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LIMITATIONS ON REGENERATION POTENTIAL FOLLOWING EVEN-AGED HARVESTS IN MIXED-OAK STANDS

A Thesis in

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by

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ABSTRACT

Forest managers are interested in factors that inhibit oak (*Quercus* spp.) success, because of wide-spread regeneration failures in the forests of the eastern United States. Using stochastic frontier analysis, this project investigated the effects of pre-harvest levels of rhizomatous fern, mountain-laurel (*Kalmia latifolia* L.), and tall shrub cover on oak, red maple (*Acer rubrum* L.), and total regeneration abundance in the decade after even-aged harvest. The data used were collected from 18 mixed-oak stands in central Pennsylvania. Stands were harvested between 1997 and 2001, and were followed through their tenth growing season. Parameter estimates were compared to determine if regeneration differed in its response to the three classes of interfering vegetation and non-modeled factors. Oak and total regeneration responded similarly to rhizomatous fern and tall shrub cover, and were inhibited least by mountain-laurel. No significant relationship was found between tall shrub cover and abundance of red maple regeneration, but this species was significantly inhibited by rhizomatous fern and mountain-laurel cover, the former having the most severe effect. Oak and red maple responded very similarly to rhizomatous fern and mountain-laurel cover, but red maple exhibited significantly more resiliency to non-modeled inhibitory factors regardless of cover type. Stochastic frontier analysis was also compared with boundary analysis to demonstrate the superiority of the former as a tool for estimating maximum values.

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Chapter 1

Introduction

The oak (*Quercus*) genus has been a dominant component of forests in the eastern United States for the last 10,000 years. Oak became prominent in the East following post-glacial warming (Abrams 1992), and disturbances associated with the activities of Native Americans and European settlers through the end of the nineteenth-century appear to have favored the emergence of oak as a predominant component of the twentieth-century forest landscape (Abrams 1992). Today, oak forest types compose 49% of the forestland in the East, with oak constituting one-quarter of the growing stock volume in the region (Smith et al. 2003). The genus is not only an important raw material for furniture, flooring, and paneling, but also a critical source of food for wildlife and an integral component of ecosystem processes (Johnson et al. 2009).

The mixed-oak forest type is prevalent in central Pennsylvania. It is the edaphic climax community on xeric sites and an early- to mid-successional community on mesic sites (Abrams and Nowacki 1991). Clearcutting and similar even-aged silvicultural systems are commonly used to regenerate oak and other ecologically important species in these forests (Johnson et al. 2009). As these systems rely heavily on regeneration established prior to harvest (advance regeneration) to replace the parent stand (Johnson et al. 2009), it is of great concern that so few undisturbed mixed-oak stands in the state possess adequate advance regeneration (McWilliams et al. 1995). Under low and high-intensity measures of tree regeneration adequacy (the number of plots in a stand containing a minimum number of stems weighted by height), McWilliams et al. (1995) found that 60% to 89% of sample locations in Pennsylvania lacked adequate advance regeneration at the time of the study. Furthermore, 72% to 94% of sample locations lacked adequate advance regeneration of commercial species such as oak. Despite the paucity of advance regeneration in the study area, the authors found that 92% of heavily disturbed stands possessed adequate tree regeneration 10 to 15 years following disturbance, but only 2% to 16% of stands possessed adequate oak regeneration. The authors concluded that these stands were largely regenerated by species such as red maple (*Acer rubrum* L.) that invaded after disturbance. This study is one of many indicating that the eastern United States is simultaneously experiencing a decline in oak regeneration and an increase in the abundance of red maple (Fei and Steiner 2007; Fei et al. 2011).

The "relatively sudden and repeated regeneration failures" of oak "over widely separated areas" is commonly referred to as "the oak regeneration problem" (Lorimer 1992). This phenomenon has been documented across the eastern Unite States (Fei et al. 2011) and is of great concern due to the ecological and economic importance of the genus. A number of factors have been implicated in the oak regeneration problem. These include, but are not limited to, acorn predation, browsing pressure, twentieth-century fire suppression, and intense competition with non-oak species. In order to appreciate the decline of oak, it is important to understand the ecology of the genus as well as the disturbance history of Eastern forests.

The perpetuation of oak following disturbance is contingent upon the accumulation of advance regeneration (Johnson et al. 2009). In even-aged stands, oak advance regeneration is typically established in the two decades preceding a stand-initiating disturbance, such as a clearcut, and "includes seedlings and seedling sprouts that originate from several acorn crops (Johnson et al. 2009)." The survival and dispersal of acorns is therefore essential to the success of oak. For this reason, acorn predation has been implicated in the oak regeneration problem. As many as 96 species of vertebrates in North America consume acorns (Hass and Heske 2005). A study in Pennsylvania estimated the level of fall consumption of unburied acorns by white-tailed deer (*Odocoileus virginianus* Boddaert) to be 49% (Steiner 1995). Another study in Pennsylvania found that nearly all unburied acorns and 78% of buried acorns were removed by rodents. When unburied acorns were protected from rodents, 63% were destroyed by insects (Galford et al. 1991). Paradoxically, acorn consumers, such as tree squirrels (*Sciurus spp*.), are essential to oak success. By scatter hoarding, squirrels improve conditions for germination and increase the likelihood that acorns will escape predation (Hass and Heske 2005). Oaks produce large “bumper” crops of acorns at irregular intervals of 3 to 5 years or more (Johnson et al. 2009), with the result that populations of consumers may not be able to consume the entirety of the occasional bumper crop (Hass and Heske 2005). Observations that mesic oak forests can contain more than 50,000 oak seedlings and seedling sprouts per acre (Johnson et al. 2009) clearly demonstrate that, despite acorn predation, seedling survival is often high enough to perpetuate the oak component of these forests. However, successful germination does not ensure survival, and browsing pressure diminishes the success of oak seedlings (Lorimer 1992). Pennsylvania, for example, has a large white-tailed deer population that originated with the enactment of strict hunting laws between 1915 and 1935 (Marquis and Brenneman 1981), and numerous studies indicate that white-tailed deer populations preferentially browse oak seedlings and negatively impact natural regeneration across the state (Bowersox et al. 1995; Marquis and Brenneman 1981; Yuska et al. 2008).

While white-tailed deer populations have increased across the eastern United States, the frequency of fire has decreased. Prior to their displacement by European settlement, Native Americans ignited fires to “clear forest undergrowth, prepare croplands, facilitate travel, reduce vermin and weeds, increase mast production and improve hunting opportunities by stimulating forage and driving or encircling game (Abrams and Nowacki 2008).” These fires removed fire-sensitive competitors, increasing levels of sunlight on the forest floor. Because most oak species are characterized by a low to intermediate shade-tolerance and adaptations to fire such as “thick bark, sprouting ability, resistance to rotting after scarring, and the suitability of fire-created seedbeds for acorn germination (Abrams 1992),” recurring fire improved growing conditions for oak species on mesic sites where, in the absence of fire, they would have been displaced by more shade-tolerant competitors. Early European settlers continued to ignite fires both intentionally and unintentionally, and the combination of land clearing and fire perpetuated and, in some instances, increased the dominance of oak (Abrams 1992; Lorimer 1992). In the nineteenth-century, for example, 120 ha of forest were cleared annually in Centre County, Pennsylvania, to meet the charcoal needs of just one of the county's nine iron furnaces (Abrams and Nowacki 1992). As wildfires often followed logging activities, it should be no surprise that forests originating in this time period were dominated by oak species (Abrams and Nowacki 1992). Initiatives to suppress forest fires in the eastern United States began in the 1930's and 1940's (Lorimer 1992) and continued for many decades resulting in a "mesophication" of Eastern forests. This phenomenon has resulted in less-flammable forests, making fire reintroduction more difficult (Nowacki and Abrams 2008). The suppression of fire in the Eastern landscape is considered by some the major limiting factor in the region-wide decline of oak regeneration (Lorimer 1992; Abrams 1992). These dramatic changes in the disturbance regime are also responsible for the rapid increase of red maple throughout the region (Abrams 1998).

Through the twentieth-century and into the present, red maple has increased in abundance throughout and beyond its native range. This is one of the most dramatic changes in the structure and composition of Eastern forests in this time period and is likely unprecedented in the history of the region (Abrams 1998; Fei and Steiner 2007). Similar to the decline of oak, the increasing abundance of red maple can be explained by a suite of physiological characteristics and the disturbance history of Eastern forests. Prior to European settlement, red maple was generally a minor component of Eastern forests and was more common in bottomland than upland sites, but twentieth-century fire suppression and preferential browsing of oak by white-tailed deer have allowed this species to expand into upland forests. The wide ecological amplitude of this species is the result of a complex and unique physiology. Unlike oak, red maple regularly produces large, wind-disseminated seed crops, and, once established, red maple seedlings can grow in the understory for long periods of time due to shade and drought tolerances (Abrams 1998). This is evident in the mixed-oak stands of Pennsylvania where oak often dominates in terms of basal area but red maple dominates in terms of stem density (Fei and Steiner 2009). Following disturbance, suppressed red maple trees left standing quickly take advantage of increased sunlight levels and cut trees sprout prolifically from the stump (Abrams 1998). Unlike oak, the sprouting potential of red maple does not diminish appreciably with increasing age and diameter. Because this species often dominates stands in the number of stems per unit area, red maple stump sprouts can contribute significantly to natural regeneration (Fei and Steiner 2009). In a study of even-aged mixed-oak forests in Pennsylvania, Fei and Steiner (2009) found that red maple stump sprouts occupied 23.2% of the total potential growing space seven years after harvest. Furthermore, slightly more than half of red maple basal area in the study area three decades after harvest originated from stump sprouts. Although red maple success is in part contingent upon the accumulation of advance regeneration and superior sprouting potential, the annual production of wind disseminated seed crops allows this species to invade stands following disturbance. Therefore, red maple, unlike oak, can succeed in the absence of advance regeneration (McWilliams et al. 1995).

Despite its prominence in the understory and sub-canopy of mixed-oak forests, red maple is not the only tree species filling the void created by oak regeneration failures. A study in central Pennsylvania identified black cherry (*Prunus serotina* Ehrh.) as the second most important species in the understory of mixed-oak stands located on mesic sites (Abrams and Nowacki 1991). Although this species is typically rated rather low in shade tolerance (Hardin et al. 2001), it is capable of surviving in the understory of undisturbed stands for many years and demonstrated vigorous growth and successful recruitment in the study area (Abrams and Nowacki 1991). Sweet birch (*Betula lenta* L.), another shade-intolerant species, was also relatively important, especially on xeric sites (Abrams and Nowacki 1991). The presence of these and other non-oak species in the understory reduces the level of sunlight on the forest floor, further compounding the oak regeneration problem (Johnson et al. 2009; Lorimer et al. 1994).

Changing disturbance regimes in Eastern forests have also benefited non-tree vegetation, such as ferns and shrubs (Kaeser et al. 2008). Like non-oak tree species, the presence of non-tree vegetation in the understory can negatively impact advance oak regeneration (Johnson et al. 2009) and likely contributes to regeneration failures (Kaeser et al. 2008). Blueberry (*Vaccinium spp.*), black huckleberry (*Gaylussacia baccata* (Wangenh.) K. Koch), hay-scented fern (*Dennstaedtia punctilobula* (Michx.) Moore), and mountain-laurel (*Kalmia latifolia* L.) are four of the most abundant non-tree species in the mixed-oak forests of Pennsylvania (Fei et al. 2004). Although these species often co-occur, they affect regeneration differently (Kaeser et al. 2008). For example, high densities of white oak (*Quercus alba* L.) and chestnut oak (*Quercus prinus* L.) advance regeneration have been correlated with moderate to high levels of blueberry and huckleberry cover. Explanations for this relationship include an affinity for xeric sites shared between ericaceous shrubs and oak species and the ability of dense low growing shrubs to hide acorns and seedlings from browsing animals (Fei et al. 2004). A study by Kaeser et al. (2008) found a significantly higher density of large (1-5 ft.) oak seedlings in cover classes dominated by blueberry and huckleberry than in other cover classes common to the mixed-oak forests of central Pennsylvania. The blueberry cover class also contained the highest density of red maple seedlings. These studies indicate that low lying heath species may not interfere appreciably with advance regeneration development.

Mountain-laurel is a tall heath species capable of reaching heights greater than 10 ft. (League 2005). Unlike blueberry and huckleberry, mountain-laurel has been found to interfere with the development of advance regeneration. In a study of pitch pine (*Pinus rigida* Mill.) gaps in the southern Appalachian Mountains, Waterman et al. (1995) found no correlation between mountain-laurel cover and importance or recruitment of the major tree species in the study area. However, mountain-laurel cover negatively affected the survivorship of scarlet oak (*Quercus coccinea* Muenchh.) and the growth of all seedlings in the study area, including shade-tolerant species such as red maple. Similarly, a study of common cover classes in central Pennsylvania (Kaeser et al. 2008) found an abundance of small oak seedlings (<1 ft.) but a paucity of large oak seedlings (1-5 ft.) growing in sample plots with cover dominated by mountain-laurel. Although this study suggests that other tall, non-tree vegetation, such as witch-hazel (*Hamamelis virginiana* L.), is less detrimental to regeneration success, evidence from a study by Lorimer et al. (1994) indicates that a dense understory of shade-tolerant vegetation can interfere with the development of desirable tree regeneration. It is therefore assumed that all tall shrubs have the capacity to interfere with the development of advance regeneration, although documentation of species-specific interactions is lacking in the literature.

As with mountain-laurel, several studies have documented that hay-scented fern interferes importantly with tree regeneration (Engelman and Nyland 2006; Fei et al. 2010; George and Bazzaz 1999; Horsley 1993). Hay-scented fern is considered a native-invasive in the northeastern United States due in part to its ability to spread aggressively by means of spores and rhizomes in response to enhanced resource availability. It is also characterized by a low palatability to herbivores, wide ecological amplitude, and the ability to interfere with seedling development (Engelman and Nyland 2006). George and Bazzaz (1999) suggest that hay-scented fern acts as an "ecological filter" that affects the seedling bank and, therefore, the composition of future stands. Their study found a negative correlation between the presence of hay-scented fern and biomass growth of northern red oak (*Quercus rubra* L), red maple, and yellow birch (*Betula alleghaniensis* Britton.). Light levels at 8 cm above the forest floor explained a significant amount the variation in biomass accumulation, suggesting that interference with seedling development was primarily the result of heavy shade cast by overlapping fronds. They also found a high persistence of northern red oak and red maple under hay-scented fern. These findings were reinforced by Kaeser et al. (2008) who found a high density of small (<1 ft.) oak seedlings but a low density of large (1-5 ft.) oak seedlings underneath a cover class dominated by hay-scented fern. Although George and Bazzaz (1999) suggest that oak is the only genus in their study capable of growing above the fern layer during its predicted residency time, seedlings that emerge from the fern are more likely to be browsed by white-tailed deer. Although hay-scented fern is the most widely studied rhizomatous fern in the northeastern United States, bracken fern (*Pteridium aquilinum* L.) and New York fern (*Thelypteris noveboracensis* L.) are wide-spread and behave similarly. It is therefore assumed that these three fern species negatively impact seedling development and contribute to regeneration failure (Engelman and Nyland 2006).

Given the number of obstacles facing natural regeneration, the ability to predict regeneration potential is important to forest managers who are contemplating harvest. Johnson et al. (2009) define oak regeneration potential as the number, spatial distribution, and size of seedlings, seedling sprouts, and stump sprouts. Potential is realized after disturbance but is inherent in the state of the advance regeneration (Johnson et al. 2009). For this reason, measurable stand variables known to affect advance regeneration may be useful in predicting potential in the years following harvest. Although it may be more difficult to estimate the potential of red maple, which does not rely solely on advance regeneration, some studies stress the importance of advance regeneration in the overall success of this species (Abrams 1998; Fei and Steiner 2007; Fei and Steiner 2009).

Of all the factors that may affect ultimate regeneration success, it is likely that the extent of non-tree vegetation cover has the largest predictable influence on the competitive success of existing tree regeneration. In this study, stochastic frontier analysis (SFA) is used to estimate natural regeneration potential in the decade after harvest as a function of pre-harvest rhizomatous fern, tall shrub, and mountain-laurel cover. More specifically, the objectives of this study are (*i*) to characterize non-tree vegetation and natural regeneration in the year before harvest and in first decade of the stand initiation stage; and (*ii*) to estimate and compare oak, red maple, and total regeneration potential in this time period as a function of pre-harvest cover by the three classes listed above. As SFA is relatively uncommon in the field of forestry, the final objective of this study is (*iii*) to illustrate the advantages of this analytical tool by comparing it with boundary analysis. This is the first application of SFA for these purposes that I am aware of, and it is my hope that these functions will provide a window into the future of even-aged mixed-oak stands in central Pennsylvania and the greater mid-Atlantic region.

Chapter 2

Methods

Study Area

The study area includes 18 mixed-oak forest stands occupying a total of 759 acres. These stands are managed by the Pennsylvania Department of Conservation and Natural Resources Bureau of Forestry and span two of Pennsylvania's physiographic provinces: the Ridge and Valley and the Appalachian Plateaus. Soils in the study area are derived from sandstone, siltstone, or shale, and average annual precipitation ranges from 38 to 45 inches (Cuff et al. 1989). Elevation in these stands ranges from 847 to 2060 ft. above sea level, and site index ranges from 48 to 75 ft. at an index age of 50 years. Prior to harvest, oak composed 71% of the basal area on average, ranging from 31 to 91%. Stands were harvested between 1997 and 2001, and the method, referred to as regeneration harvesting, reduced the overstory of these stands to 15 ft^2 of basal area per acre on average.

Data Collection

The data used in this study was collected for the Oak Regeneration Study in Pennsylvania (ORSPA). Initiated in 1996, OPSPA is an ongoing cooperative research venture between the Pennsylvania Department of Natural Resources Bureau of Forestry and the Pennsylvania State University Department of Ecosystem Science and Management (For additional information on this project, see Steiner et al. 2008).

Table **2-1**: Oak Regeneration Study in Pennsylvania stands included in this study. All stands are managed by the Pennsylvania Department of Conservation and Natural Resources Bureau of Forestry.

Stand	Bureau of Forestry District	Area (acres)	N Subplots	Year Harvested	Physiographic Province
0001	5	69	120	2001	Ridge and Valley
0003	5	53	100	2001	Ridge and Valley
9603	5	26	64	1998	Ridge and Valley
9604	5	33	88	1998	Ridge and Valley
9607	5	70	120	1997	Ridge and Valley
9612	7	69	120	1997	Ridge and Valley
9614	10	47	120	1999	Appalachian Plateaus
9701	7	27	84	1998	Ridge and Valley
9706	13	33	120	1998	Appalachian Plateaus
9711	12	34	92	1998	Appalachian Plateaus
9715	3	26	104	1998	Ridge and Valley
9717	5	39	120	1999	Ridge and Valley
9718	7	31	116	1999	Ridge and Valley
9803	5	57	100	1999	Ridge and Valley
9804	7	35	120	1999	Ridge and Valley
9806	7	74	120	1999	Ridge and Valley
9808	5	25	64	2000	Ridge and Valley
9905	3	11	48	2000	Ridge and Valley

As of August of 2011, 291 measurement cycles had been performed in 70 stands (both mixed-oak and northern hardwood forest types) as part of the larger study. For this study, 18 mixed-oak stands (see Appendix A for stand descriptions) had been remeasured periodically through at least 10 years following harvest. All measurements occurred during the summers of 1996 to 2011. Depending on stand size, 12 to 30 permanent 1/20th acre (26.3 ft. radius) sampling plots, hereafter referred to as plots, were installed systematically in these stands prior to harvest. Each plot contained four milacre (3.72 ft. radius) subplots, hereafter referred to as subplots, which were installed 16.5 ft. away from plot center in each of the four cardinal directions. The locations of plot and subplot centers were recorded as coordinates obtained by GPS measurements and marked with metal spikes buried at time of initial measurements. Each stand was measured approximately 1 year prior to harvest and 1, 4, 7, and 10 growing seasons after harvest.

