**The Pennsylvania State University**

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# EARLY DEVELOPMENT OF MIXED-OAK FOREST STANDS

A Thesis in

Ecology

by

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## Abstract

Throughout eastern America, natural regeneration of oaks (*Quercus* spp.) is often difficult to obtain even where oaks are dominant components in the overstory before harvest. Our understanding of the reasons for this is in part hindered by insufficient quantitative, descriptive information about stands undergoing this process. This study examines the composition, development, and constraints of regeneration of mixed-oak stands in the central Appalachians and proposes methods for quantifying the regeneration process.

The study employs four datasets collected in mixed-oak stands in the Ridge and Valley and the Appalachian Plateau physiographic provinces. Two distinct forest subtypes, a red maple (*Acer rubrum* L.) – northern red oak (*Q. rubra* L.) – hayscented fern (*Dennstaedtia punctilobula* (Michaux) Moore) subtype and a red maple – chestnut oak (*Q. montana* Willd.) – blueberry (*Vaccinium* spp.) subtype, were identified in the study area. Red maple was the most abundant species across the study area. Northern red oak was the most abundant oak species on the Allegheny Plateau physiographic province, while chestnut oak was the most abundant oak species in the Ridge and Valley province. Comparison of overstory tree and advance regeneration importance values suggests a trend that red maple is expanding its dominance from the Allegheny Plateau to the Ridge and Valley and black birch (*Betula lenta* L.) is expanding from the Ridge and Valley to the Allegheny Plateau, while white oak (*Q. alba* L.) and chestnut oak are losing their prominence in both physiographical provinces but especially on the Allegheny Plateau.

Associations were found between tree regeneration and biotic and abiotic factors. Red maple is abundant on most sites, but high red maple abundance is commonly associated with moist, north-facing slopes with no or low cover of mountain-laurel (*Kalmia latifolia* L.) and hayscented fern. On a plot-level basis, regeneration of the three oak species is greatly favored by the presence of overstory trees of their own kind. White oak regeneration is favored by south-facing, gentle,

lower slopes with soils in the Buchanan series. Chestnut oak tends to be associated with south-facing, steep upper slopes with stony soils. There is also a positive association between chestnut oak and the density of huckleberry (*Gaylussacia baccata* (Wangh.) Koch). Northern red oak is favored by north-facing, moist sites with Hazleton soil and low levels of mountain-laurel and hayscented fern.

Stand development after overstory removal was studied separately for stump sprouts and seed origin regeneration. Sprouting probability was high for red maple and generally fair for oak species; it was very poor for white oak. Sprouting probabilities for all the oak species were significantly influenced by stump age and/or stump diameter. On average, red maple had taller dominant sprouts, more sprouts per stump, and larger sprout crown diameters than other species, at least through age five. The pattern of growth in red maple stump sprouts appears to give that species an early advantage in the capture of future growing space. High overstory density, high sprouting and survival probability, and fast response to overstory removal makes red maple stump sprouts superior competitors with oak regeneration early in stand development.

Analysis of early-stage development of seed origin regeneration indicated that advance regeneration is the most important factor influencing regeneration abundance after harvest, except for black birch seedlings. Small advance oak regeneration grew into larger size classes after overstory removal and contributed greatly to overall regeneration success as measured by cumulative height of seedlings per unit area, a composite index of density and size. Overstory removal and herbicide treatment reduced the frequency of plots with problematic non-tree vegetation cover (> 30 percent), affording a "window of opportunity" for tree regeneration to establish and grow above the herbaceous layer. Red maple was the most abundant species of regeneration both before and after harvest. The principal advantage of red maple regeneration is its ability to accumulate in large numbers prior to harvest and carry these seedlings forward after overstory removal. Oak species had a slower response to overstory removal than non-oak species, as measured by cumulative height, and their largest seedlings also had slower height growth rate than the largest seedlings of other species. However, oak preserved its occurrence frequency and level of dominance in cumulative height at least through four years after harvest.

