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Fifty-Six Years of Forest Development Following the 1938 Hurricane in Hillsborough, New Hampshire, USA

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Received: 9 May 2017; Accepted: 19 June 2017; Published: 27 June 2017

Abstract: Forest development patterns following the 1938 hurricane were evaluated in 45 continuous forest inventory (CFI) plots monitored from 1955 to 2011 at the Caroline A. Fox Research and Demonstration Forest (Fox), in Hillsborough, New Hampshire. Long-term plot data provide a record of landscape-level changes in a managed forest setting. Changes in density, basal area, mortality, removal, and recruitment demonstrate the effects of forest management on growth and forest structure through time. Tree density peaked in 2001 at 716.1 trees/hectare, but the basal area continued to increase from 18.8 m^2/ha in 1955 to 44.7 m^2/ha 2011 despite forest management activities. Hemlock and red maple dominate stem recruitment. Tree mortality rates have increased from 0.26%/year 1955–1965 to 1.03%/year 2001–2011, while removal rates have dropped from 1.04%/year to 0.44%/year.

Keywords: CFI; forest development patterns; mortality; tree recruitment

1. Introduction

Forest development patterns following a hurricane can provide a baseline for forest management that mimics a natural disturbance. Few studies of permanent plots are of sufficient duration to document how forest composition is changing through successional time in New England [1–4], and fewer still follow managed forests [5–7]. The influences of the 1938 hurricane on New England forests provide insights into post-disturbance recovery patterns and succession in a largely single cohort forest [1,8–15].

Changes in species composition, a combination of recruitment of new stems, natural mortality and removals, reflect both the natural disturbance regime, the competitive interaction between species, and the impacts of forest management. The forests of southwestern New Hampshire were heavily damaged by the 1938 hurricane, with widespread blow down and snapped stems. There were extensive post-storm salvage operations [8,9,14,16]. Post-hurricane succession primarily reflects an even-aged stand development pattern [17].

Continuous forest inventories (CFI) are networks of permanent plots re-sampled through time and used to estimate growth rates and parameterize growth models [18–24]. Volume estimates can be used to identify allowable harvest rates. A continuous forest inventory (CFI) study established in 1955 at the Caroline A. Fox Research and Demonstration Forest (Fox) was initiated to provide forest growth and development data on state lands 17 years after the extensive damage caused by the 1938 hurricane. Following initial plot re-measurement in 1960, diameter and basal area growth at five years were analyzed [25,26] Analysis of the 1975 re-measurement focused on basal area growth at 20 years [27]. Following the 2011 re-measurement diameter growth [28], and volume growth [29] were also assessed at 56 years. This article addresses the question: How has forest composition changed in a managed forest over 56 years (1955–2011) at Fox Forest?

2. Materials and Methods

2.1. Study Site

The Caroline A. Fox Research and Demonstration Forest, New Hampshire's State Forest Research Station since 1933, consists of 585 hectares of forests, swamps and peatlands in a post-agricultural landscape in Hillsborough, New Hampshire (Figure 1). Elevation ranges from roughly 195 to 354 meters above sea level. Since 1948 the region has received an average of 0.98 meters of annual precipitation (based on the closest long-term observations at the Concord, NH, airport) [30]. Fox encompasses 20 different soil series but is dominated by Marlow stony loam, Peru stony loam, Monadnock stony fine sandy loam and the Tunbridge-Lyman-Monadnock Complex, all soils that favor hardwood forest development [31].

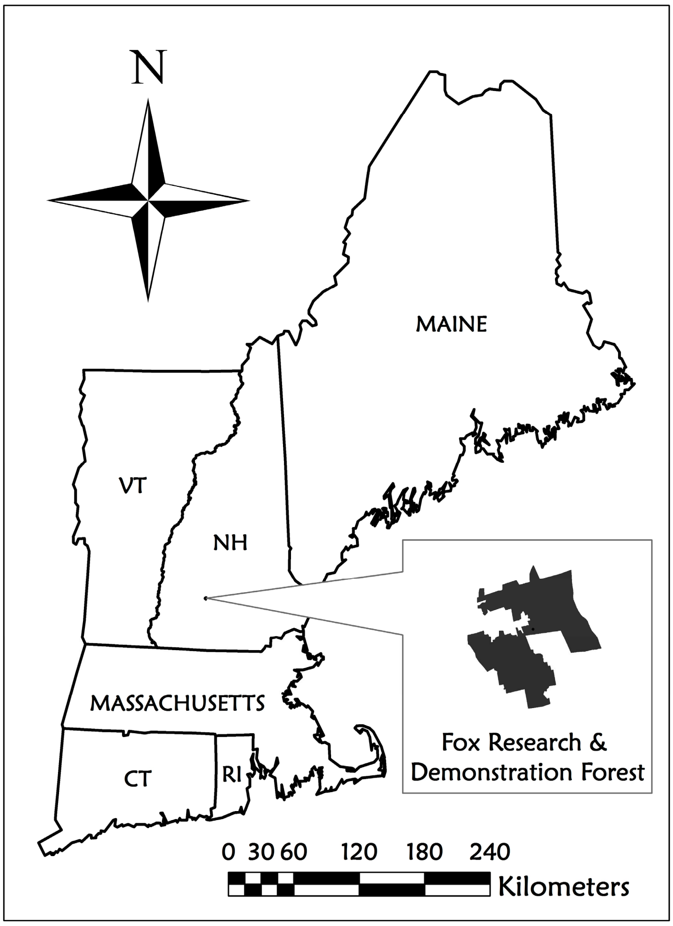


Figure 1. Map of New England showing the location of the Caroline A. Fox Research and Demonstration Forest, Hillsborough, NH, USA.

2.2. History

Though detailed descriptions of the composition prior to the hurricane are limited, most of Fox is second growth (post-agriculture). Henry Baldwin, the first State Research Forester in New Hampshire (1933–1963), indicated that Fox was ideal to "serve as a demonstration of how low-grade pastured woodlands in New England can be improved in quality by careful culture." Stand type maps of the 1935 property footprint are dominated by stands of eastern white pine, gray birch/red maple, eastern white pine/eastern hemlock, eastern white pine/northern red oak, and northern red oak hardwood types, with a small amount of eastern hemlock hardwood, red spruce/paper birch and sugar maple/basswood types.