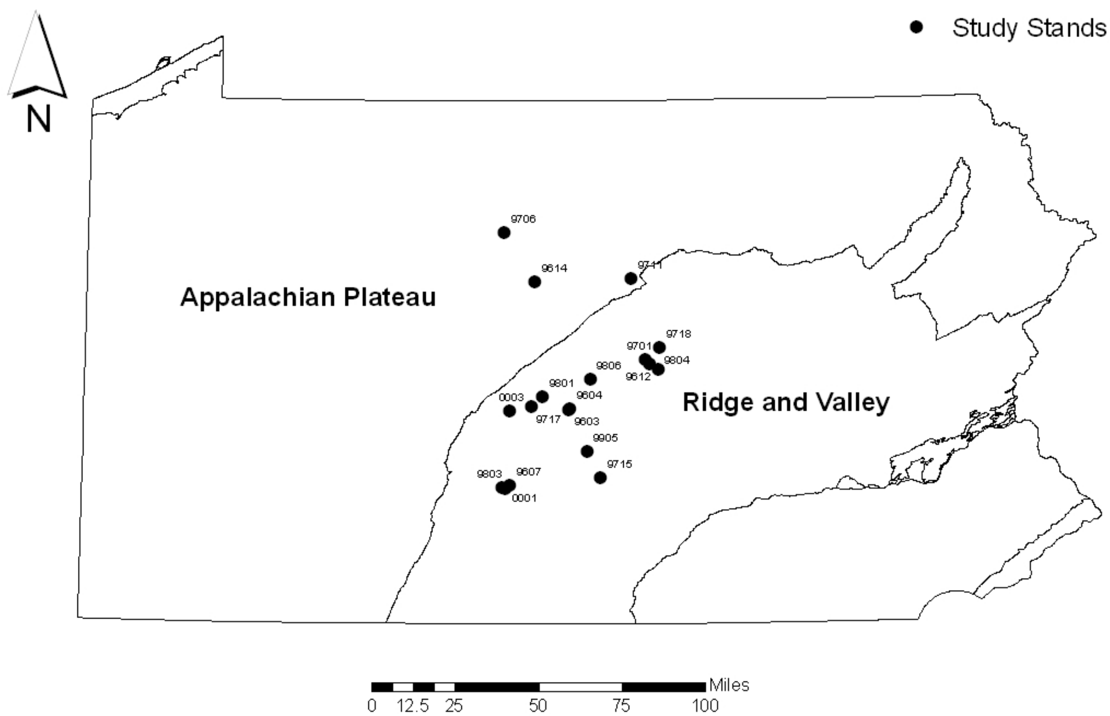

Figure **2-1**: Map of the 18 mixed-oak stands included in this study. Physiographic provinces and stand identification numbers are labeled.

During each measurement, subplot coverage of non-tree species and species groups was visually estimated as a percentage of the subplot's surface area in increments of 5%. Two strata of coverage were estimated in each measurement. Stratum 1 was the coverage of vegetation from 0 to 5 ft. giving precedence to the tallest vegetation less than or equal to 5 ft. in the subplot. Stratum 2 was the coverage of vegetation from 5 ft. to 20 ft. giving precedence to the lowest vegetation greater than or equal to 5 ft. in the subplot.

In each subplot, the height of every seedling less than or equal to 5 ft. was measured and tallied in one of the following height classes: ≤ 2 in, 2 to 6 in, 6 in to 1 ft, 1 to 2 ft, 2 to 3 ft, 3 to 4 ft, and 4 to 5 ft. The diameter at breast height of every seedling greater than 5 ft. tall was measured, and the heights of the dominant (tallest and/or healthiest) oak and non-oak seedlings were measured and recorded using the height classes listed above. If either of these heights exceeded five ft. they were rounded up to the nearest foot. Only seedlings and saplings that originated from seed were included in this study. Although stump sprouts were found in these stands, it is unlikely that they were affected by pre-harvest non-tree vegetation cover and were, therefore, excluded from this study. Artificial regeneration was also excluded.

Statistical Analysis

Development of Variables

Aggregate height, a stand density metric analogous to basal area, is the product of mean seedling height and density per unit area, in this study 0.001 acres (the size of subplots). This metric was developed by Fei et al. (2006) to characterize the density of seedling populations during early stand development and was found to be a useful metric of the prevalence of a species and its ability to persist during subsequent stand development. It was used in this study to express natural regeneration potential in the years following harvest. Oak, red maple, and total (all species) aggregate height values were developed for each subplot in all measurement years. Subplot data were then averaged to obtain plot-mean aggregate height values. The oak category included chestnut oak, northern red oak, white oak, black oak (*Q. velutina* Lam.), and scarlet oak. Because heights were recorded in classes, midpoints were used to calculate aggregate height values. For example, a single seedling tallied in the 1 to 2 ft. height class constituted 1.5 ft. of aggregate height in its subplot. The heights of most seedlings greater than 5 ft. tall were not measured. Therefore, the diameters of dominant oak and non-oak seedlings in each subplot (for which heights were measured) were used to estimate the heights for all seedlings over five feet tall. The heights of oaks, red maples, and other seedlings were estimated separately in each subplot using the linear regressions displayed in Table 2-2.

Table **2-2**: Results of three linear regressions involving the diameter and height of the dominant oak and non-oak seedlings in all subplots. These regressions were used to estimate the heights of seedlings over 5 ft. tall.

Species	α	SE	β_1	SE	P-value	R-squared
oak	4.435	0.067	8.269	0.074	<.0001	0.79
red maple	4.449	0.077	8.645	0.082	<.0001	0.83
other	5.314	0.072	7.516	0.058	<.0001	0.77

Three cover classes were developed for each plot: rhizomatous fern, tall shrub, and mountain-laurel. The first contained pre-harvest stratum 1 cover by hay-scented fern, bracken fern, and New York fern. The second contained pre-harvest stratum 1 and stratum 2 cover by tall shrubs other than mountain-laurel [primarily witch-hazel, *Viburnum* spp., spice-bush (*Lindera benzoin* L.), devil's walking stick (*Aralia spinosa* L.), *Rhododendron* spp., and mountain-holly (*Ilex montana* Torrey and Gray ex Gray)]. The final cover class contained pre-harvest stratum 1 and stratum 2 cover by mountain-laurel. Although blueberry and black huckleberry were very common in the study area as measured by frequency of occurrence and average cover (Table 3-1), preliminary analysis found no negative relationship between these species and tree regeneration. Similarly, teaberry (*Gaultheria procumbens* L.) and forbs were among the most common species as measured by frequency of occurrence, but both were characterized by a relatively low average cover. Therefore, these four species and species groups were excluded from further analysis. Plot-mean cover was developed by summing subplot coverage of the appropriate species and species groups and dividing by the number of subplots included in the plot at the time of measurement.

This number was four unless one of the permanent subplots was lost during the harvesting operation.

Frequency and average cover were summarized for all non-tree species and for the three cover classes described above in order to characterize composition in the pre-harvest environment. The natural log of year 10 cover was regressed on the natural log of pre-harvest cover of the three classes to determine how they differed in response to harvest. Values were transformed because the error variance was not constant. Relative abundance in terms of stem density and aggregate height was calculated for oak, red maple, and other tree regeneration in each of the five measurement years in order to understand changes in composition throughout the study area. These values represent the average percentage of total regeneration accounted for by various species and species groups for all stands in each measurement year.

Stochastic Frontier Functions

Developed by Aigner et al. (1977), stochastic frontier analysis (SFA) is commonly used by economists to estimate production frontiers and technical inefficiencies. It has since been used several times in forest biology to estimate self-thinning lines (Bi et al. 2000), fit tree crown shape in loblolly pine (*Pinus taeda* L.) (Nepal et al. 1996), estimate the maximum relative growth rate of red pine (*Pinus resinosa* Ait.) in Northern Michigan (Cummings et al. 2001), and estimate maximum density-size relationships for Sitka spruce (*Picea sitchensis* (Bong.) Carrière) and coastal Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) in Britain and Canada (Comeau et al. 2010). Stochastic frontier functions are modified regression functions that estimate maximum or minimum values (Cummings et al. 2001). Unlike ordinary least-squares regression, functions developed using SFA contain two error terms: the two-sided error (v_i), which represents the stochastic variability in levels of the dependent variable at a given level of the independent variable(s), and the one-sided error (u_i), which is non-positive when estimating maximum values and represents the random influences of unstudied variables that cause an observed response to lie below the line of the function (Nepal et al. 1996). In the context of this research, the one-sided error represents all the reasons for regeneration failure *other* than the variable in question, such as mountain-laurel cover.

Nepal et al. (1996) were the first to apply SFA in the field of forestry. In their example, y_i is the dependent variable and the stochastic maximum relationship between y_i and x_i is desired. Allowing z_i to represent the maximum level of y_i at a given level of x results in the following function:

$$z_i = (f, \beta(x_i)) + v_i$$

Where v_i is a random variable assumed to be distributed $N(0,\sigma^2)$. In order to substitute y_i for z_i, a second error term (u_i) is added to explain the random process that makes y_i smaller than its maximum. This results in the function:

$$y_i = (f, \beta(x_i)) + v_i + u_i$$

The two error terms are assumed to be independent of one another. While v_i is assumed to be distributed normally, u_i is assumed to have one of several one-sided distributions, most commonly the exponential or half-normal.

The dual error term is an improvement over alternative methods of estimating frontiers. For example, deterministic frontiers assume a single frontier function for all observations and possess a single, one-sided error term ε that must be ≤ 0.

$$y_i = (f, \beta(x_i)) + \varepsilon_i$$

This technique forces all observations to lie on or below the estimated frontier and is therefore extremely sensitive to outliers (Nepal et al. 1996). As previously mentioned, SFA allows the frontier to vary randomly from observation to observation, thus accounting for observations that exceed the estimated frontier because of measurement error or other causes. This method is also superior because it assumes that factors other than the independent variable(s) affect the frontier (Aigner et al. 1976).

In this study, stochastic frontier functions were developed using pre-harvest levels of rhizomatous fern, tall shrub, and mountain-laurel cover as independent variables and oak, red maple, and total aggregate height of all tree regeneration in years 1, 4, 7, and 10 as dependent variables. Plot-mean aggregate height values from each of the four post-harvest measurement years were included in each relationship and a second independent variable, years since harvest, was included to allow predictions at the different periods of stand development. Observations with plot-mean values of zero for the three cover classes were excluded from analysis.

The appropriate distribution of u_i was determined prior to formulating the final functions. Cummings et al. (2001) used Akaike's Information Criterion (AIC) to determine whether an exponential or half-normal distribution was appropriate for estimating maximum relative growth of red pine as a function of initial height, which was employed in this study. A half-normal distribution resulted in a lower AIC in seven of the nine relationships examined, and tied with an exponential distribution in one other. For this reason, a half-normal distribution was chosen for u_i in all relationships.

Stochastic frontier functions were developed using PROC QLIM in SAS 9.3. Initial parameters for these functions were derived using ordinary least-squares regression. Based on the assumption that observations having a high-level of influence on the initial parameters would have a similar level of influence on the final parameters, DFFITS values were developed using ordinary least-squares regressions in order to identify outliers. This method measures the influence that observation *i* has on the fitted value $\hat{Y}i$ (Kutner et al. 2004). Observations were considered highly influential if their DFFITS value exceeded $2\sqrt{}$(number of parameters/sample size) (Kutner et al. 2004), and those suspected of measurement error were identified and removed from the necessary data sets prior to developing final functions.

Once the distribution of u_i was chosen and highly influential observations were removed, maximum likelihood estimates of α, β_1 (cover), β_2 (years since harvest), σ^2_v, and σ^2_u were estimated iteratively using the Quasi-Newton non-linear optimization method. All dependent variables were transformed using natural log to meet the linear assumptions of the procedure, but predictions were back transformed for presentation and interpretation. In these relationships, mean milacre aggregate height for each 1/20th acre plot was used as an expression of natural regeneration abundance as a function of pre-harvest cover and the number of years since harvest. A relatively small variance of the two-sided error term (σ^2_v) indicated relatively little variation among levels of aggregate height at a given level of cover and resulted in fewer observations exceeding the estimated frontier line (Cumming et al. 2001). The variance of the one-sided error term (σ^2_u) was associated with the collective influence of stand variables, other than the cover variable, that could inhibit regeneration from achieving its estimated potential. Two-sample t-tests were conducted to compare estimates of α, β_1, β_2 among the three categories of regeneration.

Finally, functions were used to estimate aggregate height at low (1%) and high (30%) levels of each cover class in years 1, 4, 7, and 10 following harvest. These predictions were then back- transformed and plotted to compare trends of the three categories of regeneration at varying cover levels. The high level of cover represents the threshold for potential problems with interfering vegetation recommended by Marquis (1994) and is commonly used in studies of tree regeneration (Fei et al. 2004; McWilliams et al. 1995; Steiner et al. 2008).

Boundary Analysis

In the field of forestry, researchers have historically used boundary analysis to estimate relationships between dependent and independent variables when, as in this study, many observations fall below the expected function for reasons other than the independent variable. The first step in applying this method is to partition the data set into groups based on levels of the independent variable. The highest value from each group is then isolated, and the subset of maximum values is analyzed using ordinary least-squares regression. The weaknesses of this method are that it requires arbitrary decisions and data reduction. Some researchers have compared the two methods to demonstrate the superiority of SFA (Bi et al. 2000; Cummings et al. 2001; Nepal et al. 1996).

Two boundary analyses were performed in this study. For the first, oak aggregate height at year 10 was partitioned into subsets representing 5% increments of pre-harvest rhizomatous fern cover; and for the second, the same data was partitioned using 10% increments. The natural log of oak aggregate height was regressed on cover midpoints, and estimates were back transformed and plotted for interpretation. Finally, these functions were compared to a stochastic frontier function developed with the same data.

Chapter 3

Results

Natural Regeneration Characteristics

The relative abundance of oak, red maple, and other regeneration in terms of stem density and aggregate height is shown in Figures 3-1 and 3-2, respectively, for the year prior to harvest and the four post-harvest measurement years.

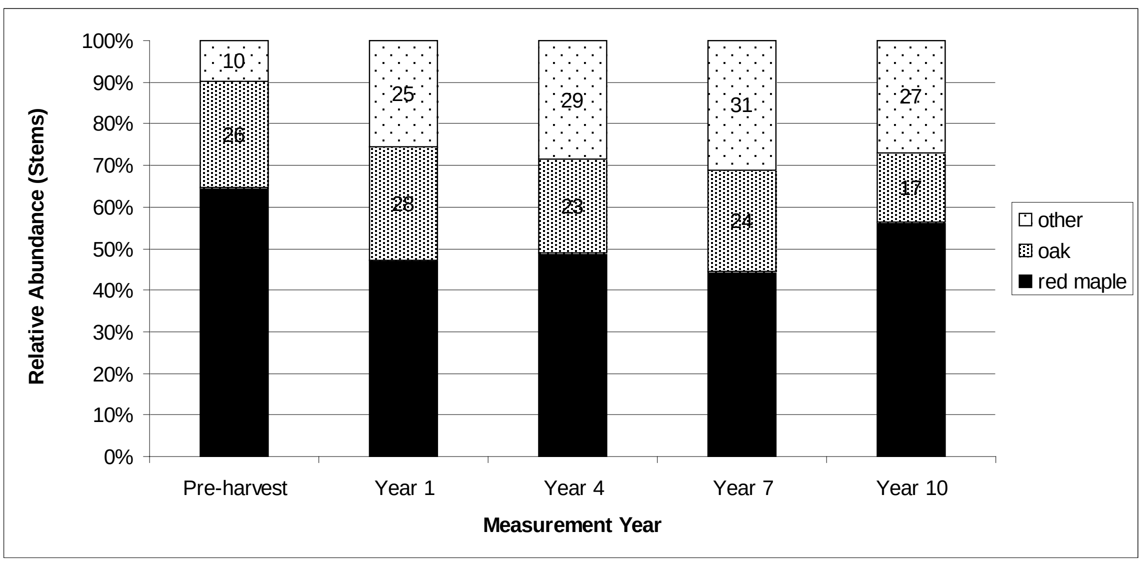

Figure **3-1**: The average percentage of total number of stems accounted for by various species and species groups for 18 stands in each measurement year.

In terms of stem density, red maple was the most abundant species in all measurement years. It composed 65% of advance regeneration and an average of 49% of post-harvest regeneration. Oak species, by comparison, composed 26% of advance regeneration and an average of 23% of regeneration after harvest. Relative oak abundance decreased appreciably between years 1 and 4 (from 28% to 23%) and between years 7 and 10 (from 24% to 17%). Chestnut oak was the most abundant oak species in all 5 measurement years, composing 59% of all oak stems on average in the study stands. By comparison, northern red oak, the second most abundant oak species, only composed 21% of all oak stems.

The relative abundance of other regeneration in terms of stem density increased markedly between pre-harvest and year 10 measurement years, nearly tripling in this time period. Sweet birch, which was found in all stands by year 10, was largely responsible for this increase. The relative abundance of this species increased from 2% in the pre-harvest environment to 16% 10 years after harvest on average, at which point it accounted for 43% of all "other" stems. However, black gum (*Nyssa sylvatica* Marsh.) and sassafras (*Sassafras albidum* (Nutt.) Nees) also contributed importantly to regeneration in some study stands, composing as much as 19% and 18% of all regeneration, respectively, by year 10.

The relative abundance of oak in terms of aggregate height remained steady over time, composing between 28% and 33% of regeneration on average in the study stands (Figure 3-2). By comparison, the relative abundance of other regeneration more than tripled between pre-harvest and year 10 measurements; and the relative abundance of red maple decreased from 53% to 29%. Red maple was the most abundant of the three species groups from the year before harvest to four years after harvest, but in year 7 it was surpassed by both oak and other regeneration. Sweet birch dominated other regeneration by the end of the decade, composing on average 43% of the regeneration in this category.