Regeneration stocking charts and equations were developed for mixed-oak stands using average maximum stand density as a reference level. Minimum stand density was estimated using crown area vs. seedling height relationship of open-growing seedlings. A developmental shifting point was observed for both open-growing seedlings and seedlings with the maximum level of competition. The crown width-seedling height ratio initially decreases rapidly as seedling height increases toward the shifting point, and then increases slowly after the shifting point as the tree grows further in height. Stocking charts were built separately for plots having average seedling height below and above the shifting point by plotting cumulative height on the y-axis and number of seedlings on the x-axis on a log-log scale. The resulting stocking charts and equations provide an objective basis for evaluating stocking of young regeneration in upland, mixed-oak forests.

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# Chapter 1

# Introduction

Throughout eastern America, natural regeneration of oaks (*Quercus* spp.) is often difficult to obtain even where oaks are dominant components in the overstory before harvest (Lorimer 1992, Abrams 1992, Crow 1988). While the problem is reported to occur widely, both geographically and by species, the failures commonly arise when there is inadequate quality or quantity of advance oak regeneration before harvest. In addition, seedlings often respond poorly to overstory removal and fail in competition with herbaceous vegetation and other woody species. Failure to obtain adequate and prompt regeneration of oak species after harvest can leave a stand unproductive for many years, cost excessive amounts to reclaim through artificial means, and severely limit the suitability of the stand for a wide range of forest values (Marquis and Twery 1992). To solve this problem, a great deal of research has been invested in discovering the possible causes of natural oak regeneration failure, in searching for successful regeneration methods and silvicultural systems, and in building practical predictive regeneration models and stocking tables.

## Possible causes of regeneration failure

Many factors are related to the failure in establishment and development of oak regeneration. Lorimer (1992) provided a thorough and thoughtful review of problems associated with oak regeneration. The major causes may change from site to site and region to region. Because of this variability, it is necessary to view "the oak regeneration problem" as having both local and regional aspects (Lorimer 1992). Generally, the failure is due to the following major causes.

Changes in the historical events that helped the establishment of the presently mature oak stands may play an important role in the failure of current oak regeneration. Disturbance, intensive logging, repeated fires, death of the American chestnut (*Castanea dentata* (Marsh.) Borkh), and perhaps climatic changes are some of the factors that may influence availability of acorns and the development oak seedlings. Carvell and Tyron (1961) concluded that disturbances improve the chances for the development of advance regeneration by reducing canopy densities and creating openings. Their hypothesis was influenced by a good correlation between amount of oak regeneration and amount of light reaching the forest floor. In a southern Wisconsin oak woods study, McCune and Cottam (1985) found that a reduction in fire frequency has created an unprecedented opportunity for shade-tolerant species in dry woods, and their success leads to the failure of regeneration and establishment of the two major oak species, black oak (*Q. velutina* Lam.) and white oak (*Q. alba* L.) in that area. Abrams (1992, 2003) compared pre-settlement and current overstory and understory conditions for various oak forest types in eastern North America. He concluded that fire and human activity have affected the past and present oak forest dramatically that there has been almost no canopy recruitment of most of the major upland oak species for at least 50 years.

Poor acorn crops, acorn destruction, and seedling damage are the other major causes of oak regeneration failure, because successful oak regeneration usually depends on the presence of seedlings in the understory in advance of harvest (advance regeneration) (Sander 1972, McQuilkin 1975). These factors can have significant impacts on the ability of oaks to compete with other species. Although unfavorable weather can lead to poor acorn crops, destruction of acorns by insects, mammals, and birds is probably a more important factor. Because of inconsistent methodology, the reports of acorn loss vary from study to study. Marquis et al. (1976) and Galford et al. (1991) reported a loss of 90 percent of the current crop. After studying five northern red oak (*Q. rubra* L.) stands over four years, Steiner (1995) reported an average loss of 46.5 percent of the acorns during the autumn, in which 7.9 percent was due to destruction by insects, and 38.6 percent to removal by vertebrates.