On 21 September 1938, the hurricane struck Fox Forest. Wind speeds of 129–161 km/h occurred in northern New England, however, the weather station at Fox failed to record wind velocities due to the loss of electrical power. Extensive rains at Fox for the five days prior to (27 cm) and during (3.8 cm) the storm saturated soils, reduced the ability of trees to resist high winds, and resulted in more extensive blow down than wind speeds would indicate. Forest stands of all ages were damaged; however, the oldest stands were most affected. The hurricane blew over more than 3776 cubic meters of timber at Fox, of which 2832 was salvaged [8]. Since 1938, no hurricanes or natural disturbance of similar magnitude have occurred at Fox.

In 1955, 52 randomly located 0.08 ha (1/5 acre) circular plots were established by Henry Baldwin. "Nearly all" of the plots were in areas that had improvement cuts during the previous 20 years [27]. Most plots have been subject to management activities of the surrounding stands since establishment. Eleven plots have received no management activities in the period of 1955–2011.

2.3. Management History

A main objective of the 1952 Fox Forest management plan was to produce high-quality saw timber [32]. At that time, stands at Fox were considered understocked, with a stated goal to increase overall stocking. The current management goals at Fox are to use wise forest management techniques to produce sustainable periodic harvest volume and maintain high-quality, high-value species within a diverse forest matrix [33]. Three species, eastern white pine (*Pinus strobus*), northern red oak (*Quercus rubra*), and sugar maple (*Acer saccharum*) are considered most valuable. Other valuable species include red maple (*Acer rubrum*), red spruce (*Picea rubens*), white ash (*Fraxinus americana*), black cherry (*Prunus serotina*), white oak (*Quercus alba*) and yellow birch (*Betula alleghaniensis*). Less valuable species include eastern hemlock (*Tsuga Canadensis*), American beech (*Fagus grandifolia*), red pine (*Pinus resinosa*), and balsam fir (*Abies balsamea*). Quality red maple has increased in value and species preferences have changed over recent decades. In 1940, Henry Baldwin observed that northern red oak was less desirable due to its susceptibility to gypsy moth [32].

Following the post-hurricane salvage, there are few records of management activities on the 52 CFI plots until the 1950s and early 1960s, when significant areas of the forest were thinned. Removals were chemically debarked or girdled for later pulpwood harvest. Between 1955 and 1965, 42% of plots were thinned for pulp (Table 1). Numerous pulp harvests in the early 1960s targeted the removal of American beech and red maple. From the late 1960s through the 1970s, management activities at Fox where dominated by intermediate harvests (thinning to improve growth on quality stems). Starting in the 1980s the maturation of stands on the Forest lead to more silvicultural practices (both even-aged and uneven-aged) focused on establishing regeneration, with some final harvest operations. This management history applies to most, but not all, of the CFI plots. While this would seem to present the opportunity to assess the effects forest management on stand development through time, management activities across the plots have been diverse, widespread, and spread out over time, making comparisons between treatments difficult.

Table 1. Management activities through time on continuous forest inventory (CFI) plots at the Caroline A. Fox Research and Demonstration Forest, Hillsborough, NH. Data based on planning reports, project maps and notes taken during CFI sampling.

Time Period	Management Activity	45 Plots
1955–1965	Debarking and pulp harvest	42% (19 plots)
1966–1984	Timber harvest	22% (10 plots)
1985–2001	Timber harvest *	13% (6 plots)
2002–2011	Timber harvest *	13% (6 plots)
	Plots unmanaged 1955–2011	24% (11 plots)

* Timber harvests from 1984 to the present include both even-aged intermediate and uneven-aged (both single tree and group selection) treatments.

2.4. Sample Design and Data Collection

Of the 52 permanent CFI plots established in 1955, 45 have complete data sets for tree diameters for the entire 56-year period. This study was established using English units of measure commonly used in forestry in the United States. Diameter data from 1965, 1984, 2001, and 2011 were used to examine changes in tree density, basal area, shifts in size class distribution, ingrowth, and mortality. Data from 1960 and 1975 was omitted from this analysis. Plot measurements included all trees 11.4 cm (4.5 inches) diameter at breast height (dbh) or larger in circular plots 16.0 meters in radius [25]. In 2001, the minimum diameter for inclusion was lowered to 7.6 cm (3 inches) dbh. Henry Baldwin reported that his study examined stems "12.7 cm (5 inches) dbh and larger" [26,27] but the measurement of stems 11.4 cm (4.5 inches) and larger suggests that stems rounded up to 12.7 cm (5 inches) were included. This report focuses on trees ≥11.4 cm dbh. Trees were renumbered in 1984, preventing the identification of ingrowth or mortality of individual trees between early measurements, and those after 1984. However tree-to-tree comparisons can be made from 1955 to 1965, and again from 1984 to 2011.

Data collected on the Fox CFI plots includes tree species, diameter at breast height (dbh), and beginning in 1984, total tree height and merchantable height. Trees were mapped using the distance to the nearest 3 cm (0.1 feet) and the azimuth from the plot center. Diameter was measured using a metal diameter tape to the nearest 0.25 cm (0.1 inches) at 1.37 meters above a permanent horizontal line designated in script paint.

2.5. Data Analysis

2.5.1. Changes in Composition

Changes in species composition are represented by changes in tree density (stems per hectare) and basal area (square meters per hectare) for the combined 45 plots with continuous data.

2.5.2. Recruitment of New Stems

Recruitment (ingrowth into the smallest size class, 11.4 cm dbh) was examined for two time periods, 1984–2001 and 2001–2011. Recruitment is presented as the number of stems/hectare/year.

2.5.3. Tree Mortality and Removal

For this study, tree mortality is identified as natural mortality. Removals include both those trees removed in harvest operations (cut) and those debarked or girdled (killed) for future pulp harvest and noted during plot sampling. Mortality rates (% stems/year) are only reported for three sample intervals: 1955–1965, 1984–2001, and 2001–2011. Mortality rates for trees 7.6–11.4 cm dbh (which are only available for the latest sample period) are only reported for the mortality by size class. They have been excluded from overall mortality rates to allow comparisons between the three sample periods. Rates have been annualized to allow comparison between sample periods of different lengths.

2.5.4. Size Class Distribution

Trees have been grouped into 10.2 cm (4″) size classes for each sample period examined to demonstrate shifts in the size class distribution as the forest ages. Trees 7.6–11.4 cm (3–4.5″) were included in 2001 and 2011 to suggest levels of future recruitment but are ignored when describing the size class distribution due to the smaller span of the size class.