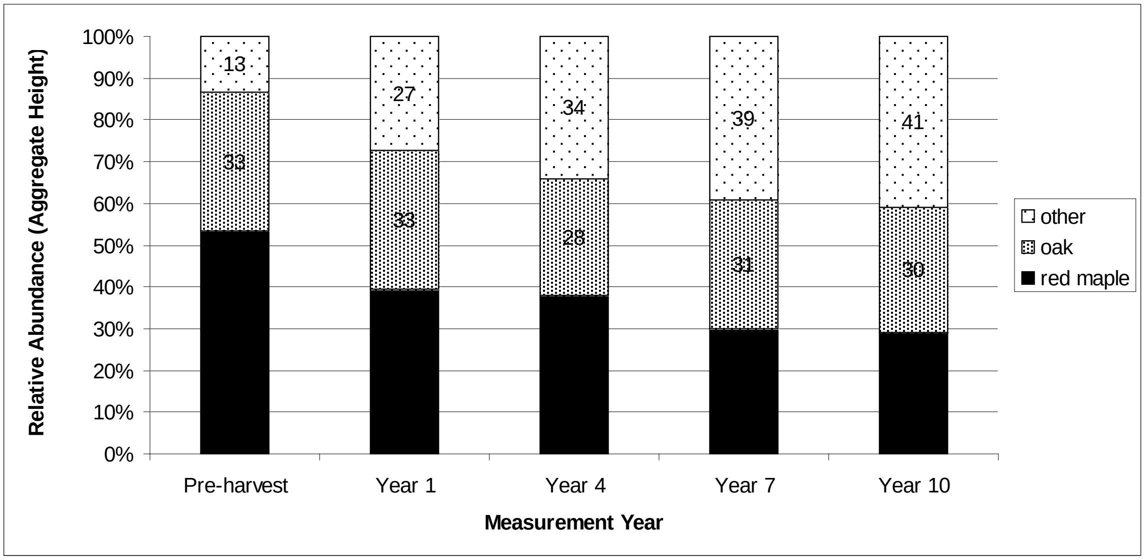

Figure **3-2**: The average percentage of total regeneration aggregate height accounted for by various species and species groups for 18 stands in each measurement year.

Non-tree Vegetation Characteristics

Frequency of occurrence and average cover at the subplot level was summarized for all non-tree species and species groups present in the pre-harvest environment. The 10 most common in terms of frequency are listed in Table 3-1. Blueberry frequency (74%) was more than twice as great as the second most common species, teaberry (36%). Blueberry average cover (12%) was also the highest. Although the frequencies of teaberry (36%) and forbs (32%) were near the top of the range, they were both characterized by a relatively low average cover (0.9%). Hay-scented fern and bracken fern were also among the most common non-tree species in the pre-harvest environment (Table 3-1). New York fern, the third component of the rhizomatous fern cover class, was uncommon with a frequency of 0.1% and an average cover of < 0.1% (not shown). Mountain-laurel and witch-hazel dominated stratum 2.

Table **3-1**: Occurrence frequency (percentage of subplots) and average cover across all subplots for the 10 most common species in stratum 1 of the pre-harvest environment.

	Stratum 1			Stratum 2		
Species	Freq. (%)	Avg. Cover (%)	SE mean	Freq. (%)	Avg. Cover (%)	SE mean
blueberry spp.	73.8	11.7	0.4	0.0	0.0	0.0
teaberry	35.7	0.9	<0.1	0.0	0.0	0.0
forbs	31.8	0.9	0.1	0.0	0.0	0.0
black huckleberry	29.9	7.6	0.4	0.0	0.0	0.0
mountain-laurel	28.0	7.1	0.4	8.1	1.2	0.1
witch-hazel	20.3	1.1	0.1	8.2	1.7	0.2
hay-scented fern	14.8	6.1	0.5	0.0	0.0	0.0
grasses	14.3	0.6	0.1	0.0	0.0	0.0
sedges	10.2	0.4	0.1	0.0	0.0	0.0
bracken fern	6.2	0.4	0.1	0.0	0.0	0.0

As shown in Table 3-2, witch-hazel was the dominant component of the tall shrub cover class in terms of frequency and average cover.

Table **3-2**: Occurrence frequency (percentage of subplots) and average cover across all subplots for the 6 species contributing to pre-harvest tall shrub cover.

	Stratum 1			Stratum 2		
Species	Freq. (%)	Avg. Cover (%)	SE mean	Freq. (%)	Avg. Cover (%)	SE mean
witch-hazel	20.3	1.1	0.1	8.2	1.7	0.2
viburnum spp.	3.1	0.1	<0.1	0.0	0.0	0.0
spice-bush	0.6	<0.1	<0.1	0.0	0.0	0.0
devil’s walking stick	0.3	<0.1	<0.1	0.2	0.1	<0.1
rhododendron	0.1	<0.1	<0.1	0.0	0.0	0.0
mountain holly	0.1	<0.1	<0.1	0.0	0.0	0.0

Of the 18 stands in this study (Figure 3-3), mountain-laurel cover in excess of 30% was found on 69% of the subplots in one stand (stand 9711), over 30% of the subplots in two others (stands 0003 and 9804), and approximately 20% of the subplots in two others (stands 9604 and 9612). Less than 10% of subplots in the remaining stands had this level of cover by mountain-laurel. Similarly, rhizomatous fern cover in excess of 30% was found on 64% of the subplots in one stand (stand 9706), 43% of the subplots in another (stand 9614), but less than 15% in all others. In contrast, tall shrub cover of greater than 30% was present on no more than 15% of the subplots in any stand.

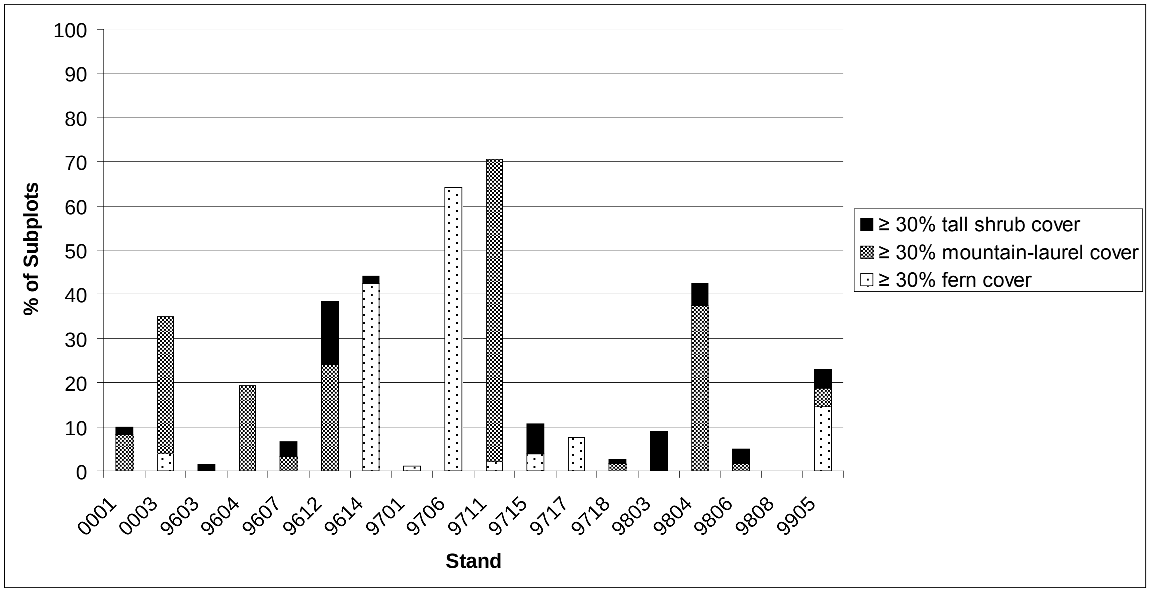

Figure **3-3**: The percentage of subplots in each stand that contained ≥ 30% cover by rhizomatous ferns, mountain-laurel, or tall shrubs in the year before harvest.

Tall shrub was the most common cover class in the pre-harvest environment as measured by frequency of occurrence. It occurred on 44% of all plots with an average cover of 3%. Rhizomatous fern and mountain-laurel were slightly less common (each occurred on 38% of all plots) but had a greater average cover (6% and 8%, respectively). One-third of all plots contained two or more of the three cover classes, and 22% contained none.

The natural log of 10-year cover was regressed on the natural log of pre-harvest cover for the three classes (Table 3-3). All relationships were highly significant ($p < .0001$) but differed in terms of fit, intercept, and slope. Rhizomatous fern had a much lower R-squared than mountain-laurel and tall shrub, suggesting that future levels of rhizomatous fern cover were less dependent on pre-harvest conditions. Rhizomatous fern also had the highest intercept, but tall shrub and mountain-laurel had larger slopes.

Table **3-3**: Results of three linear regressions involving the natural log of year 10 cover (y) and the natural log of pre-harvest cover (x) for the three classes of cover.

Species	α	SE	β_1	SE	P-value	R-squared
rhizomatous fern	0.896	0.084	0.389	0.037	<.0001	0.21
mountain-laurel	-0.557	0.046	0.773	0.019	<.0001	0.81
tall shrub	0.293	0.069	0.866	0.035	<.0001	0.60

Rhizomatous Fern and Regeneration

Table 3-4 contains parameter estimates for oak, red maple, and total regeneration aggregate height following harvest as a function of pre-harvest rhizomatous fern cover (β_1) and the number of years since harvest (β_2). The parameters σ^2_v and σ^2_u represent the variability associated with a given relationship and the sensitivity of a given class of regeneration to non-modeled inhibitory factors, respectively. In regard to the latter, a low estimate indicates low sensitivity. Note that the parameter estimates included in this chapter were developed using the natural log of aggregate height values, and that all resultant predictions were back-transformed for presentation and interpretation.

Table **3-4**: Parameter estimates for the function $Lny_i = \alpha + \beta_1 x_{i1} + \beta_2 x_{i2} + v_i + u_i$. y_i is the natural log of aggregate height as a function of pre-harvest rhizomatous fern cover (β_1) and the number of years since harvest (β_2). α is the intercept, σ^2_v is the variance of the two-sided error term, and σ^2_u is the variance of the one-sided error term. All parameters were highly significant ($p < .0001$).

	α	SE	β_1	SE	β_2	SE	σ^2_v	σ^2_u
oak	2.933	0.148	-0.019	0.003	0.111	0.018	0.519	8.129
red maple	3.165	0.145	-0.016	0.002	0.063	0.015	0.505	2.738
total	3.833	0.108	-0.008	0.002	0.121	0.012	0.239	1.946

Oak had the highest estimates of σ^2_v and σ^2_u. The former parameter was higher for oak and red maple than for total regeneration (Table 3-5). The parameter σ^2_u was considerably larger for oak than for red maple, and it was considerably larger for the latter than for all species combined. Thus, oak was the most sensitive of the three categories of regeneration to non-modeled inhibitory factors.

Estimates of α, β_1 for oak and red maple regeneration did not differ significantly (Table 3-6). Total regeneration had a significantly higher intercept (α) but a significantly smaller slope

(β_1) than oak and red maple; and red maple increased significantly less than both oak and total regeneration between measurement years (β_2).

Table **3-5**: Two-sided variance (σ^2_v) and one-sided variance (σ^2_u) of oak, red maple, and total regeneration as a function of pre-harvest rhizomatous fern cover and the number of years since harvest.

Species Comparison	N	σ^2_v
oak vs.	651	0.519
red maple	646	0.505
oak vs.	651	0.519
total	647	0.239
red maple vs.	646	0.505
total	647	0.239

Species Comparison	N	σ^2_u
oak vs.	651	8.129
red maple	646	2.738
oak vs.	651	8.129
total	647	1.946
red maple vs.	646	2.738
total	647	1.946

Table **3-6**: Results of two-sample t-tests conducted to compare parameter estimates for oak, red maple, and total regeneration as a function of pre-harvest rhizomatous fern cover and the number of years since harvest. Significant p-values (< 0.05) are in bold.

		α		β_1		β_2	
Species Comparison	N	t-statistic	P-value	t-statistic	P-value	t-statistic	P-value
oak vs. red maple	651 646	1.121	0.263	-0.750	0.453	2.087	**0.037**
oak vs. total	651 647	4.918	**<.0001**	-2.750	**0.006**	0.455	0.649
red maple vs. total	646 647	3.691	**0.0002**	-2.667	**0.008**	3.053	**0.002**

Frontier lines for oak, red maple, and total regeneration 10 years after harvest are displayed along with aggregate height values from year 10 in Figure 3-4, and frontier lines for the three categories of regeneration in the four post-harvest measurement years are displayed in Figure 3-5. Estimates of σ^2_v were similar for oak and red maple, but both were considerably larger than total regeneration. Therefore, oak and red maple had a larger proportion of observations exceed their respective frontiers than total regeneration. Higher variance on the left side of these graphs is likely a consequence fitting the regression with the natural log of aggregate height. It should also be noted that many observations, especially in the lower left hand corner, overlap.

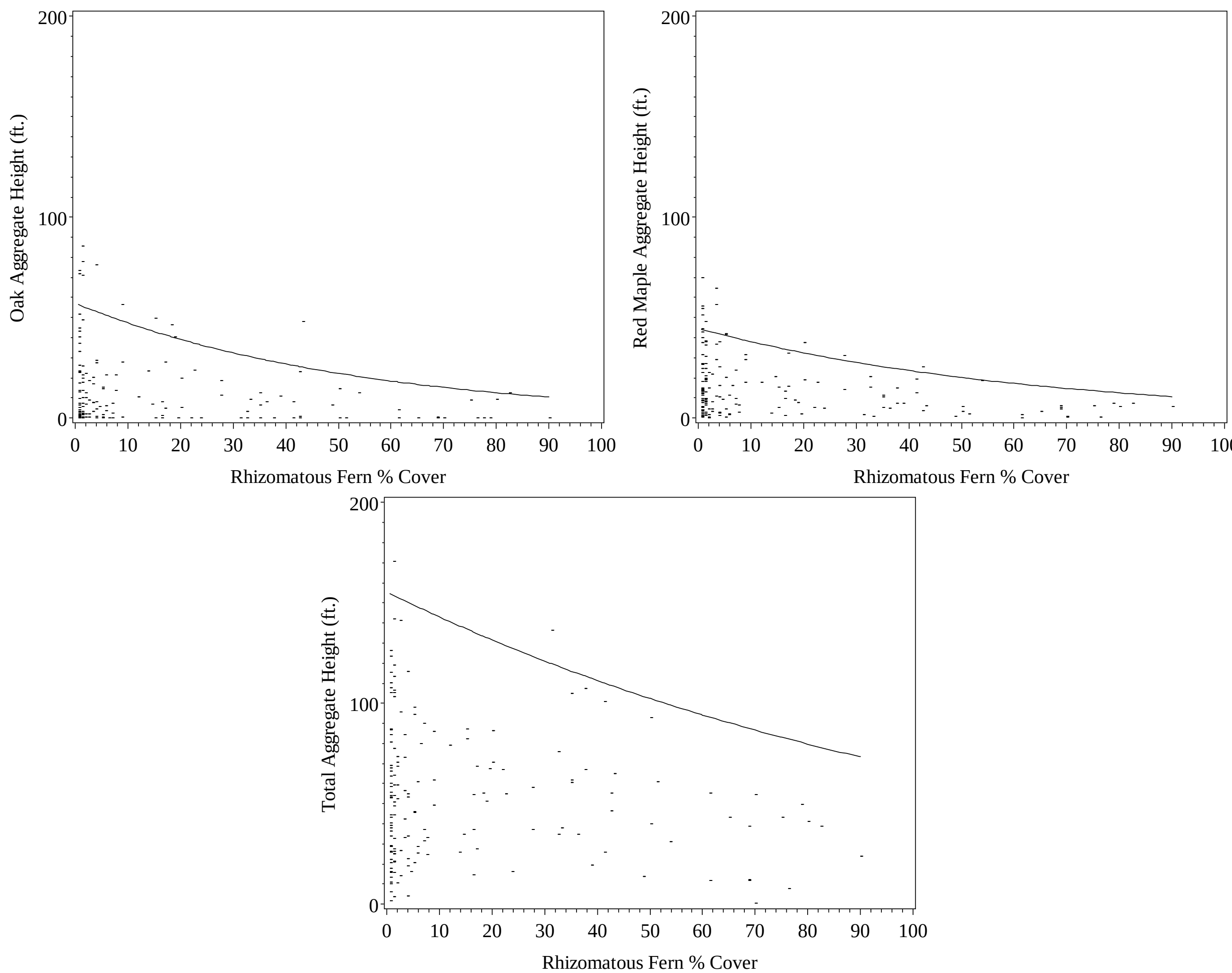

Figure **3-4**: Frontier lines for oak (top left), red maple (top right), and total (bottom center) regeneration 10 years after harvest as a function of pre-harvest rhizomatous fern cover.

The line of the function for oak crosses the line of the function for red maple in year 7 (Figure 3-5). Although the parameters α and β_1 did not differ significantly between these two relationships, oak increased at a significantly higher rate between measurement years (β_2) than red maple (Table 3-4). Figure 3-5 also demonstrates the great abundance of all species combined relative to oak and red maple, and the similarity between predictions of oak and red maple aggregate height.

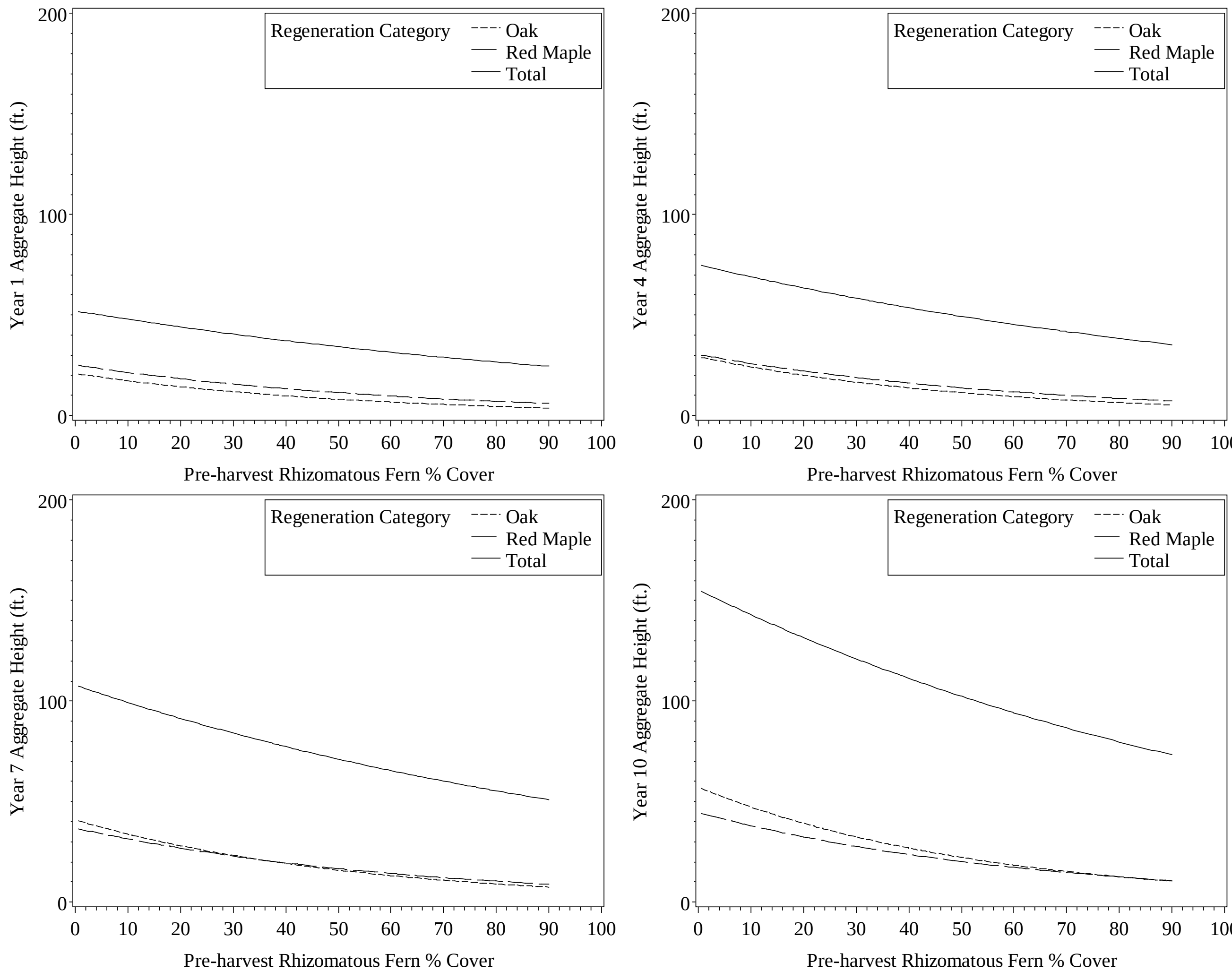

Figure **3-5**: Frontier lines for oak, red maple, and total regeneration 1 year (top left), 4 years (top right), 7 years (bottom left), and 10 years (bottom right) after harvest as a function of pre-harvest rhizomatous fern cover.