Even with significant predation, large numbers of oak seedlings still can establish after large acorn crops, but repeated defoliation and other animal damage can cause high mortality and slow growth of seedlings. Asiatic oak weevil (*Cyrtepistomus castaneus* Roelofs) can have a serious impact on oak seedlings because larvae feed on fine root hairs and adults feed on leaves (Triplehorn 1955). Another insect that has a strong impact on the seedling growth is the gypsy moth (*Lymantria dispar* L.). In one of our surveys (The Pennsylvania Oak Regeneration Assessment Project) in year 2000, there was almost one hundred percent seedling defoliation by gypsy moth. White-tailed deer (*Odocoileus virginianus* Boddaert) are clearly another big problem for oak regeneration in some places because they consume both acorns and seedlings. The deer population on parts of the Allegheny Plateau in Pennsylvania has served to create open, park-like forest stands with little undergrowth (Lorimer 1992). Similarly, high deer populations in a game preserve in Massachusetts have created savanna-like conditions (Pubanz et al. 1992).

Extreme competition from herbaceous species and shade-tolerant woody species is another explanation for the slow growth and high mortality of understory oak seedlings. Bowersox and McCormick (1987) reported that under the competition of herbaceous communities, juvenile growth of northern red oak and other species is greatly reduced. In oak stands with a heavy ground cover of hayscented fern (*Dennstaedtia punctilobula* (Michaux) Moore), the development of advance reproduction is not possible even with deer fencing (Steiner and Joyce 1999), apparently because light levels are too low to permit seedlings to grow through the fern. It is also possible that ectomycorrhizal fungi may enhance the allelopathic effects of ferns on oak seedling survival and growth (Hanson and Dixon 1987, Lyon and Sharpe 1996). Some shade tolerant species like red maple (*Acer rubrum* L.) are strong oak competitors. Lorimer (1984) investigated four upland oak forests and found all tracts had a dense understory of shade-tolerant species dominated by red maple but sparse representation of oak saplings. Abrams (1998) also pointed out that red maple, as a "super-generalist", out-competes the oaks and dominates the understory and mid-canopy of many oak forests.

## Silviculture, protection and management

In order to ensure sufficient quantities of advance reproduction and stimulate seedling growth after harvest, researchers have for years pursued appropriate silvicultural systems and successful regeneration methods. Because site variability may reflect different major causes for failure, the solutions are also likely to differ from site to site. On fair-to-poor growing sites, oaks may be regenerated by even-aged methods such as clearcutting or shelterwood, but oak regeneration becomes more difficult and complicated on better, more mesic sites (Sander and Clark 1971). Loftis (1990a) used a "noncommercial" shelterwood method to stimulate growth of existing advance red oak reproduction in the Southern Appalachians. Success was obtained by reducing basal area in mature, fully stocked stands to 60 – 70 percent stocking depending on the site index. In a study of oak forests in West Virginia, Schuler and Miller (1995) reported that shelterwood treatments fail to establish oak reproduction on mesic forest sites. Hill and Dickmann (1988) compared three common methods, clearcutting, shelterwood, and group selection, for naturally reproduced oak in southern Michigan. They found substantial reproduction of red oaks only in the clearcut and shelterwood, and white oak regeneration was virtually nonexistent.

Considering that failures are often related to competition from understory vegetation, herbicide, understory removal, and understory burning are sometimes suggested as necessary prescriptions. All these methods serve to eliminate heavy understory shade and thus stimulate oak seedling release. Improvement in size and growth rate of natural oak seedlings after reduction of understory density by herbicides has been widely reported (Horsley, 1982, Johnson et al., 1989). Lorimer et al. (1994) showed that "understory removal" plots had 10 to140 times as many natural oak seedlings five years after treatment. Some studies of both wildfire and prescribed burns have shown that fire can increase the proportion of oak by reducing shade tolerant species and creating open space that favors oak regeneration (Carvell and Tryon 1961, Maslen 1988, Brose et al.1999).