3. Results

3.1. Composition

Changes in forest composition reflect initial stocking, time since disturbance, and management activities. The initial forest composition in 1955 (17 years post-hurricane) was dominated by eastern white pine, eastern hemlock, red maple, sugar maple, American beech, and northern red oak (Table 2). Between 1955 and 2011 the largest species specific increases in density occurred in eastern hemlock (96.9 to 217.5), northern red oak (41.5 to 67.5), and red maple (108.5 to 121.3) (Figure 2). Total tree density increased from 540.2 to 642.2 stems/hectare. Basal area accumulation was dominated by eastern hemlock (3.7 to 13.0), northern red oak (2.1 to 7.5), and eastern white pine (5.1 to 11.9). The total basal area increased from 18.8 to 44.7 m^2/ha.

Table 2. Changes in tree density and basal area in forests on the Caroline A. Fox Research and Demonstration Forest, Hillsborough, NH, over the 56-year period between 1955–2011.

	1955		**1965**		**1984**		**2001**		**2011**	
Species	**Density**	**BA**	**Density**	**BA**	**Density**	**BA**	**Density**	**BA**	**Density**	**BA**
	(stems/ha ± SE *)	**(m^2/ha)**	**(stems/ha ± SE)**	**(m^2/ha)**	**(stems/ha ± SE)**	**(m^2/ha)**	**(stems/ha ± SE)**	**(m^2/ha)**	**(stems/ha ± SE)**	**(m^2/ha)**
White Pine	99.3 ± 26.7	5.1 ± 0.8	105.8 ± 27.2	7.3 ± 1.0	77.1 ± 25.0	9.3 ± 1.4	86.0 ± 24.5	11.3 ± 1.6	68.7 ± 14.8	11.9 ± 1.4
Hemlock	96.9 ± 16.8	3.7 ± 0.4	113.2 ± 19.8	4.9 ± 0.6	168.8 ± 23.5	9.2 ± 1.1	224.1 ± 25.2	12.2 ± 1.6	217.5 ± 24.2	13.0 ± 1.7
Balsam Fir	10.9 ± 7.7	0.3 ± 0.0	10.9 ± 5.9	0.3 ± 0.0	1.5 ± 0.7	0.0 ± 0.0	0.5 ± 0.5	0.0 ± 0.0	0.7 ± 0.7	0.0 ± 0.0
Red Spruce	27.7 ± 17.3	0.6 ± 0.0	27.7 ± 17.3	0.8 ± 0.1	16.6 ± 7.4	0.6 ± 0.0	14.1 ± 6.4	0.6 ± 0.0	9.6 ± 4.0	0.5 ± 0.0
Sugar Maple	31.1 ± 8.6	1.1 ± 0.3	36.1 ± 9.1	1.2 ± 0.3	39.5 ± 9.1	1.4 ± 0.3	37.1 ± 8.9	1.5 ± 0.3	37.6 ± 8.2	1.7 ± 0.3
Red Maple	108.5 ± 18.5	2.5 ± 0.3	104.5 ± 19.5	2.5 ± 0.2	141.6 ± 21.0	4.1 ± 0.4	132.9 ± 18.0	4.4 ± 0.5	121.3 ± 15.3	4.6 ± 0.5
White Ash	11.9 ± 2.5	0.3 ± 0.0	15.1 ± 3.0	0.5 ± 0.0	22.7 ± 3.7	0.9 ± 0.1	19.5 ± 4.4	0.8 ± 0.1	16.8 ± 4.2	0.9 ± 0.1
Aspen	2.2 ± 0.7	0.0 ± 0.0	7.9 ± 3.2	0.2 ± 0.0	6.7 ± 4.2	0.3 ± 0.0	4.9 ± 2.7	0.3 ± 0.0	4.0 ± 1.7	0.3 ± 0.0
Black Cherry	0.7 ± 0.5	0.0 ± 0.0	0.7 ± 0.5	0.0 ± 0.0	1.7 ± 0.5	0.0 ± 0.0	0.5 ± 0.5	0.0 ± 0.0	0.2 ± 0.2	0.0 ± 0.0
Paper Birch	41.5 ± 8.6	1.2 ± 0.1	48.9 ± 10.4	1.7 ± 0.1	46.7 ± 10.9	1.9 ± 0.2	41.8 ± 8.2	2.1 ± 0.2	17.3 ± 3.7	1.0 ± 0.1
Yellow Birch	9.9 ± 3.2	0.3 ± 0.0	10.9 ± 3.2	0.4 ± 0.0	16.8 ± 4.7	0.6 ± 0.1	18.8 ± 5.2	0.8 ± 0.1	14.8 ± 4.2	0.7 ± 0.1
Black Birch	10.1 ± 3.0	0.3 ± 0.0	7.7 ± 2.2	0.2 ± 0.0	16.6 ± 4.2	0.6 ± 0.0	19.0 ± 5.4	0.7 ± 0.1	21.3 ± 5.9	0.8 ± 0.1
Beech	32.4 ± 13.1	1.0 ± 0.2	32.1 ± 13.1	1.1 ± 0.2	33.1 ± 13.6	1.3 ± 0.2	40.5 ± 14.6	1.8 ± 0.2	39.8 ± 13.3	1.8 ± 0.2
Basswood	1.7 ± 0.5	0.0 ± 0.0	1.7 ± 0.2	0.0 ± 0.0	1.7 ± 0.2	0.1 ± 0.0	1.7 ± 0.5	0.1 ± 0.0	1.7 ± 0.7	0.1 ± 0.0
Red Oak	41.5 ± 9.1	2.1 ± 0.3	45.0 ± 9.1	2.8 ± 0.4	68.2 ± 11.4	5.4 ± 0.7	70.7 ± 10.9	6.9 ± 0.9	67.5 ± 9.9	7.5 ± 0.9
Other *	13.8 ± 4.0	0.3 ± 0.0	13.8 ± 4.4	0.3 ± 0.0	6.4 ± 3.0	0.2 ± 0.0	4.4 ± 2.7	0.2 ± 0.0	3.5 ± 1.2	0.2 ± 0.0
Total	540.2	18.8	582.2	24.1	665.2	36.0	716.1	43.7	642.2	44.7

* black ash, black oak, butternut, chestnut, elm, gray birch, hophornbeam, shagbark hickory, pitch pine, white oak; basal area (BA). standard error of the mean (SE).