In order to facilitate comparisons over time, aggregate height for the three categories of regeneration was predicted in the four post-harvest measurement years at both low (1%) and high (30%) levels of cover (Figure 3-6). At both levels of cover, aggregate height for all three categories of regeneration increased over the entire decade. Oak and red maple aggregate height were 42% and 37% lower, respectively, at the high level of cover than at the low level of cover in all years. Oak and red maple regeneration were affected more severely than total regeneration, which was only 22% lower at the high level of cover.

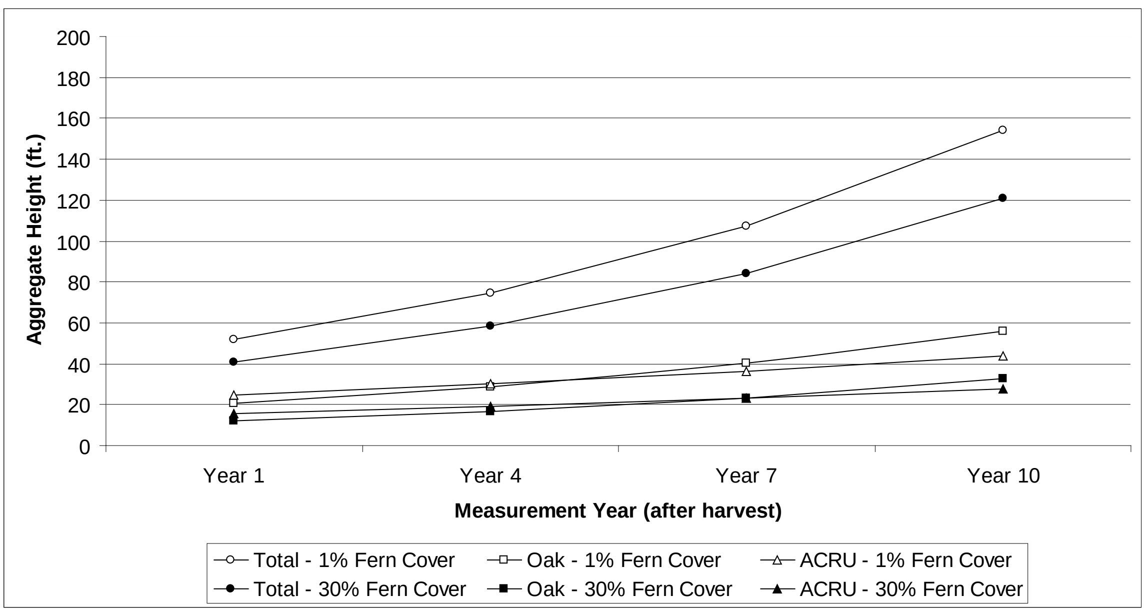

Figure **3-6**: Estimates of oak, red maple, and total regeneration (aggregate height per milacre) in the four post-harvest measurement years at high (30%) and low (1%) levels of pre-harvest rhizomatous fern cover.

Mountain-laurel and Regeneration

Regression parameter estimates are shown in Table 3-7 for oak, red maple, and total regeneration following harvest as a function of pre-harvest mountain-laurel cover (β_1) and the number of years since harvest (β_2).

Table **3-7**: Parameter estimates for the function $\text{Ln}y_i = \alpha + \beta_1 x_{i1} + \beta_2 x_{i2} + v_i + u_i$. y_i is the natural log of aggregate height as a function of pre-harvest mountain-laurel cover (β_1) and the number of years since harvest (β_2). α is the intercept, σ^2_v is the variance of the two-sided error term, and σ^2_u is the variance of the one-sided error term. All parameters were highly significant ($p < .0001$).

	α	SE	β_1	SE	β_2	SE	σ^2_v	σ^2_u
oak	2.817	0.177	-0.010	0.003	0.129	0.017	0.468	6.687
red maple	2.762	0.135	-0.009	0.002	0.118	0.014	0.398	3.306
total	3.363	0.123	-0.013	0.002	0.174	0.010	0.422	0.854

Oak had a greater σ^2_v than red maple and total regeneration (Table 3-8). The parameter σ^2_u was considerably larger for oak than for red maple, and it was considerably larger for the latter than for all species combined, which suggests that oak was the most sensitive of the three categories to non-modeled inhibitory factors.

Estimates of α, β_1, β_2 did not differ significantly between oak and red maple (Table 3-9). Slope (β_1) also did not differ among the three categories of regeneration, but total regeneration had a significantly higher intercept (α) than oak and red maple. Total regeneration also increased significantly more than oak and red maple between measurement years (β_2). Frontier lines for oak, red maple, and total regeneration 10 years after harvest are displayed along with aggregate height values from year 10 in Figure 3-7, and frontier lines for the three categories of regeneration in the four post-harvest measurement years are displayed in Figure 3-8.

Table **3-8**: Two-sided variance (σ^2_v) and one-sided variance (σ^2_u) of oak, red maple, and total regeneration as a function of pre-harvest mountain-laurel cover and the number of years since harvest.

Species Comparison	N	σ^2_v
oak vs.	680	0.468
red maple	679	0.398
oak vs.	680	0.468
total	679	0.422
red maple vs.	679	0.398
total	679	0.422

Species Comparison	N	σ^2_u
oak vs.	680	6.687
red maple	679	3.306
oak vs.	680	6.687
total	679	0.854
red maple vs.	679	3.306
total	679	0.854

Table **3-9**: Results of two-sample t-tests conducted to compare parameters estimates for oak, red maple, and total regeneration as a function of pre-harvest mountain-laurel cover and the number of years since harvest. Significant p-values (< 0.05) are in bold.

		α		β_1		β_2	
Species Comparison	N	t-statistic	P-value	t-statistic	P-value	t-statistic	P-value
oak vs. red maple	680 679	0.247	0.805	-0.250	0.803	0.500	0.617
oak vs. total	680 679	2.528	**0.012**	-0.750	0.453	2.368	**0.018**
red maple vs. total	679 679	3.284	**0.001**	-1.333	0.183	3.294	**0.001**

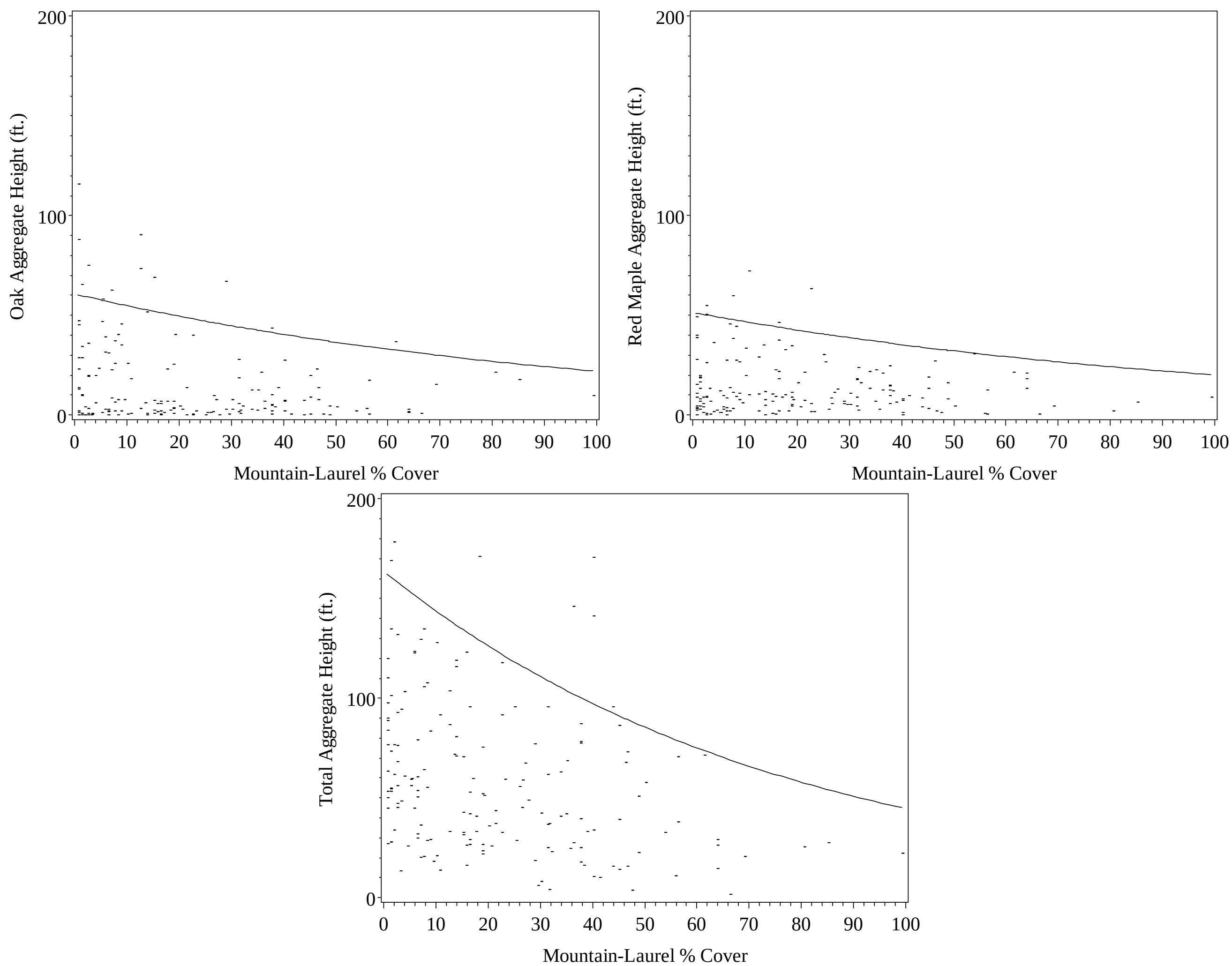

Figure **3-7**: Frontier lines for oak (top left), red maple (top right), and total (bottom center) regeneration 10 years after harvest as a function of pre-harvest mountain-laurel cover.

The similarity between oak and red maple is further demonstrated in Figure 3-8. Although the parameters of these two functions did not differ significantly (Table 3-7), it is evident that oak abundance increased at a slightly greater rate between measurement years.

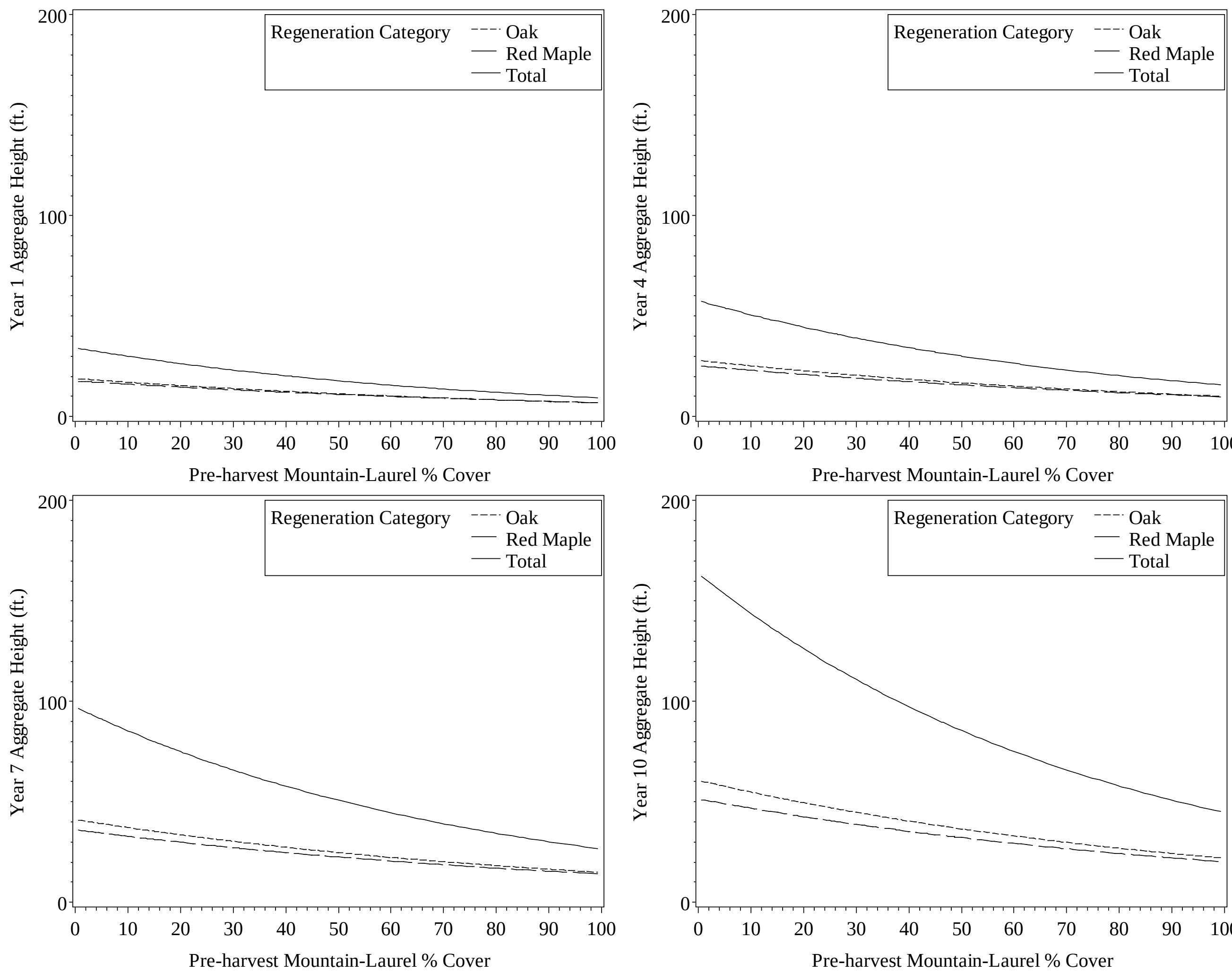

Figure **3-8**: Frontier lines for oak, red maple, and total regeneration 1 year (top left), 4 years (top right), 7 years (bottom left), and 10 years (bottom right) after harvest as a function of pre-harvest mountain-laurel cover.

Predictions for the three categories of regeneration at low (1%) and high (30%) levels of cover are shown in Figure 3-9. At both levels of cover, regeneration for all three categories of regeneration increased over the entire decade. Oak, red maple, and total aggregate height were affected similarly by the high level of cover. These three categories of regeneration were 26%, 24%, and 31% lower, respectively, at the high level of cover than at the low level of cover in all years.

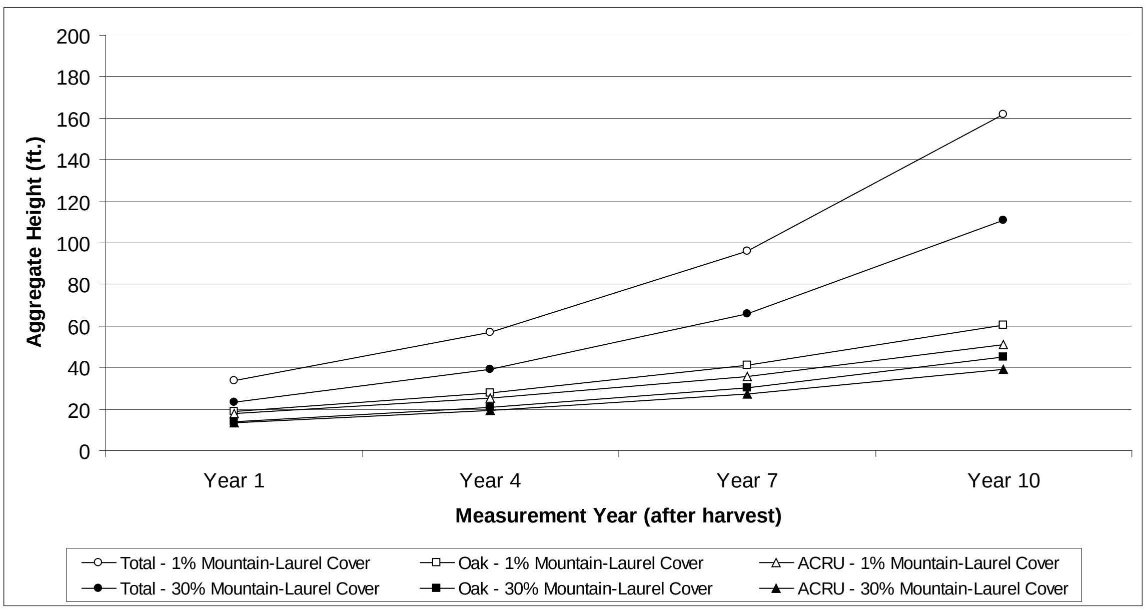

Figure **3-9**: Estimates of oak, red maple, and total regeneration (aggregate height per milacre) in the four post-harvest measurement years at high (30%) and low (1%) levels of pre-harvest mountain-laurel cover.

Tall Shrub and Regeneration

Table 3-10 contains parameter estimates for oak, red maple, and total regeneration following harvest as a function of pre-harvest tall shrub cover (β_1) and the number of years since harvest (β_2). All parameters were highly significant for oak and total regeneration, but no significant relationship was found between pre-harvest tall shrub cover and red maple regeneration ($p = 0.1114$).

Table **3-10**: Parameter estimates for the function $\text{Ln}y_i = \alpha + \beta_1 x_{i1} + \beta_2 x_{i2} + v_i + u_i$. y_i is the natural log of aggregate height as a function of pre-harvest tall shrub cover (β_1) and the number of years since harvest (β_2). α is the intercept, σ^2_v is the variance of the two-sided error term, and σ^2_u is the variance of the one-sided error term.