In some regions, oak regeneration failure is partially due to heavy deer browsing. The use of deer exclosures to reduce the incidence of browsing on natural regeneration is highly recommended where deer browsing is intensive (Marquis and Brenneman 1981, Trumbull et al. 1989, George et al. 1991). Steiner and Joyce (1999) suggested that getting advance oak regeneration to grow after establishment might be achieved by both controlling the density of understory fern and fencing to exclude deer, but neither would work alone. Under the shade of ferns, survival one year after germination was 72.3 percent for protected seedlings and 15.8 percent for unprotected seedlings, suggesting approximately 56 percent additional mortality from deer browsing.

## Regeneration modeling

It is important to understand the underlying causes of oak regeneration failure and develop methods to solve problems mentioned above. At the same time, however, other questions arise, such as how many oak seedlings of what size constitute successful regeneration? One challenge for researchers is to develop models to help us understand and predict oak regeneration. Although several growth-yield models such as STEMS (Belcher et al.1982), OAKSIM (Hilt 1985), and TWIGS (Miner et al.1988) have been devised for the purpose of projecting stand changes, they are only applicable to stands in which the minimum diameter at breast height (DBH) is 2 inches or more, and thus these do not address the regeneration period that immediately follows overstory removal. The regeneration period is a very dynamic stage of rapidly changing tree growth and species composition, and it almost completely determines the character of the mature stand. It is essential to have good prediction tools applicable to this period.

From an ecological perspective, regeneration models could be defined as predictors of the outcome of short-term secondary succession associated with planned disturbances (Rogers, 1998). Successional models usually do not provide the stand-level accuracy needed by silviculturists even though they possess generality and realism (Waldrop et al., 1986). Because of the seemingly unpredictable responses in oak stands related to the variety of potentially important factors, modeling natural oak regeneration is difficult and challenging.

Several hardwood regeneration models have been built to predict stand development after final harvest for the purpose of evaluating alternative prescriptions before imposing an actual harvest (Johnson 1977, Sander et al. 1984, Waldrop et al. 1986, Lowell et al. 1987, Johnson and Sander 1988; Marquis and Ernst 1988, Loftis 1990b, Dey 1991, Rogers and Johnson 1993). Predictions are typically based on pre-harvest inventories of advance reproduction, overstory composition, and other site factors. Oak stump sprouting, which is considered to be an important component of regeneration, has also been modeled (Johnson 1975, 1977, Johnson and Rogers 1984).

Sander et al. (1984) developed a regeneration model for the Missouri Ozarks. It calculates a predicted "stocking value" for reproduction on individual plots based upon the probability of individual oak seedlings surviving and growing to become members of the dominant or codominant crown classes. The model predicts the adequacy of future oak stocking based on seedling size, plot aspect, slope position, and site quality. Regeneration is considered to have sufficient potential if projected stocking of dominant and codominant oaks at stand age 20 is equal to or greater than 30 percent. This model is widely used to evaluate the adequacy of potential oak regeneration. Non-oak species are not considered in this model.

Marquis and Ernst (1988) developed an expert system, SILVAH, for modeling Allegheny hardwood forests regeneration. During the pre-harvest inventory, site factors, interference species competition, and deer browsing intensity are recorded. Species, numbers of stems, and regeneration size are inventoried on six-foot radius plots to determine level of stocking. Oaks in the overstory are also inventoried. Stocking contributed by oak stump sprouting at age 20 is estimated using models developed by Sander et al. (1984). They assumed that successful regeneration will occur if 70 percent of the plots are stocked with desirable advance reproduction.

Loftis (1990b) developed a regeneration model for Southern Appalachians. Based on pre-harvest advance regeneration measurements and site quality, the model predicts the height and crown class of northern red oak eight years after harvest. Height and basal diameter of advance regeneration oak seedlings and site index are used to estimate oak seedling height at stand age eight after harvest. Basal diameter and site index are used to predict the probability that a given oak will be in the dominant or codominant crown classes eight years after overstory removal.