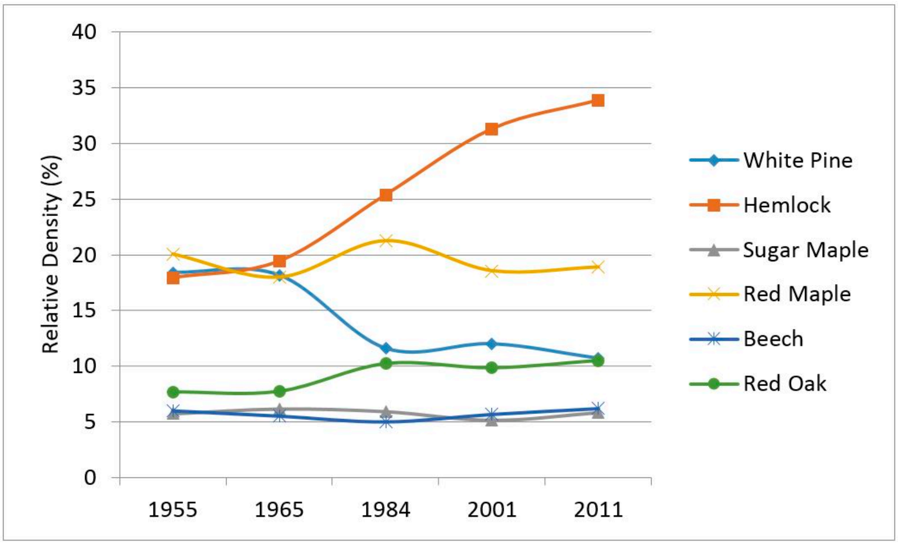


Figure 2. Changes in relative density (%) of major tree species at Caroline A. Fox Research and Demonstration Forest, Hillsborough, NH, USA.

3.2. Recruitment

Stem recruitment can be an indicator of how forest composition and species dominance will change through time. However, management activities, differential growth of newly recruited stems, and mortality can modify expected trends. In 1965, recruitment into the 11.4 cm size totaled 11.9 trees/hectare/year and was dominated by red maples, eastern hemlock, and early successional species (Figure 3). White pine, red oak, American beech, and sugar maple were also well-represented in the recruitment. Total recruitment decreased to 6.7 trees/hectare/year in 1984–2001 and further decreased to 4.8 stems/hectare/year in 2001–2011. Red maple and eastern hemlock continued to dominate. Early successional species and white pine also were common recruits 1955–1965, but dropped precipitously in later samples. Red oak and sugar maple continue to be recruited in stable numbers while American beech has increased in later samples.

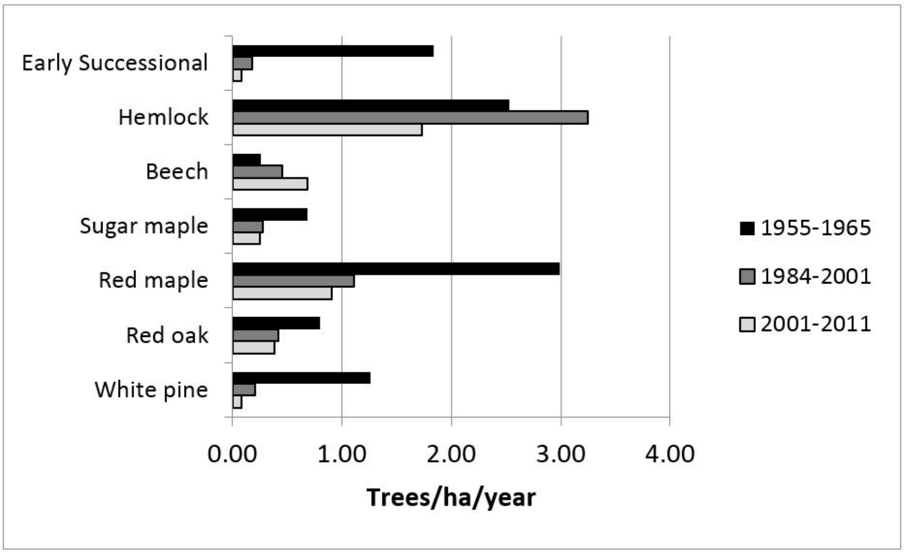


Figure 3. Recruitment of new stem ≥11.4 cm diameter at breast height (dbh) into CFI plots at the Caroline A. Fox Research Forest, Hillsborough, NH, in stems/hectare/year. Early successional species include aspen, gray birch, and paper birch.

3.3. Tree Mortality and Removal

Between 1955 and 2011 the rate of mortality increased from 0.26%/year 1955–1965 to 0.87%/year 1984–2001 and 1.03%/year 2001–2011 for all species (Table 3). Early successional species mortality rates increased from 0.34%/year in 1955–1965 to 2.18%/year in 1984–2001 and 4.21%/year in 2001–2011, by far the largest increase in mortality rate. Mortality rates for red oak and red maple do not reflect the overall pattern and began to decrease in 2001–2011. Removal rates peaked at 1.04%/year from 1955–1965 and hit a low of 0.12%/year between 1984 and 2001. In 1955–1965, removals were dominated by red maple (2.71%/year) and beech (1.44%/year). Between 1984 and 2001, red maple (0.25%/year) and white pine (0.23%/year) were the most frequently removed species. By 2001–2011, early successional species (1.07%/year) and red oak (0.74%/year) dominated removals.

Examining tree mortality across size classes provides insight into which size classes have the highest mortality rates and how patterns have changed through time. In 1955–1965, mortality rates were low, 0.18 to 0.29%/year (Figure 4), and stable across size classes. As tree density and size increased, small tree mortality rates increased. Mortality began to increase for smaller size classes in 1984–2001. Between 2001 and 2011, mortality rates decreased with size class up to 41.9–51.8 cm dbh and stabilized at 0.29%/year for larger stems.

Table 3. Tree mortality and removal rates for trees ≥11 cm dbh on the Caroline A. Fox Research and Demonstration Forest, Hillsborough, NH, over the 27-year period of 1984–2011. Early successional species include aspen, gray birch, and paper birch.

Species	Density (stems/ha)	1955–1965 (%/year)	Density (stems/ha)	1984–2001 (%/year)	Density (stems/ha)	2001–2011 (%/year)
White pine	99.3		77.1		86.0	
Mortality		0.36		0.85		1.03
Cut/Killed		0.30		0.23		0.19
Eastern hemlock	96.9		168.8		224.1	
Mortality		0.07		0.31		0.43
Cut/Killed		0.07		0.03		0.48
Sugar maple	31.1		39.5		37.1	
Mortality		0.36		0.92		1.04
Cut/Killed		0.36		0.08		0.22
Red maple	108.5		141.6		132.9	
Mortality		0.28		1.09		0.91
Cut/Killed		2.71		0.25		0.38
Northern red oak	41.5		68.2		70.7	
Mortality		0.14		0.42		0.37
Cut/Killed		0.90		0.15		0.74
American beech	32.4		33.1		40.5	
Mortality		0.08		0.49		1.45
Cut/Killed		1.44		0.00		0.29
Early successional	47.7		53.6		46.7	
Mortality		0.34		2.18		4.21
Cut/Killed		0.68		0.03		1.07
All Species	540.2		665.2		716.1	
Mortality		0.26		0.87		1.03
Cut/Killed		1.04		0.12		0.44