	α	SE	β_1	SE	β_2	SE	σ^2_v	σ^2_u
oak	3.336	0.151	-0.022	0.005	0.118	0.017	0.343	8.613
red maple	3.200	0.113	-0.007	0.004	0.087	0.012	0.289	2.889
total	3.980	0.082	-0.012	0.003	0.116	0.009	0.129	1.833

Oak had a greater σ^2_v than red maple and total regeneration. The parameter σ^2_u was considerably larger for oak than for red maple, and considerably larger for the latter than for all species combined, suggesting that oak was the most sensitive of the three categories to non-modeled inhibitory factors (Table 3-11).

Total regeneration had a significantly higher intercept (α) than oak and red maple, but total and oak regeneration had a similar relationship with tall shrub cover (β_1) (Table 3-12). Because no significant relationship was found between tall shrub cover and red maple, this class of cover necessarily had a greater affect on oak and total regeneration. The three categories of regeneration, however, increased at a similar rate between measurement years (β_2).

Table **3-11**: Two-sided variance (σ^2_v) and one-sided variance (σ^2_u) of oak, red maple, and total regeneration as a function of pre-harvest tall shrub cover and the number of years since harvest.

Species Comparison	N	σ^2_v
oak vs.	757	0.343
red maple	754	0.289
oak vs.	757	0.343
total	756	0.129
red maple vs.	754	0.289
total	756	0.129

Species Comparison		
oak vs.	757	8.613
red maple	754	2.889
oak vs.	757	8.613
total	756	1.833
red maple vs.	754	2.889
total	756	1.833

Table **3-12**: Results of two-sample t-tests conducted to compare parameters estimates for oak and total regeneration as a function of pre-harvest tall shrub cover and the number of years since harvest. Significant p-values (< 0.05) are in bold.

		α		β_1		β_2	
Species Comparison	N	t-statistic	P-value	t-statistic	P-value	t-statistic	P-value
oak vs. total	757 756	3.744	**0.0002**	-1.667	0.096	0.105	0.916

Frontier lines for the three categories of regeneration 10 years after harvest are displayed along with aggregate height values from year 10 in Figure 3-10, and frontier lines for oak and total regeneration in the four post-harvest measurement years are displayed in Figure 3-11. Unlike rhizomatous fern and mountain-laurel, tall shrub cover rarely exceeded 30% plot-mean cover in the pre-harvest environment.

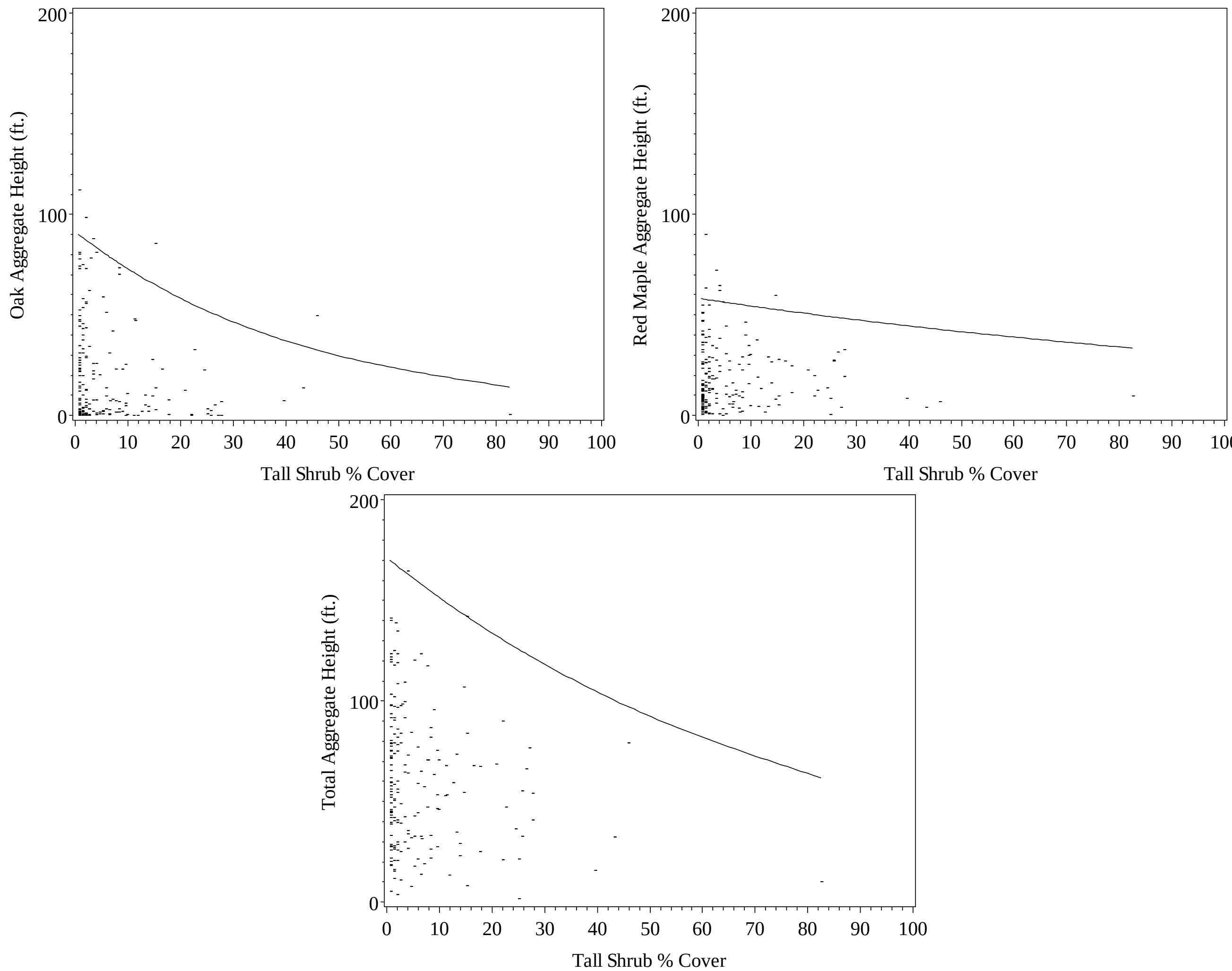

Figure **3-10**: Frontier lines for oak (top left), red maple (top right), and total (bottom center) regeneration 10 years after harvest as a function of pre-harvest tall shrub cover.

Figure 3-11 further demonstrates the similarity between total regeneration and oak regeneration in terms of slope (β_1) and the rate of increase between measurement years (β_2).

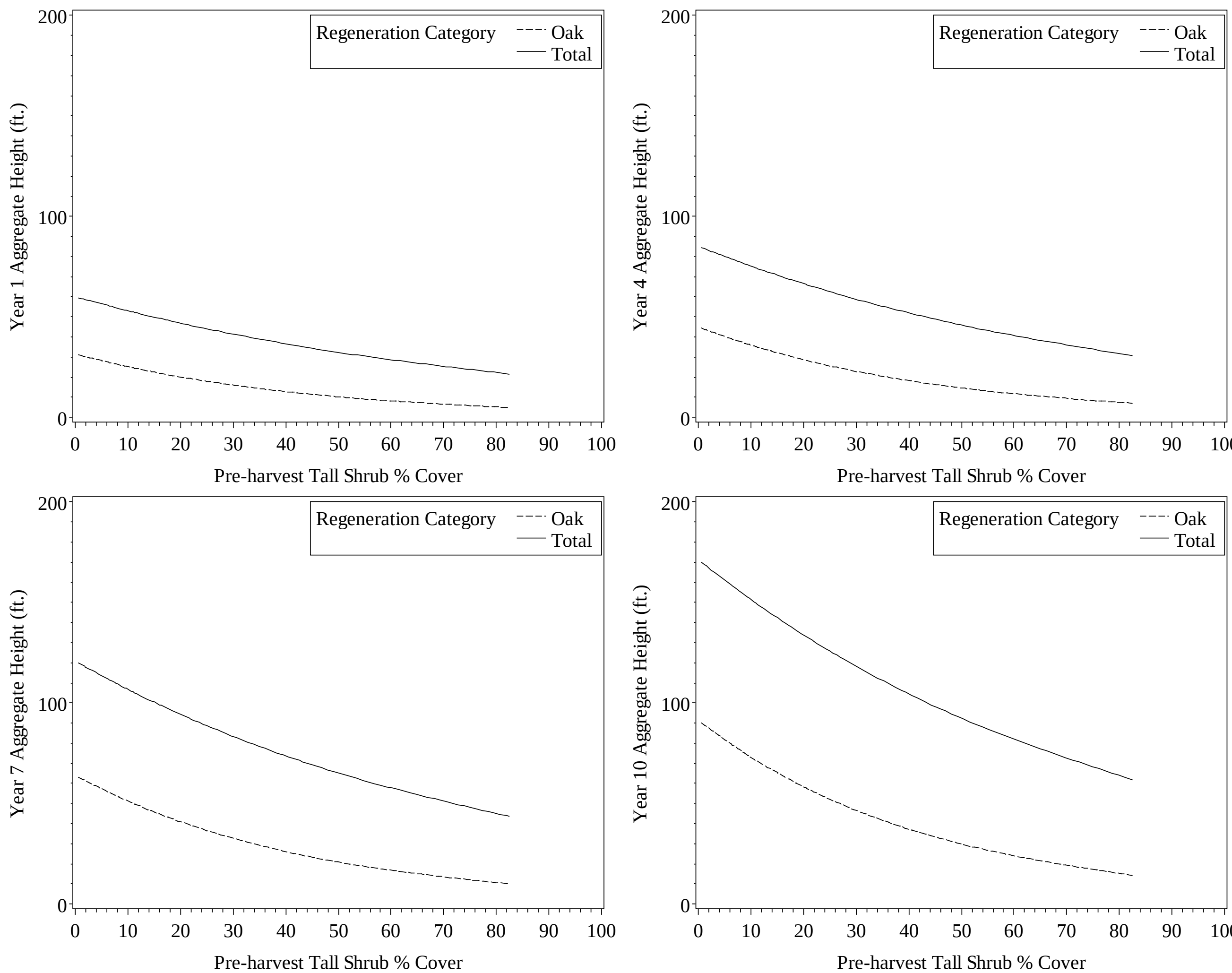

Figure **3-11**: Frontier lines for oak and total regeneration 1 year (top left), 4 years (top right), 7 years (bottom left), and 10 years (bottom right) after harvest as a function of pre-harvest tall shrub cover.

Predictions for oak and total regeneration at low (1%) and high (30%) levels of cover are shown in Figure 3-12. At both levels of cover, aggregate height for the two categories of regeneration increased over the entire decade. Oak aggregate height was 48% lower at the high level of cover than at the low level of cover in all years. This reduction in aggregate height was nearly twice the reduction in abundance caused by the same level of mountain-laurel cover (26%), but was relatively similar to the reduction caused by this level of rhizomatous fern cover (42%). However, the reduction in the abundance of total regeneration caused by the high level of tall shrub cover (30%) was similar to that caused by the same level of mountain-laurel (31%) and rhizomatous fern cover (22%).

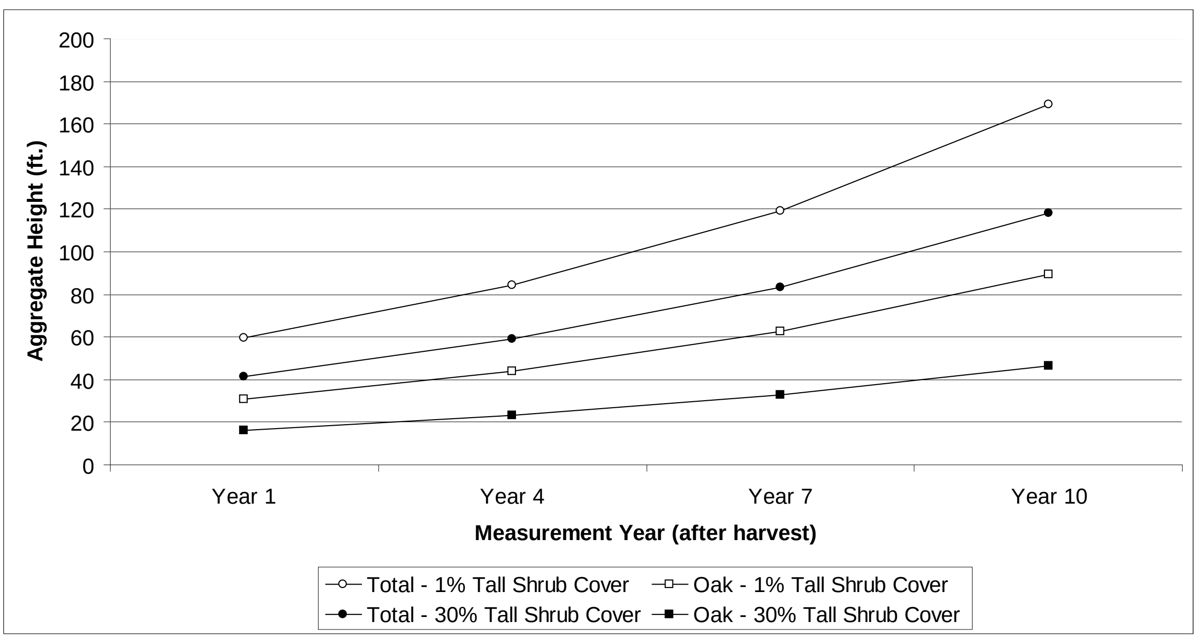

Figure **3-12**: Estimates of oak and total regeneration (aggregate height per milacre) in the four post-harvest measurement years at high (30%) and low (1%) levels of pre-harvest tall shrub cover.

Overview of Non-tree Vegetation and Regeneration

Estimates of β_2 for oak regeneration did not differ significantly among the three classes of cover; nor did the parameter β_1 differ between rhizomatous fern and tall shrub, suggesting that these two classes of cover had a similar effect on oak regeneration (Table 3-13). The parameter β_1 was significantly smaller in the function involving mountain-laurel (β_1 = -0.010) than in the functions involving rhizomatous fern (β_1 = -0.019) and tall shrub (β_1 = -0.022), indicating that mountain-laurel had the weakest negative effect on oak regeneration.

Table **3-13**: Results of two-sample t-tests conducted to compare parameter estimates for oak regeneration among the three classes of cover. Significant p-values (< 0.05) are in bold.

		α		β_1		β_2	
Cover	N	t-statistic	P-value	t-statistic	P-value	t-statistic	P-value
fern mountain-laurel	651 680	0.502	0.616	-2.250	**0.025**	0.720	0.472
fern tall shrub	651 757	1.909	0.057	-0.500	0.617	0.280	0.779
mountain-laurel tall shrub	680 757	2.228	**0.026**	-2.000	**0.046**	0.458	0.647

No significant relationship was found between red maple regeneration and tall shrub cover. Therefore, this class of cover necessarily had a significantly weaker negative effect on red maple regeneration (β_1) than rhizomatous fern and mountain-laurel (Table 3-14). The estimate of β_1 was also significantly larger for red maple as a function of rhizomatous fern (α =3.165 and β_1 = -0.016) than as a function of mountain-laurel (α = 2.762 and β_1 = -0.009), suggesting that the former had the strongest negative effect on this species. The estimate of α was significantly lower as a function of mountain-laurel; but the parameter β_2 was significantly larger for red maple as a function of mountain-laurel (β_2 = 0.118) than as a function of rhizomatous fern (β_2 = 0.063).

Table **3-14**: Results of two-sample t-tests conducted to compare parameter estimates for red maple regeneration under rhizomatous fern and mountain-laurel cover. Significant p-values (< 0.05) are in bold.

		α		β_1		β_2	
Cover	N	t-statistic	P-value	t-statistic	P-value	t-statistic	P-value
fern mountain-laurel	646 679	2.035	**0.042**	-2.333	**0.019**	2.619	**0.009**

For total regeneration, the functions involving rhizomatous fern and tall shrub did not differ significantly, suggesting that these two classes of cover affected total regeneration similarly (Table 3-15). As with red maple, the parameter β_2 was significantly larger for total regeneration as a function of mountain-laurel ($\beta_2 = 0.174$) than as a function of rhizomatous fern ($\beta_2 = 0.121$) or tall shrub ($\beta_2 = 0.116$). The parameter β_1 did not differ significantly among the three classes of cover. The parameter α was significantly smaller in the function involving mountain-laurel ($\alpha = 3.363$) than in those involving the rhizomatous fern ($\alpha = 3.833$) and tall shrub ($\alpha = 3.980$).

Table **3-15**: Results of two-sample t-tests conducted to compare parameter estimates for total regeneration among the three classes of cover. Significant p-values (< 0.05) are in bold.

		α		β_1		β_2	
Cover	N	t-statistic	P-value	t-statistic	P-value	t-statistic	P-value
fern mountain-laurel	647 679	2.866	**0.004**	-1.667	0.096	3.313	**0.001**
fern tall shrub	647 756	1.081	0.279	-1.000	0.318	0.333	0.739
mountain-laurel tall shrub	679 756	4.169	**<.0001**	-0.250	0.803	4.143	**<.0001**

The estimate of σ^2_u for oak regeneration as a function of mountain-laurel was considerably smaller than as a function of rhizomatous fern and tall shrub. Estimates of this parameter did not differ appreciably between rhizomatous fern and tall shrub (Table 3-16).

Table **3-16**: One-sided variance (σ^2_u) of oak as a function of rhizomatous fern, mountain-laurel, and tall shrub.

Cover	N	σ^2_u
fern	651	8.129
mountain-laurel	680	6.687
fern	651	8.129
tall shrub	757	8.613
mountain-laurel	680	6.687
tall shrub	757	8.613

In contrast with oak, the estimate of this parameter for red maple was smallest in the function involving rhizomatous fern and largest in the function involving mountain-laurel (Table 3-17).

Table **3-17**: One-sided variance (σ^2_u) of red maple as a function of rhizomatous fern, mountain-laurel, and tall shrub.

Cover	N	σ^2_u
Fern	646	2.738
Mountain-laurel	679	3.306
Fern	646	2.738
tall shrub	754	2.889
Mountain-laurel	679	3.306
tall shrub	754	2.889

As with oak, the parameter σ^2_u for total regeneration did not differ appreciably in the functions involving rhizomatous fern and tall shrub and was smallest in the function involving mountain-laurel.

Table **3-18**: One-sided variance (σ^2_u) of total regeneration as a function of rhizomatous fern, mountain-laurel, and tall shrub.

Cover	N	σ^2_u
fern	647	1.946
mountain-laurel	679	0.854
fern	647	1.946
tall shrub	756	1.833
mountain-laurel	679	0.854
tall shrub	756	1.833

Boundary Analysis

The results of two boundary analyses involving rhizomatous fern and oak aggregate height in year 10 are displayed in Figure 3-13 with the frontier line for this relationship. The regression functions developed using these methods are displayed in Table 3-19.

