline. The most represented species included red maple and red oak that were found in nine of the 18 sites. The representative numbers of red maple and red oak were quite small in all sites except Wells where red maple, especially, was well represented. There was no visual evidence of decline in the crowns of either species. Red maple is able to stop growing under dry conditions and can produce a second growth flush when conditions improve (Walters and Yawney 1990). This allows red maple to deal better with drought conditions. Red oak is typically a deep rooted species compared to white pine and should be less susceptible to drought where white pine rooting depth is restricted (Harlow and Harrar, 1968).

CHAPTER 4: CONCLUSION

Historical agricultural use and subsequent land abandonment has resulted in the establishment of pure white pine stands in southern Maine. Some of these white pine stands are growing on sites where soils structure can impede rooting depth. The evidence found in this study supports the hypothesis that shallow rooting depth predisposed white pine to other stresses. The data showed that density could be an additional predisposing factor. The high incidence of white pine mortality in 1996-1997 correlated well with a 1995 drought in the surrounding area and is likely the inciting stress of the decline.

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