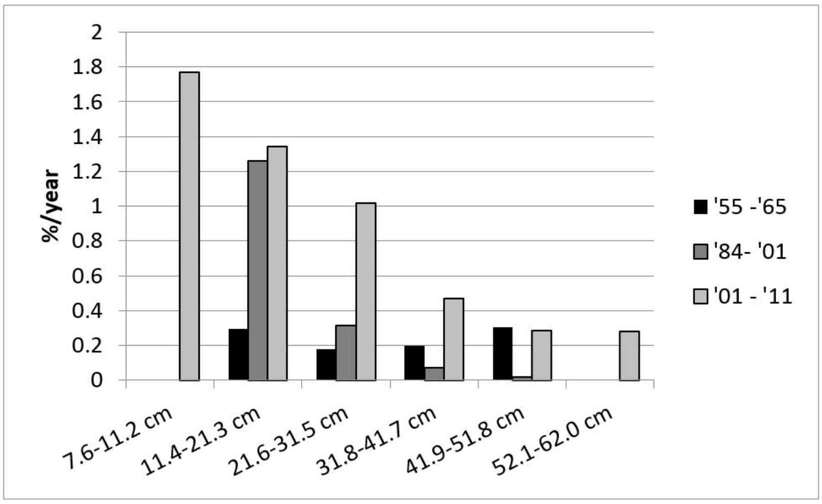


Figure 4. Changes in tree mortality rates by size class at the Fox Forest through time.

3.4. Size-Class Distribution

The cumulative effects of recruitment, growth, mortality, and removals have been characterized by shifts in size class distributions through time. The smallest size class should be ignored for the purposes of discussing shift in size-class distribution due to a lack of pre-2001 data and a smaller size range. Looking at two species, northern red oak and eastern hemlock, with dissimilar shade tolerance, a distinct change in size class distribution emerges over time.

Moderately shade-tolerant northern red oak shifted from a negative exponential or inverse J distribution in 1955 to a skewed modal distribution by 2011 (Figure 5). White pine had a similar pattern but the peak stem density has shifted from 11.4–21.3 cm to 41.9–51.8 cm size class by 2001.

By contrast the (shade-tolerant) eastern hemlock has maintained a negative exponential size-class distribution. Hemlock densities continue to peak in the 11–21 cm size class despite 56 years of growth, mortality, and removals (Figure 5). Stems have moved into larger size classes, however, in-growth into the smallest size class outpaced both mortality and growth into larger size classes through 2011. Similar patterns were observed in sugar maple, red maple, and beech.

Hemlock

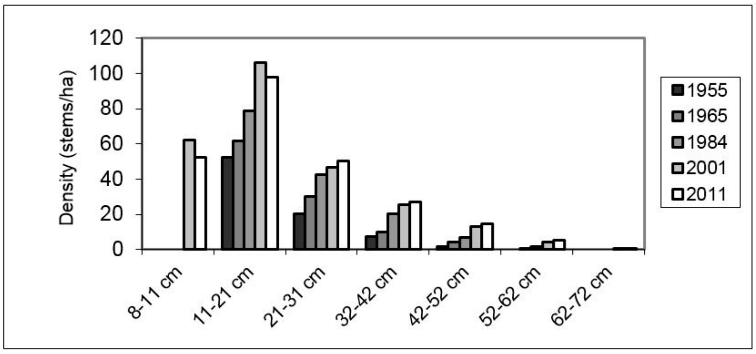
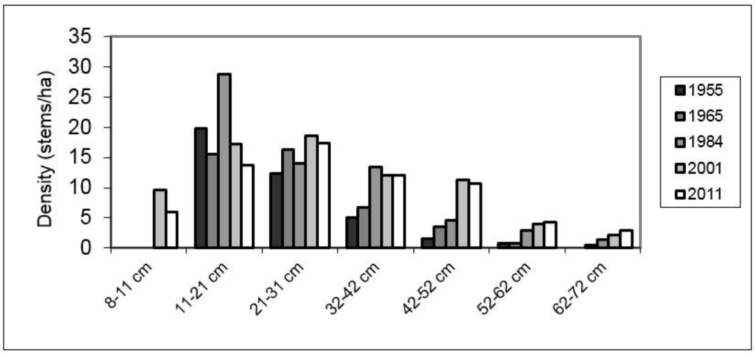
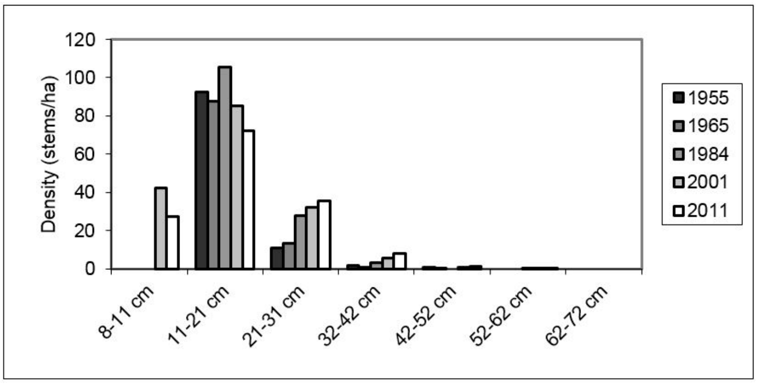


Figure 5. *Cont.*

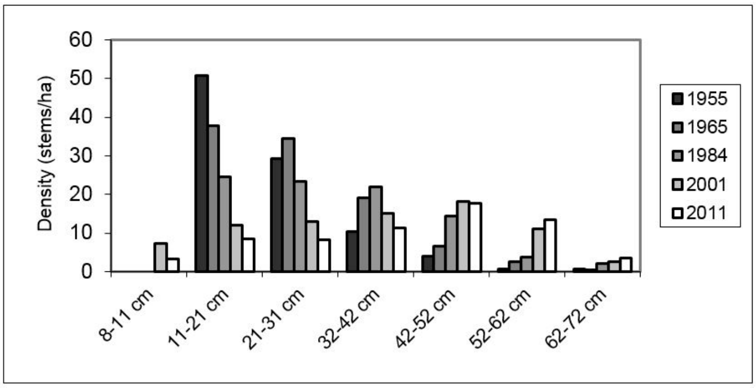
Red oak



Red maple



White pine



Sugar maple

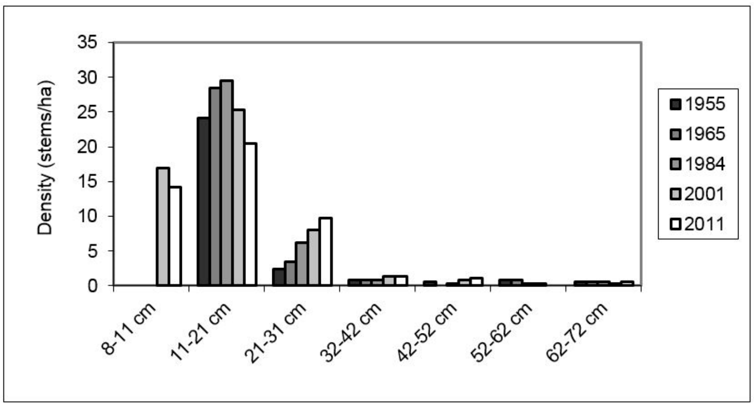


Figure 5. *Cont*.