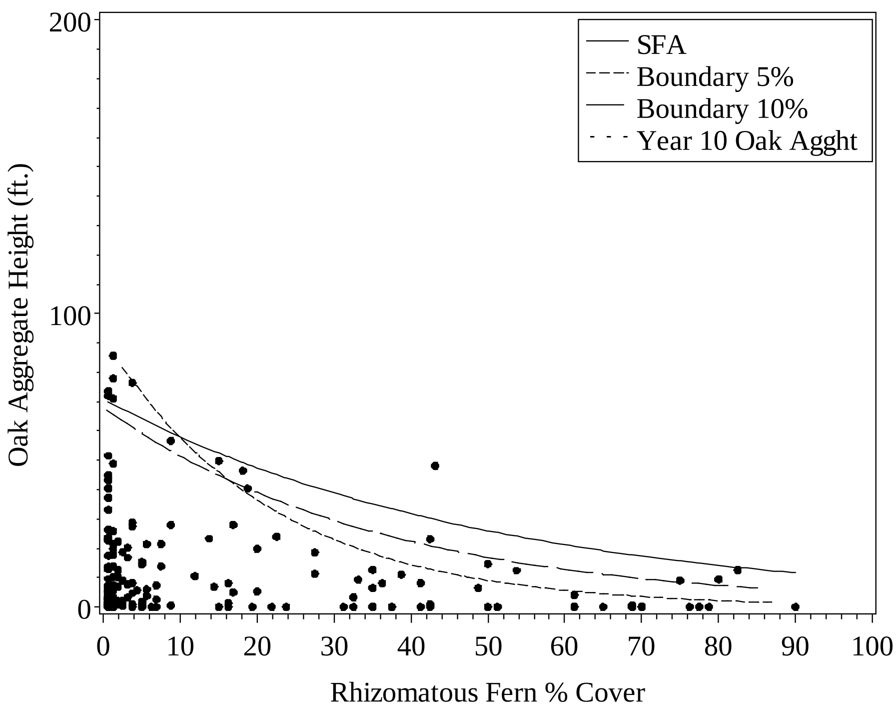

Figure **3-13**: Comparison of two boundary analyses and a stochastic frontier analysis of year 10 oak aggregate height values regressed on pre-harvest rhizomatous fern cover.

The boundary analyses performed used two selection criteria for data reduction and resulted in slopes and intercepts that differed from one another and from the frontier function. Because boundary analysis involves arbitrary subsets of data, standard errors represent a biased sample and not a random sample from an oak population. This method also provided no information on non-maximum observations. The selection criteria for the two boundary analyses also changed the scope of the data. The frontier function, which utilized all data, spanned all levels of cover. The first boundary analysis, which partitioned the data into 5% increments of cover, only extended to 87.5% cover, and the second, which partitioned the data into 10% increments of cover, only extended to 85% cover. It should also be noted that the frontier function displayed here was developed for comparison with boundary analysis and differs from the function displayed in Table 3-4. The former was developed using year 10 values of oak aggregate height, while the latter was developed using all post-harvest aggregate height values and the number of years since harvest.

Table **3-19**: Comparison of two boundary analyses and a stochastic frontier analysis of year 10 oak aggregate height values regressed on pre-harvest rhizomatous fern cover.

Method	α	SE	β_1	SE
boundary - 5%	4.519	0.539	-0.046	0.011
boundary - 10%	4.219	0.352	-0.028	0.007
frontier	4.262	0.196	-0.020	0.004

Chapter 4

Discussion

The three categories of interfering vegetation examined were relatively abundant in the study area. Hay-scented fern was by far the dominant component of the rhizomatous fern cover class; and although this species was only the seventh most common overall as measured by frequency of occurrence in all subplots, it was the fourth most abundant species in terms of average cover. Mountain-laurel was more abundant than hay-scented fern in stratum 1 by both measures of abundance. This species and witch-hazel, the dominant component of the tall shrub category, were the primary species in stratum 2, where they were similar in terms of frequency of occurrence and average cover.

The presence of these species and species groups does not necessarily influence seedling growth. Marquis (1994) recommended 30% cover as the threshold for potential problems with interfering vegetation. Mountain-laurel and rhizomatous fern achieved this level of cover in more than 60% of the subplots in two stands and more than 30% of the subplots in three others. Tall shrub achieved this level of cover in no more than 15% of the subplots in any stand. Thus, with the exception of tall shrub, this level of cover reflects a real and occasionally extreme condition encountered in forest stands within the region. Interfering vegetation also appeared to be a stand or plot feature rather than a subplot feature. As a stand feature, one of the three classes of cover typically dominated each stand; and as a plot feature, the majority that contained any of the three classes of cover contained only one.

Red maple dominated the regeneration in these stands, on average, in all years of measurement. Although there was a sharp drop in the average density of red maple stems after harvest, red maple continued to compose approximately half of the seedling stems in all years after harvest. Oaks made up about half of the remainder (approximately 25% of the total) throughout the decade following harvest, and all other species similarly composed about 25% of all stems. The other species group contained a large number of species, but sweet birch was the most common. This species was present in all stands by year 10, composing, on average, 43% of all “other” stems. Black gum and sassafras also contributed importantly to regeneration in some stands, composing as much as 19% of all stems by the end of the decade. There were no apparent trends in the relative density of any species group between the first and tenth year after harvest. Thus, regeneration in these stands behaved much as it has in many other formerly oak-dominated stands within the region by appearing to shift toward a predominance of red maple during the stand initiation phase of development. Fei and Steiner (2009), for example, found that although red maple was subordinate to oak in the pre-harvest overstories of 54 mature stands, it dominated the advance regeneration cohort. They also found that red maple regeneration maintained a distinct advantage over oak in terms of stem density and growth through the seventh year of stand development following harvest.

Red maple regeneration was less dominant when measured as aggregate height. Before harvest, red maple comprised slightly more than 50% (on average) of the aggregate height of all advance regeneration, but red maple abundance by this measure declined monotonically in each year of measurement after harvest, reaching 29% by year 10. By contrast, oak maintained a relatively constant proportion (approximately 30%) of aggregate height throughout the study period, and “other” species increased steadily in abundance from 13% of total aggregate height before harvest to 41% in year 10. Once again, sweet birch was the dominant “other” species, composing nearly half of the aggregate height in this regeneration category, on average, in year 10. This species produces a prolific number of wind dispersed seeds that travel long distances (Hardin et al. 2001), allowing it to readily invade forest stands after disturbance. However, the dominance of this species is often temporary. Beck and Hooper (1986) found that the abundance of sweet birch increased rapidly following clearcut but declined steadily after 15 years of stand development. Similarly, a study of stand development following catastrophic disturbance in central New England demonstrated the transitory nature of other pioneer species, such as pin cherry (*Prunus pennsylvanica* L.f.), that were locally important in my study area (Hibbs 1983). Black gum also contributed importantly to regeneration in some stands 10 years after harvest; and although this long-lived, slow-growing species is a common associate in mixed-oak stands, it rarely achieves dominance (Burns and Honkala 1990).

All three classes of interfering vegetation affected total regeneration negatively, creating an upper limit on regeneration potential at all levels of competition cover. For example, the prediction of total aggregate height was 22% lower at 30% rhizomatous fern cover compared to 1% cover and approximately 30% lower at this level of tall shrub and mountain-laurel cover. The slopes of the three functions did not differ significantly, suggesting that they affected this category of regeneration similarly. However, total regeneration increased at a significantly greater rate between measurement years under mountain-laurel cover than under rhizomatous fern or tall shrub cover. Thus, at a given cover level, mountain-laurel was the least inhibiting of the three cover classes in the development of total forest tree regeneration through time. Vegetation primarily interferes with regeneration development by limiting light availability (Beckage et al. 2000; George and Bazzaz 1999; Horsley 1993). Light levels as low as 2% have been recorded below dense thickets of mountain-laurel (Chapman 1950). Despite this, some researchers have found an insignificant or weak relationship between this species and tree regeneration. For example, Beier et al. 2005 found that mountain-laurel did not suppress first year oak seedlings by limiting carbon or other resources. Clinton et al. 1994 compared the effects of great rhododendron (*Rhododendron maximum* L.) and mountain-laurel on seedling density and found significantly lower densities under the former relative to the latter. Similarly Kittredge and Ashton 1990 found no relationship between mountain-laurel cover and regeneration as a whole. The authors of these studies agree that light levels can vary enough under even very dense mountain-laurel cover to allow for the successful development of tree regeneration.

Similarly, oak regeneration responded negatively to increasing levels of competition with all three classes of cover but differed in its response to each. Although oak regeneration abundance increased at a similar rate between measurement years regardless of cover type, the upper limit of potential decreased more sharply in response to increasing levels of rhizomatous fern and tall shrub cover than to increasing levels of mountain-laurel. Oak aggregate height was only 26% lower at 30% mountain-laurel cover compared to 1% cover. By comparison, it was 42% and 48% lower at the same level of rhizomatous fern and tall shrub cover, respectively. Thus, like total regeneration, mountain-laurel had the weakest negative effect on oak regeneration under our estimates of abundance. Several studies have demonstrated a negative relationship between tree regeneration and hay-scented fern competition (Engelman and Nyland 2006; Fei and Steiner 2008; George and Bazzaz 1999; Kaeser et al. 2008; Horsley 1993). However, the evidence that tall shrubs affect regeneration similarly is less definitive. Kaeser et al. (2008) concluded that the shade cast by tall understory plants is less detrimental to seedling establishment than the shade cast by lower lying plants like hay-scented fern and mountain-laurel. By comparison, Lorimer et al. (1994) found that removing tall understory vegetation dramatically increased the recruitment, growth, and survival of oak seedlings; and Loftis (1992) concluded that northern red oak regeneration was more successful on high-quality sites following the removal of mid-story vegetation. Because tall shrubs rarely achieved high levels of cover relative to rhizomatous ferns and mountain-laurel, it is surprising that they had such a strong negative effect on regeneration; but the findings of this study indicate that these species meaningfully impact oak regeneration and tree regeneration as a whole. Red maple, however, did not respond significantly to tall shrub cover. There is evidence in the literature that tall shrubs such as great rhododendron negatively affect red maple establishment by reducing light levels in the understory (Beckage et al. 2000). It is, therefore, possible that tall shrubs, which rarely exceeded 30% plot-mean cover, cast too little shade to interfere with this highly tolerant species.

Rhizomatous fern and mountain-laurel did significantly inhibit red maple regeneration, and the effect was significantly greater under fern than mountain-laurel cover. Red maple regeneration abundance declined more rapidly under increasing levels of rhizomatous fern than mountain-laurel, and red maple developed nearly twice as fast through time under mountain-laurel than under the same level of fern. George and Bazzaz (1999) found that the relative growth rate of red maple in terms of total biomass was 90% lower in plots with fern cover compared to fern-free plots and that the presence of ferns reduced the survivorship of this species. By comparison, Waterman et al. (1995) found that the presence of mountain-laurel did not affect the survivorship of red maple. They also found that although mountain-laurel cover reduced the growth of small red maple seedlings, this species had the highest importance, recruitment, and biomass growth of all the tree species in the study area. Therefore, like oak and total regeneration, mountain-laurel was less inhibitory to red maple than rhizomatous fern.

Oak and red maple responded very similarly to one another in competition with both rhizomatous fern and mountain-laurel. Both species declined in abundance at very similar rates in response to increasing levels of mountain-laurel, and both developed at about the same rate through time. For this reason, these functions produced estimates of aggregate height that never differed by more than 10 ft. between the two species in the post-harvest decade. Similarly, both species responded almost identically to increasing levels of fern. However, at any given level of fern aggregate height of oak developed more rapidly though time than that of red maple. Because tall shrub cover did not significantly affect red maple regeneration, it necessarily impacted oak regeneration more severely.

Several studies have demonstrated a negative effect of mountain-laurel and hay-scented fern competition on both red maple and oak regeneration. Fei and Steiner (2008), for example, found that the abundance of red maple and three common oak species in Pennsylvania were negatively associated with moderate to high levels of mountain-laurel and hay-scented fern cover. George and Bazzaz (1999) demonstrated that the relative growth rates of red maple and northern red oak were reduced equivalently under fern cover. In this study, these classes of inhibitory vegetation created an upper limit of growth that was similar for red maple and oak regeneration. The convergence of oak and red maple aggregate height at the end of the post-harvest decade is likely unrelated to competition with inhibitory vegetation. Despite overwhelming evidence that the forests in the eastern United States are experiencing a shift from oak to red maple, several studies have demonstrated the ability of oak to maintain dominance despite having a disadvantage in the pre-harvest environment. For example, Oliver (1978) found that northern red oak maintained dominance in mixed stands 40 years after harvest despite an initial advantage by red maple and black birch, which was attributed to a reduction in the growth rate of these initially fast growing species. Similarly, Heiligmann et al. (1985) found an abundance of oak crop trees 28 years after a variety of harvesting treatments in upland oak stands. More recently, Morrissey et al. (2008) found that oaks had persisted in stands in southern Indiana after clearcutting and were competing well in the early stem exclusion stage. Therefore, despite an overall trend of oak decline, these species as a group appear capable of competing in modern Eastern forests.

It should be noted that the estimates of aggregate height presented in this study represent seed-origin regeneration only. Sprout-origin regeneration was omitted from analyses because it is unlikely that it was affected strongly by pre-harvest non-tree vegetation cover. Fei and Steiner (2009) concluded that red maple's success in the post-harvest decade is largely due to the high survival and rapid growth of stump sprouts. Similarly, Morrissey et al. (2008) found that 45% of all oak stems in their study originated as stump sprouts. Therefore, the methods used in this study likely underestimated the true growth potential of these species, Although seed-origin red maple and oak regeneration responded similarly to competition with rhizomatous fern and mountain-laurel, oak was much more sensitive to non-modeled inhibitory factors than red maple. This was demonstrated by comparing the variance of the one-sided error term, which represents the difference between observations and their stochastic frontiers (Aigner et al. 1977). In the context of this study, these differences were attributed to factors, other than competition with non-tree vegetation, that inhibit natural regeneration. As a function of all three cover classes, this parameter was 2 to 3 times greater for oak than for red maple regeneration. Therefore, although rhizomatous fern and mountain-laurel inhibited oak and red maple aggregate height similarly, mean oak aggregate height was consistently lower than that of red maple at varying levels of cover. At 20-35% fern cover, for example, mean oak aggregate height was around 6 ft. lower than that of red maple. Because the variance of the one-sided error is related to mean aggregate height, it is striking that oak, which had a smaller mean aggregate height, would have a substantially larger error variance than red maple. This discrepancy further demonstrates the sensitivity of oak and the resilience of red maple to adverse environmental conditions.

The resilience of red maple is likely the result of a flexible physiology and a positive response to changes in the disturbance regime. This species has been called a “super generalist” because of its wide ecological amplitude and ability to behave as both an early and late successional species. It has also benefited from modern changes to disturbance regimes, such as fire suppression, while oak has suffered (Abrams 1992, Abrams 1998). This finding reinforces the hypothesis that red maple is a serious competitor with oaks while offering a new perspective on the oak to maple transition. According to the results of my study, one should not conclude that seed-origin red maple regeneration has a greater growth potential than oak in the decade following harvest but that red maple is more resilient to adverse environmental conditions and, therefore, better at achieving its potential. Not surprisingly, total regeneration was the most resilient to non-modeled inhibitory factors of the three categories of regeneration examined in my study. The alternative regeneration strategies of the species found in the study area likely improved the resilience of regeneration as a whole to various growing conditions.

Resilience to non-modeled inhibitory factors also varied according to cover class. Oak and total regeneration were significantly more resilient under mountain-laurel than under rhizomatous fern or tall shrubs. The differential response of regeneration is likely associated with site conditions. As previously mentioned, interfering vegetation appears to have been a stand or plot feature. Because mountain-laurel is typically associated with xeric soils (Monk et al. 1985), oak may have had an intrinsic advantage in these areas. Conversely, red maple was significantly more resilient under rhizomatous fern cover than under mountain-laurel. Due to the wide ecological amplitude of rhizomatous ferns, their presence reveals very little about site conditions (Engelman and Nyland 2006). However, a study of the distribution and dynamics of hay-scented fern in Pennsylvania found that high levels of this species were positively associated with cooler, moister aspects, and that its presence was positively correlated with red maple abundance (Fei et al. 2010).

Unlike the variance of the one-sided error discussed thus far, the variance of the two-sided error term is essentially the pure error associated with ordinary least-squares regression (Nepal et al. 1996). Therefore, it provides a statistical explanation for observations that exceed their frontier. The presence of these observations is typically a consequence of measurement error (Cummings et al. 2001), which may be partially responsible for extreme observations in my study. Another potentially large source of error is that estimates of aggregate height were predicted using pre-harvest conditions, which do not entirely determine the trajectory of regeneration after disturbance.

As demonstrated here, stochastic frontier analysis is a simple approach that yields a large amount of information. This approach has become popular in the field of forest resources as an alternative to boundary analysis (see Nepal et al. 1996, Cummings et al. 2001, Bi et al. 2000). Boundary analysis uses ordinary least-squares regression to estimate maximums based on a subset of data. The dilemma is that the selection of this subset is necessarily arbitrary. This was demonstrated in this study by conducting boundary analysis on two subsets derived from two arbitrary selection criteria. The two analyses resulted in different slopes and intercepts, and yielded no information on non-maximum data points. Stochastic frontier analysis, by comparison, estimated maximums iteratively and, therefore, required no data reduction. This approach also provided information on the sensitivity of dependent variables to non-modeled factors. If boundary analysis had been used to compare red maple and oak potential, for example, no conclusions could have been drawn on the resilience of these competing categories of regeneration to unknown factors.

Due to the number of factors affecting natural regeneration development, the difficulty of predicting potential in the decade following harvest cannot be overstated. The challenge lies in separating the effect of one variable from the collective influence of all others that play a role in this ecological process. Stochastic frontier analysis is a simple tool capable of overcoming this obstacle and was successful in predicting regeneration potential in this time period as a function of common interfering vegetation, while also yielding information on the sensitivity of regeneration to non-modeled inhibitory factors.

Chapter 5

Conclusion

As a consequence of analyzing oak as a group, this study failed to address how oak species might differ in their response to inhibitory vegetation and non-modeled factors. Because chestnut oak composed an average of 59% of the oak category, the conclusions of this study pertain mainly to this species. Chestnut oak regeneration abundance has been associated with xeric, south-facing slopes (Fei and Steiner 2008) generally favored by oak (Lorimer 1992). Therefore, chestnut oak may have demonstrated a greater resilience to non-modeled inhibitory factors than, for example, northern red oak, which has been associated with mesic, north- facing slopes (Fei and Steiner 2008) where oak regeneration failures are most likely to occur (Lorimer 1992). Similarly, hay-scented fern abundance has been positively associated with sites experiencing a shift from northern red oak to red maple dominance (Fei et al. 2010; Kaeser et al. 2008). Therefore, rhizomatous ferns may have affected northern red oak more severely than red maple, although red maple and oak as a group responded similarly to this class of cover. As more data is collected for the Oak Regeneration Study in Pennsylvania, these differences should be examined to better understand how individual oak species differ from one another and from red maple in their response to various inhibitory factors.