Dey (1991) developed a regeneration model called A Comprehensive Ozark

Regenerator (ACORn) to simulate the regeneration of even-aged stands in the Missouri Ozarks. It is based on the measurements of individual stems before and after clearcutting. ACORn comprises two modules that simulate the development of advance reproduction and stump sprouts respectively, two major sources of reproduction in the mixed oak stands in Missouri Ozarks. Each module contains models for estimating future heights, diameters, and survival of stems by species based on initial tree size and site factors. Projections for non-oak species such as hickory (*Carya* spp.) and blackgum (*Nyssa sylvatica* Marsh.) also can be obtained from ACORn. Data from pre-harvest inventories of overstory and advance reproduction in the form of tree lists provide input to survival and growth models that generate predicted diameter distributions and stand structure in the future, which can be used as the input into growth and yield models.

Rogers and Johnson (1993) developed a model called SIMSEED, which simulates the fluctuation in the density of northern red oak regeneration. The model performs simulations based on two factors: seedling recruitment and seedling survival rates. They assumed that acorn crops, and thus seedling crops, occur randomly but with probabilistically known frequencies. Then they used survival rates and population densities reported in the literature as a yardstick to simulate dynamic population processes. They claimed this model facilitates projecting hypothetical situations that can provide insight into potential regeneration problems such as identifying the key factor that leads to insufficient regeneration numbers under certain site conditions. In particular, SIMSEED provides the generality needed to characterize regeneration dynamics in different ecosystems by using model coefficients as signatures that represent those systems (Rogers and Johnson 1998).

As reviewed above, the models developed by Sander, Marquis, Loftis, and Dey are statistically derived models built on large field datasets. Hence, these models give reasonably accurate predictions of density, height, diameter, and/or crown classes within the limits of this datasets. However, these models lack generality because they are limited in their application to the conditions represented by the data. Their applicability needs to be carefully re-considered when used in areas outside the conditions under which they were developed. In Marquis's model, they adapted Sander's model to predict the oak component. For example, when applying Marquis's model in the mixed-oak forest in Pennsylvania, foresters and researchers find that this model is too conservative in predicting oak regeneration. Although Rogers's probabilistic model can be applied in any region, local research is still needed to provide the actual values of coefficients used in the model. Currently, there is no fully developed regeneration model for the mixed-oak region of the central Appalachians. It will be very helpful to have a research-based regeneration model that can be applied for this region.

## Regeneration stocking

Appropriate stocking tables or charts, which serve as yard stick to measure the level of adequacy, have long been sought by foresters. Stocking is a subjective term used to describe the adequacy of any observed level of stand density with respect to a silvicultural goal (Bickford et al. 1957, Gingrich 1964). Reineke (1933) proposed the first stocking diagram based on relative density. Since then, many stocking charts, diagrams, and monographs have been developed (Chisman and Schumacher 1940, Gevorkiantz 1944, Wilson 1946, Briegleb 1952, Krajicek 1961, Gingrich 1967, Leak et al. 1969, Roach 1977, MacLean 1979, Curtis 1982, Sampson 1983, Stout et al. 1987, McGill et al. 1999, Gilmore 2003, and Willams 2003). All these stocking guides, in general, reflect a common concept that as undisturbed stands grow from the seedling to the sapling or small pole stage, they reach a maximum degree of crowding and continue to develop at that degree of crowding unless disturbed. Stocking can be measured using numbers of trees, quadratic mean diameter, mean volume, dominant height, or other stand properties. Generally, there are two common formats for measuring stand stocking: Reineke's stand density index and Gingrich's stand density diagram.

Reineke's (1933) stand density index (SDI) measures stocking for undisturbed, even-aged stands based on stand density. Reineke introduced the following relationship between average tree size and tree number per unit area:

$$\log (N) = -1.605 \log D + k \qquad [1.1]$$

in which $N$ is the number of trees per unit area, $D$ is the quadratic mean tree diameter, and $k$ is a constant varying with species. Reineke then developed this relationship into a stand density index (SDI) by converting the equivalent stand densities to a common quadratic mean diameter of 10 inches. SDI allows the comparison of stocking between stands with different density and size.