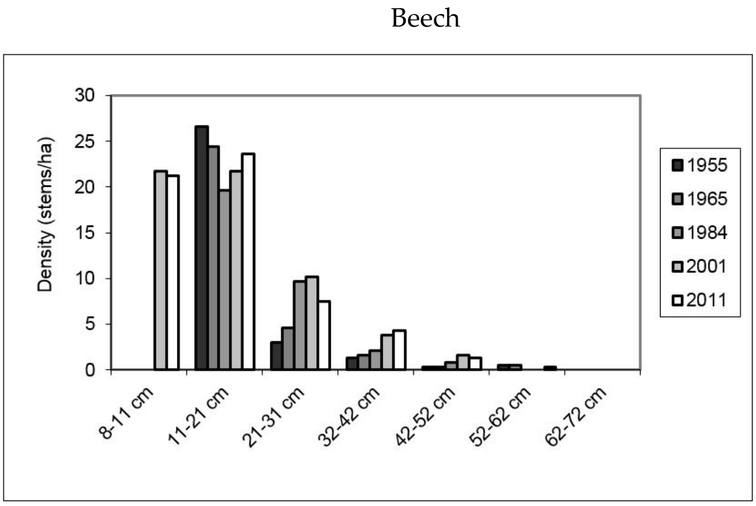


Figure 5. Size class distribution for eastern hemlock, northern red oak, red maple, eastern white pine, sugar maple, and beech in CFI plots at the Caroline A. Fox Research Forest, Hillsborough, NH.

4. Discussion

In New England, the abandonment of agricultural land resulted in a forested landscape where species composition was changing in a predictable pattern as forests age [34]. In the absence of disturbance, early successional species gradually decrease while late successional species increase. One factor influencing these patterns is the emergence of pathogens that target the late successional species like hemlock, beech, and sugar maple. Forests like Fox, which were struck by the 1938 hurricane, experienced widespread damage followed by extensive salvage operations, setting back post-agriculture successional trends. By 1955 species with intermediate shade tolerance (red oak, white pine, red maple) dominate tree density and reflect the broader trends occurring across New Hampshire. Over time shade-tolerant species (eastern hemlock, sugar maple, American beech) have become established as a key component of stands at Fox despite management activities that favored the removal of beech. Across the state, growing stock increased for eastern hemlock, northern red oak, sugar maple, red maple, and eastern white pine from 1983 to 2007 [35,36].

However, unlike New Hampshire as a whole, red maple and beech are not the most common species at Fox [36]. This represents a shift from 1955 when red maple was the most commonly occurring species. Efforts to control red maple and beech at Fox included chemical debarking and pulp harvests in the 1950s and 1960s effectively limited the increases of these species in larger size classes. Statewide, red maple has shown large increases in density from 1960 to 2007, while beech has increased in sapling density [36,37]. Red maple and beech at Fox runs counter to the statewide trend with only small increases in density over 56 years.

The recruitment of new stems into the 11 cm dbh size class is a function of understory light levels and the composition of the seedling and sapling pools. Under closed canopies, shade-tolerant species like hemlock and beech are the only species that thrive. CFI plots at Fox include both managed and unmanaged plots providing a range of understory light levels. Since re-entry periods and management intensity vary across the CFI plots, it is difficult to associate the impact of management on recruitment across Fox Forest. Shade-intolerant early successional species like paper birch and aspen were the third most common recruit in 1955–1965, but are poorly represented in recruitment over the last 27 years. Changes in white pine recruitment rates have been very similar to those for early successional species. White pine recruitment on sites with predominantly hardwood soil (fine and washed tills) may be limited to extreme disturbance like agricultural abandonment or severe hurricane damage. In contrast, shade-tolerant species (hemlock, beech, and sugar maple) were only 30% of recruited stems in 1955–1965 but made up 56 to 59% of recruitment 1984–2011. Until recently, silvicultural applications at Fox have focused on intermediate treatments in a primarily even-aged, relatively young forest. A lack of recent heavy cutting practices may account for the dominance of later seral species in ingrowth. As the forest has matured, more recent management activities have included treatments planned to establish desired regeneration. Both even-aged (chiefly shelterwood) and uneven-aged (chiefly group selection) approaches have been utilized to encourage the establishment of desired mid-successional species like northern red oak and eastern white pine. Regeneration from these activities has not yet reached the threshold size for measurement in the CFI plots. However, the next re-measure may begin to capture the results of these management actions. The dominance of soils with hardwood tendencies means that eastern white pine regeneration will continue to face stiff hardwood competition. While management will likely result in the continued presence of eastern white pine at Fox, it is unlikely to remain as strong a component.

Rates of mortality at Fox are within the range of natural mortality (0.26–1.04%/year) but are increasing through time. From 1997 to 2007 the mortality rate for trees in NH was 1.0% per year by volume [36]. New Hampshire statewide data [36] reported mortality rates have increased since the 1970s from 0.6%/year to 1.0%/year in 2007. The distribution of mortality rates across size classes at Fox very closely resemble statewide patterns of increasing mortality with size [36]. These results would be expected during the stem exclusion stage of even-aged forest development. Thinning young stands should depress natural mortality rates by reducing competition and partially explains low mortality rates in 1955–1965. As forest-wide tree crowding has increased from 1955 to 2011 [38], despite thinning, mortality rates have steadily increased for all species. In 2001, when socking levels at Fox passed 100% relative density [37] (the equivalent to the A-line on a stocking chart), density dependent mortality increased, particularly for early successional species. In fact, mortality rates for early successional species ballooned to 4.21%/year in 2001–2011, which exceeded the 3.3%/year reported for paper birch in NH in 1997–2007 [36]. Contributing factors to overall mortality rates include forest pathogens like ash yellows, beech bark disease, and white pine needle casts. Ash yellows was first identified in New Hampshire at Fox in 1997 [39] with resulting mortality near grassy openings. American beech had a mortality rate in 2001–2011 of 1.49%/year, close to the statewide average for the species [36]. Increased mortality of stems infected with beech bark disease has recently been observed and appears to be confirmed by the elevated beech mortality rates from 2001–2011. This contributes to the development of root sprouts and recruitment of new beech stems. Research on white pine needle cast is ongoing at Fox [40].