An important finding of this study was the differential response of oak and red maple to non-modeled inhibitory factors. The variance of the one-sided error term was used to demonstrate sensitivity to these factors, but other methods exist to estimate the difference between an observation and its stochastic frontier (Battese and Coelli 1995; Jondrow et al. 1982), which is commonly referred to in the field of econometrics as “technical inefficiency.” PROC QLIM in SAS 9.3 is capable of calculating technical inefficiency values, which could be correlated with other plot-level factors, such as slope, elevation, aspect, abundance of competing tree species, microtopography, deer browse intensity, soils, etc., in order to identify factors strongly associated with the success of oak. This type of analysis could, for example, prove the hypothesis that oak is less sensitive to non-modeled inhibitory factors under mountain-laurel, because oak and mountain-laurel share an affinity for xeric sites.

A major shortcoming of this study was the failure to address autocorrelation. Some stands, for example, had very high levels of rhizomatous fern cover, and others had very low levels. Therefore, it is likely that estimates of error variance were biased (Kutner et al. 2004). No option currently exists to address autocorrelation in the PROC QLIM procedure. Therefore, exploring alternative programming techniques would likely improve the application of stochastic frontier analysis in the field of forestry.

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Appendix A

Stand Descriptions

The following stand descriptions were developed by various parties involved in the Oak Regeneration Study in Pennsylvania between 1996 and 2011. The management activities outlined in these descriptions were developed by the Pennsylvania Department of Conservation and Natural Resources Bureau of Forestry in accordance with management objectives and were not experimentally controlled.

PSU Regeneration Study Location #0001

General Information

Type of Stand: Mixed-Oak
Ecological Unit: Northern Ridge and Valley
District: 5- Rothrock
Centroid Coordinates: 40.30804N, 78.09965W
Elevation: 1398 ft.
General Aspect: 240 degrees
Slope Position: Ridge
Average Slope: 6%
Area: 69 acres
Forester: Cole
Sale No: 05-99BC02
Name of Sale: Pipeline
Sale Block(s): 2, 3, 4, 5, 6

Stand Activities

June 15, 1999: Timber sale proposed.
Key Points: Regeneration from the stand analysis averages 10,200 seedlings per acre. Northern red oaks make up about half the total, while mixed-oaks make up most of the other half with white oak and black oak occurring most often. Chestnut oak, northern red oak, scarlet oak, hickory (*Carya* spp.) and eastern white pine (*Pinus strobus* L.) were also present. Gypsy moth (*Lymantria dispar* L.) mortality is evident.

May 22-26, 2000: PSU regeneration assessment #000100.
Comments: Three dominant trees (age, height): Quercus alba (94, 92); Quercus alba (101, 98); Quercus alba (89, 90). Site index : 75. Soils (% sale): CvB (70); BxB (30).

November 2000- April 2001: Regeneration harvest.

Sawtimber Volume Before Harvest (for 69 acres)

Species	Number of Trees	Net Volume (M Bd. Ft.)	Gross Volume (M Bd. Ft.)
Red Oak	46	17.5	20.4
Black Oak	268	58.2	69.6
Scarlet Oak	50	12.3	15.0
White Oak	1666	310.6	365.1
Chestnut Oak	785	136.5	158.8
MISC Species	211	24.8	28.8
Totals	3026	560.6	658.7

Pulpwood Volume Before Harvest (for 69 acres)

Species Group	Number of Trees	Volume (ft.^{3}/100)
Mixed Oak	688	75
Mixed Oak (dead)	6	1
Mixed Hardwood	709	102
Totals	2437	178

September 2001: Overstory removal completed.

April 6, 2012: Jacob Mazzei informed Dr. Steiner that an 11 acre brush fire occurred in the southeastern portion of the stands. It is likely that plots 25, 26, 27, 28, 29, and 30 were impacted.

PSU Regeneration Study Location #0003

General Information

Type of Stand: Mixed-Oak
Ecological Unit: Northern Ridge and Valley
District: 5- Rothrock
Centroid Coordinates: 40.64497N, 78.07533W
Elevation: 1647 ft.
General Aspect: 269 degrees
Slope Position: Ridge
Average Slope: 18%
Area: 53 acres
Forester: Wetzel
Sale No: 05-99BC04
Name of Sale: The Grinch
Sale Block(s): 2, 3

Stand Activities

November 2, 1999: Timber sale proposed.
Key Points: Desirable regeneration levels are present in this stand with chestnut oak seedlings dominating. Other species on the site include red maple, black birch, eastern white pine, and northern red oak. All the advanced seedlings are one foot tall or less. There is evidence of heavy deer browsing which necessitates the construction of a fence. Mountain-laurel is present throughout the site. Some overstory mortality has occurred, which has resulted in encroachment of striped maple (*Acer pensylvanicum* L.).

August 8-10, 2000: PSU regeneration assessment #000300.
Comments: Three dominant trees (age, height): Quercus prinus (74, 80); Quercus prinus (81, 85); Quercus prinus (72, 65). Site index: 70. Soils (% sale): MKD (100). Timber trees are predominantly chestnut oak. Some red maple and black gum present. Stand contains abundant chestnut oak and red maple regeneration, as well as moderate levels of northern red oak and black oak regeneration.

November 2000- February 2001: Regeneration harvest.
Basal area removed: 90 sq. ft. per acre
Residual basal area: 14 sq. ft. per acre

Sawtimber Volume Before Harvest (for 53 acres)

Species	Number of Trees	Net Volume (M Bd. Ft.)	Gross Volume (M Bd. Ft.)
Red Oak	86	28.4	31.5
Black Oak	13	2.8	3.2
Scarlet Oak	10	1.8	2.1
White Oak	3	0.9	1.1
Red Maple	33	2.5	3.3
Chestnut Oak	1744	243.0	282.7
Yellow Poplar	7	2.7	3.1
Sweet Birch	5	0.4	0.6
Hickory	2	0.2	0.2
Totals	1903	282.7	327.8

Pulpwood Volume Before Harvest (for 53 acres)

Species Group	Number of Trees	Volume (ft.^{3}/100)
Mixed Oak	701	45
Red Maple	1202	77
Totals	1903	122

April 2001: Overstory removal completed.

May 2003: Woven wire fence installed.

PSU Regeneration Study Location #9603

General Information

Type of Stand: Mixed-Oak
Ecological Unit: Northern Ridge and Valley
District: 5- Rothrock
Centroid Coordinates: 40.65070N, 77.74019W
Elevation: 1270 ft.
General Aspect: 241 degrees
Slope Position: Lower slope
Average Slope: 23%
Area: 26 acres
Forester: Long
Sale No: 05-95BC02
Name of Sale: Barrville Road
Sale Block(s): 10

Stand Activities

July 18, 1995: Timber sale proposed.
Key Points: Portions of the stand were experiencing decline in crown and growth at the time of harvest. There is a large component of oak regeneration and deer fencing has been proposed for this block. The opening of the crown has resulted in encroachment of striped maple.

May 1996: Handcut striped maple and sprayed stumps with Tordon.

May 22, 1996: PSU regeneration assessment #960300.
Comments: Three dominant trees (age, height): Quercus prinus (58, 80); Quercus rubra (88, 75); Quercus rubra (110, 90). Site index: 68. Soils (% sale): LcD (100).

November 25, 1997- January 8, 1998: Regeneration harvest.
Basal area removed: 100 sq. ft. per acre
Residual basal area: 16 sq. ft. per acre

Sawtimber Volume Before Harvest (for 26 acres)

Species	Number of Trees	Net Volume (M Bd. Ft.)	Gross Volume (M Bd. Ft.)
Sugar Maple	11	2.2	2.4
Red Oak	225	69.5	74.2
Black Oak	21	6.8	7.3
Scarlet Oak	7	2.3	2.4
White Oak	5	1.4	1.5
Chestnut Oak	214	35.3	37.7
Yellow Birch	31	4.6	4.9
Misc. Species	5	0.9	1
Totals	519	123	131.4

Pulpwood Volume Before Harvest (for 26 acres)

Species Group	Number of Trees	Volume ($ft.^3/100$)
Oak (mixed)	307	22
Hrdwds (NRN)	205	10
Hrdwds (MXD)	102	7
Totals	614	39

PSU Regeneration Study Location #9604

General Information

Type of Stand: Mixed-Oak
Ecological Unit: Northern Ridge and Valley
District: 5- Rothrock
Centroid Coordinates: 40.65680N, 77.72976W
Elevation: 1365 ft.
General Aspect: 318 degrees
Slope Position: Lower slope
Average Slope: 25%
Area: 33 acres
Forester: Wetzel
Sale No: 05-95BC02
Name of Sale: Barrville Rd.
Sale Block(s): 11, 12, 13

Stand Activities

July 18, 1995: Timber sale proposed.
Key Points: There is no record of previous treatment for this sale, though historical records indicate some operations in this compartment from 1898 to 1906. Portions of this stand are experiencing decline in crown and growth. The opening of the crown cover has resulted in encroachment of striped maple.

May 28, 1996: PSU regeneration assessment #960400.
Comments: Three dominant trees (age, height): Quercus prinus (100, 70); Quercus prinus (105, 85); Quercus prinus (120, 65). Site index: 58. Soils (% sale): LcD (85); BxD (15).

July 1997- June 1998: Regeneration harvest.
Basal area removed: 100 sq. ft. per acre
Residual basal area: 16 sq. ft. per acre

Sawtimber Volume Before Harvest (for 33 acres)

Species	Number of Trees	Net Volume (M Bd. Ft.)	Gross Volume (M Bd. Ft.)
Sugar Maple	15	2.6	2.8
Red Oak	265	80.6	86.1
Black Oak	26	11.9	12.7
Scarlet Oak	26	10.0	10.7
White Oak	9	1.5	1.6
Chestnut Oak	1376	315.5	336.8
Yellow Birch	85	10.7	11.4
Misc. Species	8	1.2	1.4
Totals	1810	434	463.5

Pulpwood Volume Before Harvest (for 33 acres)

Species Group	Number of Trees	Volume ($ft.^3/100$)
Maple (red)	101	3
Oak (mixed)	1155	94
Hrdwds (NRN)	631	28
Totals	1887	125

July 2000: Woven wire fence installed.

PSU Regeneration Study Location #9607

General Information

Type of Stand: Mixed-Oak
Ecological Unit: Northern Ridge and Valley
District: 5- Rothrock
Centroid Coordinates: 40.32461N, 78.07307W
Elevation: 1529 ft.
General Aspect: 174 degrees
Slope Position: Lower slope
Average Slope: 6%
Area: 70 acres
Forester: Cole
Sale No: 05-94BC07
Name of Sale: Stever
Sale Block(s): 5, 6, 7, 8

Stand Activities

January 4, 1995: Timber sale proposed.
Key Points: Openings in crown. Some overstory trees have been removed for firewood and windthrow has affected many others, but an estimated 15% of mortality has been attributed to gypsy moth.

June 13, 1996: PSU regeneration assessment #960700.
Comments: Three dominant trees (age, height): Quercus prinus (70, 77); Quercus prinus (93, 70); Quercus prinus (87, 64). Site index: 56. Soils (% sale): BxB (35); BxD (25); AoB (20); BsD (15); CvC (5).

December 1996- May 1997: Regeneration harvest.
Basal area removed: 96 sq. ft. per acre
Residual basal area: 12 sq. ft. per acre

Sawtimber Volume Before Harvest (for 70 acres)

Species	Number of Trees	Net Volume (M Bd. Ft.)	Gross Volume (M Bd. Ft.)
Red Oak	173	30	34.6
Black Oak	493	68.7	79
White Oak	964	108.7	125.6
Chestnut Oak	1253	110.6	127.4
Misc. Species	198	20.6	28.3
Totals	3081	342.8	394.9

Pulpwood Volume Before Harvest (for 70 acres)

Species Group	Number of Trees	Volume ($ft.^3/100$)
Oak (mixed)	1379	145
Dead Oak (mixed)	108	6
Hrdwods (mixed)	1059	53
Totals	2546	204

Until November 1997: Firewood cutting of down material permitted.

PSU Regeneration Study Location #9612

General Information

Type of Stand: Mixed-Oak
Ecological Unit: Northern Ridge and Valley
District: 7- Bald Eagle
Centroid Coordinates: 40.84924N, 77.27213W
Elevation: 847 ft.
General Aspect: N/A
Slope Position: Lower slope
Average Slope: N/A
Area: 69 acres
Forester: (Hofman) Lylo
Sale No: 9505
Name of Sale: Ario's Road
Sale Block(s): 1, 2

Stand Activities

A severe oak leaf roller (*Archips semiferanus* Walker) outbreak occurred in late 1960's and early 1970's.

1993: Good acorn crop.

July 22, 1996: PSU regeneration assessment #961200.
Comments: Three dominant trees (age, height): Quercus alba (98, 80); Quercus alba (83, 77); Quercus alba (77, 93). Site index: 65. Soils (% sale): BxD (30); BxB (30); LbB (30); LdD (10).

November 1996- June 1997: Regeneration harvest.
Basal area removed: 82 sq. ft. per acre
Residual basal area: 10 sq. ft. per acre

Sawtimber Volume Before Harvest (for 69 acres)

Species	Number of Trees	Net Volume (M Bd. Ft.)	Gross Volume (M Bd. Ft.)
Red Maple	13	1.1	1.3
Red Oak	394	70.4	80.9
Black Oak	132	24.4	28.4
Scarlet Oak	797	144.6	168.1
White Oak	543	66.2	75.3
Chestnut Oak	542	54.2	63.4
Totals	2421	360.9	417.4

Pulpwood Volume Before Harvest (for 69 acres)

Species Group	Number of Trees	Volume ($ft.^3/100$)
Maple (Red)	Undetermined	14
Oak (Mixed)	Undetermined	292
Aspen	Undetermined	312
Totals	Undetermined	518

2000: A one acre fence (8' woven wire) was erected. This was done on an experimental basis to monitor species richness in absence of deer browsing.

PSU Regeneration Study Location #9614

General Information

Type of Stand: Mixed-oak
Ecological Unit: Allegheny Mountain Plateau
District: 10- Sproul
Centroid Coordinates: 41.20955N, 77.93075W
Elevation: 1752 ft.
General Aspect: 255 degrees
Slope Position: Plateau
Average Slope: 12%
Area: 47 acres
Forester: Long
Sale No: 9602
Name of Sale: Lonely Trail
Sale Block(s): 4

Stand Activities

May 16-17, 1996: Timber sale proposed.
Key Points: The area is acceptably stocked with primarily sweet birch regeneration at 6,900 stems per acre. The stand was partially salvaged in 1983 and present stand stocking is below C Level.

August 5, 1996: PSU regeneration assessment #961400.
Comments: Three dominant trees (age, height): Quercus prinus (98, 85); Quercus prinus (65, 84); Quercus prinus (50, 85). Site index: 75. Soils (% sale): HsB (50); HsD (50).

April 1997: Planted 5,000 eastern white pine seedlings.
Comments: The seedlings were planted at a density of 250 per acre. No tree tubes were used.

November 1998- February 1999: Regeneration harvest.
Basal area removed: 32 sq. ft. per acre
Residual basal area: 10- 20 sq. ft. per acre

Sawtimber Volume Before Harvest (for 47 acres)

Species	Number of Trees	Net Volume (M Bd. Ft.)	Gross Volume (M Bd. Ft.)
Red Oak	86	18.8	21.9
Black Oak	43	7.3	9.0
Scarlet Oak	2	0.3	0.4
White Oak	9	1.4	1.6
Red Maple	379	64.9	84.3
Chestnut Oak	78	9.8	11.8
MISC Species	34	4.5	5.6
Red Oak (dead)	3	1.0	1.2
Totals	634	108.0	135.8

Pulpwood Volume Before Harvest (for 47 acres)

Species Group	Number of Trees	Volume ($ft.^3/100$)
Mixed Oak	312	50
Red Maple	1038	143
Totals	1350	193

May 2000: Planted 5,000 northern red oak seedlings.
Comments: The seedlings were planted at a density of 100 per acre, and Tree Pro tree tubes were used.

PSU Regeneration Study Location #9701

General Information

Type of Stand: Mixed-Oak
Ecological Unit: Northern Ridge and Valley
District: 7- Bald Eagle
Centroid Coordinates: 40.87099N, 77.29459W
Elevation: 1266 ft.
General Aspect: 158 degrees
Slope Position: Mid slope
Average Slope: 17%
Area: 27 acres
Forester: Strausbaugh
Sale No: 9507
Name of Sale: Deep Hollow
Sale Block(s): 2

Stand Activities

September 7, 1995: Timber sale proposed.
Key Points: Soils on this sale are Laidig Extremely Stony Loam and Buchanan Very Stony Loam. Large stones are found on large areas (3-50%) of both soil types. The stand is mixed-oak of average quality, which experienced moderate mortality in the late 1970's. Acceptable regeneration of northern red oak and red maple is present with 9,000 oak seedlings/acre recorded.

May 14, 1997: PSU regeneration assessment #970100.
Comments: Three dominant trees (age, height): Quercus rubra (80, 79); Quercus rubra (78, 76); Quercus rubra (77, 68). Site index: 60. Soils (% sale): BxB (10); LdD (90). Overstory is composed of northern red oak, black oak, and chestnut oak with an ericaceous understory.

September 1- 29, 1998: Regeneration harvest.
Basal area removed: 72 sq. ft. per acre
Residual basal area: 13 sq. ft. per acre

Sawtimber Volume Before Harvest (for 27 acres)

Species	Number of Trees	Net Volume (M Bd. Ft.)	Gross Volume (M Bd. Ft.)
Red Maple	7	1.0	1.1
Red Oak	549	108.5	124.7
Dead Red Oak	1	0.1	0.1
Black Oak	211	31.4	36.5
Scarlet Oak	7	1.6	1.9
White Oak	127	18.0	20.5
Chestnut Oak	310	33.4	38.8
Sweet Birch	1	0.1	0.1
Yellow Poplar	20	5.2	6.0
Totals	1233	199.3	229.7

Pulpwood Volume Before Harvest (for 27 acres)

Species Group	Number of Trees	Volume ($ft.^3/100$)
Maple (Red)	Undetermined	9
Oak (Mixed)	Undetermined	132
Totals	Undetermined	132

May 1999: 6-strand electric fence erected.

PSU Regeneration Study Location #9706

General Information

Type of Stand: Mixed-Oak
Ecological Unit: Allegheny Deep Valley
District: 13- Elk
Centroid Coordinates: 41.42159N, 78.10681W
Elevation: 2060 ft.
General Aspect: 107 degrees
Slope Position: Upper Slope
Average Slope: 16%
Area: 33 acres
Forester: Jim McGarvey
Sale No: 9615
Name of Sale: Brooks Tower
Sale Block(s): 1, 2, 3

Stand Activities

November 4, 1996: Timber sale proposed.
Key Points: This stand is dominated by northern red oak, red maple, and black oak. Advance regeneration of any type is scarce, and ferns are abundant throughout the stand.

June 12, 1997: PSU regeneration assessment #970600.
Comments: Three dominant trees (age, height): Quercus rubra (59, 79); Quercus rubra (79, 81); Quercus rubra (94, 95). Site index: 70. Soils (% sale): Hazelton channery loam (100).