Removal rates peaked at 1.04%/year from 1955 to 1965 and a low of 0.12%/year between 1984 and 2001. In 1955–1965, removals were concentrated on red maple and beech with a stated management goal of reducing these less preferred species. Between 1984 and 2001, red maple and white pine were the most frequently removed species. By 2001–2011, early successional species and red oak dominated removals. Removal rates reflect a shift from early intermediate harvests designed to improve species mix to later thinning that maximize growth on high-quality stems and treatments, which regenerate preferred species. As removal rates have dropped, tree mortality rates have climbed. This also reflects a shift from pole-size timber that was 50% stocked to somewhat overstocked mature stands. Statewide, removal rates have exceeded morality rates in New Hampshire since the 1940s [41].

Overall trends in size class distribution for the state of New Hampshire indicate that the small trees are decreasing in density (1983–2007), while mid-size and large trees are increasing in density [36]. At Fox all six canopy dominant tree species experienced decreases in the 11–21 cm size-class and increases in density of larger stems over a similar time period. At Fox, northern red oak and eastern white pine have shifted from reverse J-shaped or negative exponential distribution to a skewed modal distribution. Statewide, white pine has a skewed modal distribution with very few stems in the smaller size classes [36]. Limited recruitment of new white pine stems may reflect that most of Fox has soils that favor hardwoods. Eastern hemlock, American beech, sugar maple, and red maple all continue to have negative exponential size-class distributions at Fox. Size-class distributions for hemlock in second growth stands in Massachusetts, USA, differed from old growth stands by having skewed unimodal and negative exponential distributions while old-growth had bell-shaped and rotated sigmodal distributions [42]. In late successional hemlock hardwood forests, Woods found that size class distributions for eastern hemlock were negative exponential in shape and stable over three decades in Michigan. The fact that this shade-tolerant species at Fox still maintains negative exponential size-class distributions reflects the successional status of the forest 74 years post hurricane. Hemlock at Fox contrast sharply with statewide trends of limited numbers sapling size trees, and a somewhat modal size class distribution [36].

5. Conclusions

The results of this study reflect natural successional processes [34] confronted with active forest management, which have resulted in shifts in overall size and species composition. Management activities have slowed but not reversed natural successional trends. Management has neither favored nor worked against eastern hemlock, and has not limited it from increasing in density and basal area. Management that worked against young red maple (particularly in the 1950s and 1960s) appears to be the reason this species, which dominated Fox in 1955, and still dominates New Hampshire in general [41], was not the most frequently occurring species at Fox in 2011. However, despite these early management activities to limit red maple, it continues to be the second most commonly recruited species on the property. Management has maintained the post agricultural/post disturbance eastern white pine component on soils with strong hardwood tendencies, but thus far been unable to regenerate this off-site species in the abundance shown post-farm abandonment and post hurricane. The component of northern red oak has continued to increase in size and density primarily due to rapid growth, which can be attributed to productive hardwood soils and management actions which favor this valuable species.

Acknowledgments: The authors of this study wish to thank the following: NH State Research Foresters, Henry I. Baldwin, Peter H. Allen, and Phil Verrier and former Fox Program Forester Kenneth M. Desmarais for study design, study establishment and early data collection (Pre 2005). Former Fox Forestry Fellow Susan E. Moury for her work in 2001 to locate, re-monument, and re-measure the Fox CFI plots, as well as scanning and putting the historical plot data in digital format. Mark J. Ducey of the University of New Hampshire (UNH), Department of Natural Resources & the Environment for assisting Susan in with funding and protocols. Former Fox Intern Peter Lucas, for locating plots and re-measuring all the east side plots during the winter of 2011, and former Fox Intern Alex Metzger, for his assistance completing data collection during the summer of 2011. Patricia L Shaw-Allen for statistical consultation. Funding for this work was provided by the UNH Undergraduate Research Opportunity Grant and the Caroline A. Fox trust.

Author Contributions: B.A. collected and analyzed data and wrote manuscript. I.S. collected data, managed study and wrote the manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Hibbs, D.E. Forty years of forest succession in central New England. *Ecology* **1983**, *64*, 1394–1401. [CrossRef]
2. Whitney, G.G. Fifty years of change in the arboreal vegetation of Heart's Content, an old-growth hemlock-white pine- northern hardwood stand. *Ecology* **1984**, *65*, 403–408. [CrossRef]
3. Franklin, J.S.; DeBell, D.S. Thirty-six years of tree population changes in old-growth Pseudotsuga-Tsuga forest. *Can. J. For. Res.* **1988**, *18*, 633–639. [CrossRef]
4. Mabry, C.; Korsgren, T. A permanent plot study of vegetation and vegetation-site factors fifty years following disturbance in central New England, USA. *Ecoscience* **1998**, *5*, 232–240. [CrossRef]
5. Leak, W.B. Fifty years of compositional change in deciduous and coniferous forests in New Hampshire. *Can. J. For. Res.* **1987**, *17*, 388–393. [CrossRef]
6. Ward, J.S.; Smith, D.M. *Dynamics of Connecticut Hemlock Stands*; USDA Forest Service General Technical Report: Newtown Square, PA, USA, 2000.
7. Leak, W.B.; Yamasaki, M. *Seventy-Year Record of Changes in the Composition of Overstory Species by Elevation on the Bartlett Experimental Forest*; U.S. Department of Agriculture: Washington, DC, USA, 2010.
8. Baldwin, H.I. *Hurricane Damage to the Fox Forest*; DRED, Div. Forest and Lands: Hillsboro, NH, USA, 1939.

9. Spurr, S.H. Natural restocking of forests following the 1938 hurricane in central New England. *Ecology* **1956**, *37*, 443–451. [CrossRef]
10. Bormann, F.H.; Likens, G.E. Catastrophic disturbance and the steady state of northern hardwood forests. *Am. Sci.* **1979**, *67*, 660–669.
11. Hemond, H.F.; Niering, W.A.; Goodwin, R.H. Two decades of vegetation change in the Connecticut Arboretum Natural Area. *Bull. Torrey Bot. Club* **1983**, *110*, 184–194. [CrossRef]
12. Merrens, E.J.; Peart, D.R. Effects of hurricane damage on individual growth and stand structure in hardwood forest growth in New Hampshire, USA. *J. Ecol.* **1992**, *80*, 787–795. [CrossRef]
13. Peart, D.R.; Cogbill, C.V.; Palmiotto, P.A. Effects of logging history and hurricane damage on canopy structure in a northern hardwood forest. *Bull. Torrey Bot. Club* **1992**, *119*, 29–38. [CrossRef]
14. Foster, D.R. Disturbance history, community organization and vegetation dynamics of old-growth Pisgah Forest, South-Western New Hampshire, USA. *J. Ecol.* **1988**, *76*, 105–134. [CrossRef]
15. Scharz, P.A.; Fahey, T.J.; Martin, C.W.; Siccama, T.G.; Bailey, A. Structure and composition of three northern hardwood-conifer forests with differing disturbance histories. *For. Ecol. Manag.* **2001**, *144*, 201–212. [CrossRef]
16. Foster, D.R.; Boose, E.R. Patterns of forest damage resulting from catastrophic wind in central New England, USA. *J. Ecol.* **1992**, *89*, 79–90. [CrossRef]
17. Foster, D.R. Species and stand response to catastrophic wind in central New England, USA. *J. Ecol.* **1988**, *76*, 135–151. [CrossRef]
18. Ware, K.D.; Cunia, T. Continuous Forest Inventory with partial replacement of samples. *For. Sci.* **1962**, *3*, 1–40.
19. Woodcock, H.; Patterson, W.A., III; Davies, K.M., Jr. The relationship between site factors and white ash (*Fraxinus americana* L.). *For. Ecol. Manag.* **1993**, *60*, 271–290. [CrossRef]
20. Soares, P.; Tomé, M.; Skovsgaard, J.P.; Vanclay, J.K. Evaluating a growth model for forest management using continuous forest inventory data. *For. Ecol. Manag.* **1995**, *71*, 251–265. [CrossRef]
21. Scott, C.T. Sampling methods for estimating change in forest resources. *Ecol. Appl.* **1998**, *8*, 228–233. [CrossRef]
22. Moisen, G.G.; Frescino, T.S. Comparing five modelling techniques for predicting forest characteristics. *Ecol. Model.* **2002**, *157*, 209–225. [CrossRef]
23. Zhao, D.; Borders, B.; Wilson, M. Individual-tree diameter growth and mortality models for bottomland mixed-species hardwood stands in the lower Mississippi alluvial valley. *For. Ecol. Manag.* **2004**, *199*, 307–322. [CrossRef]
24. Poso, S. Change monitoring with permanent sample plots. In *Managing Forest Ecosystems*; Springer: Dordrecht, The Netherlands, 2006; Volume 10, pp. 65–84.
25. Baldwin, H.I. Diameter growth on Fox Forest. *Fox For. Note* **1961**, *91*, 1.
26. Baldwin, H.I. Basal area growth on the Fox Forest. *Fox For. Note* **1962**, *95*, 1.
27. Baldwin, H.I.; Verrier, P. Twenty years of basal area growth on Fox Forest. *Fox For. Note* **1997**, *114*, 1.
28. Allen, B.P.; Seaboyer, I.V.; Desmarais, K.M. Diameter Growth on Fox Forest 1955–2011. *Fox For. Note* **2014**, *129*, 6.
29. Allen, B.P.; Seaboyer, I.V.; Desmarais, K.M. Volume Growth on Fox Forest 1984–2011. *Fox For. Note* **2014**, *130*, 5.
30. Historical Weather Data, Concord Municipal Airport, Concord, NH, National Climate Data Center, NOAA. Available online: https://www.ncdc.noaa.gov (accessed on 9 May 2017).
31. Spielman, J.; Pilgrim, S.; Bolanger, R. The role of soils maps in forestry. In *Forest Notes*; Society for the Protection of New Hampshire Forests: Concord, NH, USA, 1984; pp. 5–9.
32. Baldwin, H.I.; Natti, T. *Fox Forest Management Plan*; NH DRED Forest and Lands: Hillsboro, NH, USA, 1952.
33. Desmarais, K.M.; Seaboyer, I.V. *Management Plan for the Caroline A. Caroline A. Fox Research and Demonstration Forest*; NH DRED Forest and Lands: Hillsboro, NH, USA, 2009.
34. Frieswyk, T.; Widmann, R. *Forest Statistics for New Hampshire: 1983 to 1997*; USDA Forest Service, Northeastern Research Station Resource Bulletin: Newtown Square, PA, USA, 2000; p. 130.
35. Morin, R.S.; Barnett, C.J.; Brand, G.J.; Butler, B.J.; Domke, G.M.; Francher, S.; Hansen, M.H.; Hatfield, M.A.; Kurtz, C.M.; Moser, W.K.; et al. *New Hampshire's Forests 2007*; USDA Forest Service, Northeastern Research Station Resource Bulletin: Newtown Square, PA, USA, 2011; p. 56.

36. Frieswyk, T.; Malley, A.M. *Forest Statistic for New Hampshire 1973 and 1983*; USDA Forest Service, Northeastern Research Station Resource Bulletin: Newtown Square, PA, USA, 1985; p. 100.
37. Allen, B.P.; Seaboyer, I.V.; Desmarais, K.M. *Changes in Relative Density over Fifty-Six Years Following the 1938 Hurricane at Fox Research and Demonstration Forest, Hillsboro, New Hampshire*; DRED, Div. Forest and Lands: Hillsboro, NH, USA; p. 14.
38. Bofinger, J. (NH Division of Forests and Lands, Insect and Disease Section, Concord, NH, USA). Personal communication, 1997.
39. Munck, I.; Burns, B.; Ostrofsky, W.; Lombard, K.; Weimer, J. *Eastern White Pine Needle Damage Survey, 2011: In Maine, New Hampshire, and Vermont*; USDA FS Final Report; USDA Forest Service: Durham, NH, USA, 2012.
40. Morin, R.S.; Woodall, C.W. New Hampshire's forest resources, 2011. *Res. Note* **2012**, *140*, 4.
41. D'Amato, A.W.; Orwig, D.A.; Foster, D.R. The influence of successional processes and disturbance on the structure of Tsuga Canadensis forests. *Ecol. Appl.* **2008**, *18*, 1182–1199. [CrossRef] [PubMed]
42. Woods, K.D. Dynamics in late-successional hemlock-hardwood forests over three decades. *Ecology* **2000**, *81*, 110–126.