August- November 1998: Regeneration harvest.
Basal area removed: 88 sq. ft. per acre
Residual basal area: 19 sq. ft. per acre

Sawtimber Volume Before Harvest (for 33 acres)

Species	Number of Trees	Net Volume (M Bd. Ft.)	Gross Volume (M Bd. Ft.)
Red Maple	97	11.6	12.1
Red Oak	1045	211.7	240.6
Dead Red Oak	74	11.3	12.7
Black Oak	270	34.3	40.3
Dead Blck Oak	14	1.5	1.8
White Oak	67	8.4	9.4
Dead Whte Oak	5	0.6	0.7
Chestnut Oak	78	7.3	8.4
Dead Chest Oak	13	0.9	1.0
Dead MISC Species	2	0.2	0.2
Totals	1665	287.8	328.2

Pulpwood Volume Before Harvest (for 33 acres)

Species Group	Number of Trees	Volume ($ft.^3/100$)
Maple (Red)	Undetermined	49
Oak (Mixed)	Undetermined	45
Totals	Undetermined	94

May 1999: 1,000 eastern white pine seedlings planted in sale block 3.
Comments: 100 seedlings per acre density.

August 1999: Woven wire fence installed.

April 2000: Planted 1,000 eastern white pine seedlings in sale block 2 and 500 northern red oak seedlings in sale block 3.

PSU Regeneration Study Location #9711

General Information

Type of Stand: Mixed-Oak
Ecological Unit: Allegheny Deep Valley
District: 12- Tiadaghton
Centroid Coordinates: 41.22260N, 77.37833W
Elevation: 1761 ft.
General Aspect: 153 degrees
Slope Position: Mid slope
Average Slope: 14%
Area: 34 acres
Forester: Miller
Sale No: 9611
Name of Sale: Big Spring South
Sale Block(s): 3

Stand Activities

December 11, 1996: Timber sale proposed.
Key Points: This 34 acre block contains low quality mixed-oak sawtimber and pulpwood with patches of old mortality. Mixed-oak and red maple advanced regeneration is at an acceptable level. A good chestnut oak seed crop in 1996 will supplement this regeneration. Dense mountain laurel thickets are found throughout the stand.

July 8, 1997: PSU regeneration assessment #971100.
Comments: Three dominant trees (age, height): Quercus prinus (80, 52); Quercus prinus (78, 57); Quercus prinus (77, 66). Site index: 48. Soils (% sale): Dekalb very stony soils (100).

May- September 1998: Regeneration harvest.
Basal area removed: 47 sq. ft. per acre
Residual basal area: 20 sq. ft. per acre

Sawtimber Volume Before Harvest (for 34 acres)

Species	Number of Trees	Net Volume (M Bd. Ft.)	Gross Volume (M Bd. Ft.)
Red Oak	7	0.5	0.6
Black Oak	37	3.3	3.8
Dead Blck Oak	33	2.4	2.9
Scarlet Oak	62	6.2	6.9
Dead Sclt Oak	21	1.4	2.0
White Oak	31	2.9	3.4
Dead Whte Oa	28	2.2	2.8
Chestnut Oak	167	13.2	15.3
Dead C. Oak	14	0.9	0.1
Misc. Species	1	0.1	0.1
Totals	401	33.1	39.0

Pulpwood Volume Before Harvest (for 34 acres)

Species Group	Number of Trees	Volume ($ft.^3$/100)
Maple (Red)	Undetermined	20
Oak (Mixed)	Undetermined	106
Dead Oak (Mixed)	Undetermined	31
Totals	Undetermined	157

Spring, 2004: Clipped lower branches on regenerating oaks.

Winter, 2006/2007: Clipped lower branches on oak stems. About one stem per 10-20 feet was clipped.

February 5, 2008: Tree of heaven (Ailanthus altisima) treated. The DCNR will continue to treat tree of heaven on the site and further down the road leading to the site.

PSU Regeneration Study Location #9715

General Information

Type of Stand: Mixed-Oak
Ecological Unit: Northern Ridge and Valley
District: 3- Tuscarora
Centroid Coordinates: 40.35721N, 77.55599W
Elevation: 1476 ft.
General Aspect: 269 degrees
Slope Position: Upper slope
Average Slope: 29%
Area: 26 acres
Forester: Beleski
Sale No: 9703
Name of Sale: Mumper Springs
Sale Block(s): 3

Stand Activities

Early 1980's: Site suffered mortality and was salvaged.

March 13, 1997: Timber sale proposed.
Key Points: Total area is above B level, but the acceptable growing stock is well below C level. This site has acceptable regeneration with a good mixture of species already present.

July 28, 1997: PSU regeneration assessment #971500.
Comments: Three dominant trees (age, height): Quercus prinus (85, 70); Quercus prinus (87, 76); Quercus prinus (81, 76). Site index: 58. Soils (% sale): HfB (50); HfD (50). The overstory is primarily mixed-oak and red maple, and the understory is primarily striped maple, red maple, and oak. Forest floor is largely bare with patches of hay-scented fern and blueberry.

November 1998: Regeneration harvest.
Basal area removed: 75 sq. ft. per acre
Residual basal area: 15 sq. ft. per acre

Sawtimber Volume Before Harvest (for 26 acres)

Species	Number of Trees	Net Volume (M Bd. Ft.)	Gross Volume (M Bd. Ft.)
Red Maple	1	0.1	0.1
Red Oak	214	71.1	88.9
Black Oak	48	15.6	19.5
Scarlet Oak	2	0.8	1.0
White Oak	1	0.4	0.5
Chestnut Oak	354	77.2	95.3
Misc Species	42	4.7	5.9
Totals	662	169.9	211.2

Pulpwood Volume Before Harvest (for 26 acres)

Species Group	Number of Trees	Volume ($ft.^3/100$)
Maple (Red)	561	59
Oak (Mixed)	225	30
Totals	786	89

May 1999: Approximately 50 extra oak seedlings planted**.**

PSU Regeneration Study Location #9717

General Information

Type of Stand: Mixed-Oak
Ecological Unit: Northern Ridge and Valley
District: 5- Rothrock
Centroid Coordinates: 40.66515N, 77.94907W
Elevation: 1086 ft.
General Aspect: 142 degrees
Slope Position: Mid slope
Average Slope: 27%
Area: 39 acres
Forester: Pfister
Sale No: 05-96BC05
Name of Sale: PSU Watershed 3
Sale Block(s): 2, 3

Stand Activities

May 22, 1996: Timber sale proposed.
Key Points: The sale boundaries were located to salvage wood in an area with mortality where logging is feasible. While most of the mortality is too old and deteriorated for salvage, these 39 acres contain sufficient volume for a commercial sale and acceptable regeneration.

August 4, 1997: PSU regeneration assessment #971700.
Comments: Three dominant trees (age, height): Quercus prinus (85, 100); Quercus prinus (80, 78); Quercus prinus (82, 85). Site index: 70. Soils (% sale): LcD (25); HTF (50); HTD (25). Heavy, old mortality with average to poor quality black oak, chestnut oak, white oak, and northern red oak. Regeneration consists primarily of red maple with occasional black birch, black cherry, scarlet oak, northern red oak, and white oak seedlings.

November 1998- April 1999: Regeneration harvest.
Basal area removed: 55 sq. ft. per acre
Residual basal area: 16 sq. ft. per acre

Sawtimber Volume Before Harvest (for 39 acres)

Species	Number of Trees	Net Volume (M Bd. Ft.)	Gross Volume (M Bd. Ft.)
Red Oak	107	19.2	21.3
Black Oak	393	61.3	68.1
Dead Black Oak	9	0.9	1.2
Scarlet Oak	57	10.1	11.1
Dead Scarlet Oak	1	0.1	0.1
White Oak	160	21.8	26.3
Chestnut Oak	474	49.4	61.7
Dead Chestnut Oak	4	0.4	0.5
White Pine	1	0.1	0.1
Red Maple	1	0.2	0.2
Misc. Species	31	4	4.8
Totals	1238	167.5	195.4

Pulpwood Volume Before Harvest (for 39 acres)

Species Group	Number of Trees	Volume (ft.^{3}/100)
Oak (mixed)	1440	142
Dead Oak (mixed	450	41
Hrdwds (mixed)	450	33
Totals	2340	206

PSU Regeneration Study Location #9718

General Information

Type of Stand: Mixed-Oak
Ecological Unit: Northern Ridge and Valley
District: 7- Bald Eagle
Centroid Coordinates: 40.91891N, 77.21581W
Elevation: 1257 ft.
General Aspect: 145 degrees
Slope Position: Upper slope
Average Slope: 17%
Area: 31 acres
Forester: Lylo
Sale No: 9702
Name of Sale: Bartley Gap
Sale Block(s): 2

Stand Activities

May 30, 1997: Timber sale proposed.
Key Points: The stand is comprised of a pole sized eastern white pine plantation understory and intermediate canopy that has since been overtopped by northern red, black, scarlet, and chestnut oaks in the pole and sawtimber size classes. Quality of the stand is poor with a low amount of acceptable growing stock. Regeneration on the site is acceptable.

August 7, 1997: PSU regeneration assessment #971800. (see attached photographs)
Comments: Site index: 55. Soils (% sale): LaC (10); LdD (90). Overstory composed mainly of eastern white pine and mixed-oak. Understory is bare except for an ericaceous patch at southwest end of sale.

June 30, 1998- October 27, 1999: Regeneration harvest.
Comments: An estimated 6 sq. ft. of basal area was lost due to logging damage.
Basal area removed: 75 sq. ft. per acre
Residual basal area: 20 sq. ft. per acre

PSU Regeneration Study Location #9803

General Information

Type of Stand: Mixed-Oak
Ecological Unit: Northern Ridge and Valley
District: 5- Rothrock
Centroid Coordinates: 40.31550N, 78.11609W
Elevation: 1188 ft.
General Aspect: 252 degrees
Slope Position: Ridge
Average Slope: 8%
Area: 57 acres
Forester: Cole
Sale No: 9608
Name of Sale: “C” Dorm
Sale Block(s): 6-9

Stand Activities

March 5, 1997: Timber sale proposed.
Key Points: From the soil survey, timber growing site quality over the sale area runs from fair (about 1%) to good (about 60%) to very good (about 40%). The only listed problems for tree growth are severe seedling mortality and windthrow hazard in the soils along the streams. These stands are primarily oak-hickory, but are also rather diverse with at least 12 other commercial species present. All areas of this sale were cut selectively with timber sales and permits between 1956 and 1962. Gypsy moth mortality is evident, but mostly light to moderate. Regeneration in the sale area is desirable, with 7,500 seedlings per acre. Oaks compose the majority of regeneration.

July 21, 1998: PSU regeneration assessment #980300.
Comments: Three dominant trees (age, height): Quercus alba (92, 91); Quercus alba (77, 84); Quercus alba (92, 89). Site index: 69. Soils (% sale): MkD (100). Overstory throughout the sale was predominantly mixed oak- hickory with eastern white pine. Blocks 8 and 9 contained moderate levels of eastern white pine advanced regeneration. Block 6 is a mix of advanced red maple regeneration and some eastern white pine regeneration. Block 7 contained large amounts of regeneration of over 12 species of hardwoods.

April 1999- September 1999: Regeneration harvest.
Basal area removed: 92 sq. ft. per acre
Residual basal area: 10 sq. ft. per acre

Sawtimber Volume Before Harvest (for 57 acres)

Species	Number of Trees	Net Volume (M Bd. Ft.)	Gross Volume (M Bd. Ft.)
White Pine	278	110.4	135.2
Red Oak	169	44	53.8
Black Oak	309	74.9	91.7
Scarlet Oak	234	64.1	78.4
White Oak	911	187.5	229.6
Chestnut Oak	514	90.2	110.4
Hickory	231	34.5	42.1
MISC Species	209	25.9	31.7
Totals	2855	631.5	772.9

Pulpwood Volume Before Harvest (for 57 acres)

Species Group	Number of Trees	Volume ($ft.^3/100$)
Oak (mixed)	986	104
Hardwoods (mixed)	1103	71
Totals	2089	175

PSU Regeneration Study Location #9804

General Information

Type of Stand: Mixed-Oak
Ecological Unit: Northern Ridge and Valley
District: 7- Bald Eagle
Centroid Coordinates: 40.82651N, 77.22527W
Elevation: 1627 ft.
General Aspect: 239 degrees
Slope Position: Ridge
Average Slope: 14%
Area: 35 acres
Forester: Lehman
Sale No: 9716
Name of Sale: Horseshoe Bend
Sale Block(s): 1, 2

Stand Activities

October 29, 1997: Timber sale proposed.
Key Points: The sale is located on the north side of Front Mountain where the slope ranges from 3-25%. The soils are well drained and have slight seedling mortality rates. The stands are approximately 80 to 100 years old. The stands are predominately chestnut oak, and dense patches of mountain laurel can be found scattered throughout the area. Regeneration is poor, but what is present consists mainly of chestnut oak and red maple, with some northern red oak, black oak, and eastern white pine scattered throughout.

July 28, 1998: PSU regeneration assessment #980400.
Comments: Three dominant trees (age, height): Quercus prinus (100, 77); Quercus prinus (95, 88); Quercus prinus (95, 67). Site index: 59. Soils (% sale): HuF (10); HuD (30); HuB (50); UoD (10). The overstory is predominantly chestnut oak, red oak, and black gum with pole sized red maple. The understory is characterized by a lack of regeneration and an abundance of blueberry, huckleberry, and mountain-laurel.

1999: 6 strand electric fence installed.

January 13, 1998- September 10, 1999: Regeneration harvest.
Basal area removed: 75 sq. ft. per acre
Residual basal area: 15 sq. ft. per acre

May 2000: Planted 10,500 eastern white pine seedlings at a density of 300 per acre. Tree tubes were not used and the seedlings were not flagged.

October 3, 2006: The electric fence was deemed ineffective and removed.

PSU Regeneration Study Location #9806

General Information

Type of Stand: Mixed-Oak
Ecological Unit: Northern Ridge and Valley
District: 7- Bald Eagle
Centroid Coordinates: 40.78243N, 77.61421W- plot 7
Elevation: 1715 ft.
General Aspect: 164 degrees
Slope Position: Upper slope
Average Slope: 26%
Area: 74 acres
Forester: Hofman
Sale No: 9711
Name of Sale: Potter Run
Sale Block(s): 2, 3, 4

Stand Activities

July 24, 1997: Timber sale proposed.
Key Points: The stand is 85 to 90 years old and located on a southeastern slope of Kohler Mountain. Well-established, desirable seedling sprouts, such as chestnut oak, are present on this site.

August 12, 1998: PSU regeneration assessment #980600.
Comments: Three dominant trees (age, height): Quercus prinus (60, 55); Quercus prinus (73, 71); Quercus prinus (79, 60). Site index: 53. Soils (% sale): AoB (45); WeD (45); LaC (10). Site is dominated by chestnut oak, but also contains black oak, white oak, northern red oak, and scarlet oak. The lower slope has abundant advanced chestnut oak and red maple regeneration; abundant mountain-laurel, blueberry, and huckleberry characterize the upper slope.

April 8, 1999- June 28, 1999: Regeneration harvest.
Basal area removed: 116 sq. ft. per acre
Residual basal area: 13 sq. ft. per acre

PSU Regeneration Study Location #9808

General Information

Type of Stand: Mixed-Oak
Ecological Unit: Northern Ridge and Valley
District: 5- Rothrock
Centroid Coordinates: 40.71074N, 77.88943W- plot 18
Elevation: 1513 ft.
General Aspect: 141 degrees
Slope Position: Mid slope
Average Slope: 16%
Area: 25 acres
Forester: Pfister
Sale No: 05-97BC02
Name of Sale: Roaring Run
Sale Block(s): 5, 11

NOTE: This location was created from part of the original Location 9801.

Stand Activities

April 16, 1998: Timber sale proposed.
Key Points: The sale boundaries were located to salvage mortality, protect stream riparian zones, and to take advantage of existing advanced regeneration. This area was last treated by Timber Sale 5-80BC1. This stand contains high quality northern red oak and black oak at an 83% stocking level as well as good quality white oak at a 95% stocking level. The 50 acres that contain acceptable reproduction will be harvested, 25 of which are included in this stand.

June 29, 1998: PSU regeneration assessment #980100. (see attached photographs)
Comments: Three dominant trees (age, height): Quercus rubra (87, 82); Quercus rubra (96, 92); Quercus rubra (107, 78). Site index: 64. Soils (% sale): Hazelton-Dekalb association moderately steep (85); Hazelton-Dekalb association steep (15). The overstory is composed of mature northern red oak (high quality), black oak, and white oak, with black gum, red maple and chestnut oak as co-dominant species. Huckleberry and blueberry dominate the understory. The upper slope contains advanced red maple and striped maple regeneration. The lower slope is poorly drained.

July 1999: Woven fence installed.

December 2000: Regeneration harvest.
Basal area removed: 82 sq. ft. per acre
Residual basal area: 14 sq. ft. per acre

Sawtimber Volume Before Harvest (for 25 acres, Blocks 5, 11)

Species	Number of Trees	Net Volume (M Bd. Ft.)	Gross Volume (M Bd. Ft.)
Red Oak	111	41.7	46.5
Black Oak	214	64.3	71.2
Scarlet Oak	4	1.2	1.3
White Oak	140	38.5	42.9
Chestnut Oak	325	63.7	71.2
Miscelleneous	5	1.2	1.3
Red Oak	27	22.1	24.8
Totals	826	232.7	259.2

Pulpwood Volume Before Harvest (for 25 acres, Blocks 5, 11))

Species Group	Number of Trees	Volume ($ft.^3/100$)
Mixed Oak	189	27
Mixed Oak (dead)	10	1
Mixed Hardwood	20	1
Totals	219	29

February – March 2002: Cutting in Blocks 5 and 11 completed inside of fence.

PSU Regeneration Study Location #9905

General Information

Type of Stand: Mixed-Oak
Ecological Unit: Northern Ridge and Valley
District: 3- Tuscarora
Centroid Coordinates: 40.46828N, 77.63472W
Elevation: 1470 ft.
General Aspect: 139 degrees
Slope Position: Upper slope
Average Slope: 25%
Area: 11 acres
Forester: Johnson
Sale No: 9803
Name of Sale: Headwaters Regeneration
Sale Block(s): 1, 2

Stand Activities

1993: Salvage cut.

1998: Salvage cut.

May 7, 1998: Timber sale proposed.
Key Points: The residual stand, after salvage cutting, consists mainly of mixed-oak sawtimber in the 18-23 inch diameter classes. Advance oak regeneration in the area consists mostly of chestnut oak, with some northern red oak, black oak, and scarlet oak as well. Seedlings are 2-7 feet tall. Deer browse is a problem, with over 66% of the milacre plots containing seedlings with browse damage. Striped maple is also present on the site.

July 20-22, 1999: PSU regeneration assessment #990500. (see attached photographs)
Comments: Three dominant trees (age, height): Quercus rubra (77, 79); Quercus rubra (78, 84); Quercus rubra (74, 71). Site index: 66. Soils (% sale): HTF (100). Good oak regeneration in sale area. Well stocked with advanced regeneration.

April- June, 2000: Regeneration harvest.

May 2002: Woven wire fence erected.

December 2005: Woven wire fence removed.