One of the good properties of the SDI approach is that it has been shown to be nearly independent of stand age and site quality (Daniel et al. 1979, Curtis 1982, Long 1985, Jack et al. 1996). In addition, the reference lines themselves help us to understand the universality of stand development. However, as stated by Reineke (1933), although the reference level does not change from stand to stand for a given species, the reference level does change for different species. Therefore, a SDI developed upon a given type of forest can only be applied to forest types that have similar stand compositions.

Gingrich's (1967) stand density diagram was developed for even-aged upland oak stands. Gingrich's diagram presented average maximum stand density in relation to basal area, trees per acre, and quadratic mean stand diameter. The diagram is based on two tree-area ratio equations: a minimum tree area ratio equation and a maximum tree area ratio equation. Both equations can be expressed as:

$$TAR = a + bD + cD^2 \qquad [1.2]$$

where $TAR$ is the estimated minimum or maximum percentage of area, $a$, $b$, and $c$ are coefficients, and $D$ is the DBH (diameter at breast height, 4.5 feet) of a given tree. The maximum tree area ratio equation was derived from the relationship between crown size and DBH for open growing trees. The minimum tree area ratio equation was derived by regression by assuming that the sum of the tree areas for all trees on an acre of undisturbed, normally stocked forest is equal to 100 percent of an acre. For the first time, it presented an *A* line that represents average maximum stocking; a *B* line that indicates a minimum requirement for crown closure; and a *C* line that represents a position where 10 years of future growth will bring the stand back to the *B* line.

Oak stocking guides have been developed for other regions based upon

Gingrich's methodology, including Sampson's (1983) for New England, Stout et al. (1987) for northwestern Pennsylvania, Dey et al. (1998) for Missouri Ozarks, and McGill and others' (1999) for Wisconsin. Unfortunately, all of these stocking guides deal only with stems with average DBH over 2 inches after crown closure. No stocking guide for the regeneration period has ever been developed. There exist no tools to measure the level of regeneration adequacy before stands reach that threshold size. Hence, it is necessary and pressing need to provide a stocking guide for the regeneration stage.

## Research objectives

This study used data from mixed-oak stands in Pennsylvania to explore the forest composition, to understand regeneration potentials and limitations, and to project and evaluate regeneration in the early stage of stand development. The specific objectives of this study are as follows:

1. To describe the vegetation structure in these mixed-oak stands;
2. To discover the relationship between advance regeneration abundance and site factors;
3. To comprehend the relationship between stand regeneration abundance after harvest based on the remaining overstory composition, advance regeneration, stump sprouting, and stand conditions; and,
4. To understand the development of major regeneration species after overstory removal.

The final goal of this study is to model/simulate the early-stage stand dynamics of regenerating mixed-oak stands after overstory removal, and develop a regeneration stocking guide for the mixed-oak forest in the central Appalachian region.

In the following chapters, general information about the study area and databases used in this research will be presented in Chapter 2; a summary of vegetation structure in the mature mixed-oak forest will be reported in Chapter 3; cumulative height, a useful tool to study regeneration, will be discussed in Chapter 4; relationships between regeneration abundance and biotic and abiotic factors will be checked out in Chapter 5; stand development after overstory removal will be studied in Chapter 6 and 7; and finally, a stocking guide for the central Appalachian region will be built in Chapter 8.

# Chapter 2

# Study Area and Data Sources

*"Data! Data! Data!" he cried impatiently. "I can't make bricks without clay!"*

Sherlock Holmes<br>*The Adventure of the Copper Beeches*

## Study Area

The study area is located in 11 counties in central Pennsylvania (latitude 40.21 to 41.76 N, and longitude 77.20 to 78.59 W) (Figure 2.1). It crosses the Allegheny Plateau and Ridge and Valley physiographic provinces of Pennsylvania, which are considered distinct ecoregions (Bailey et al. 1994; Cuff et al. 1989). All the stands included in this study are State Forest and managed by the Pennsylvania Bureau of Forestry, Department of Conservation and Natural Resources.

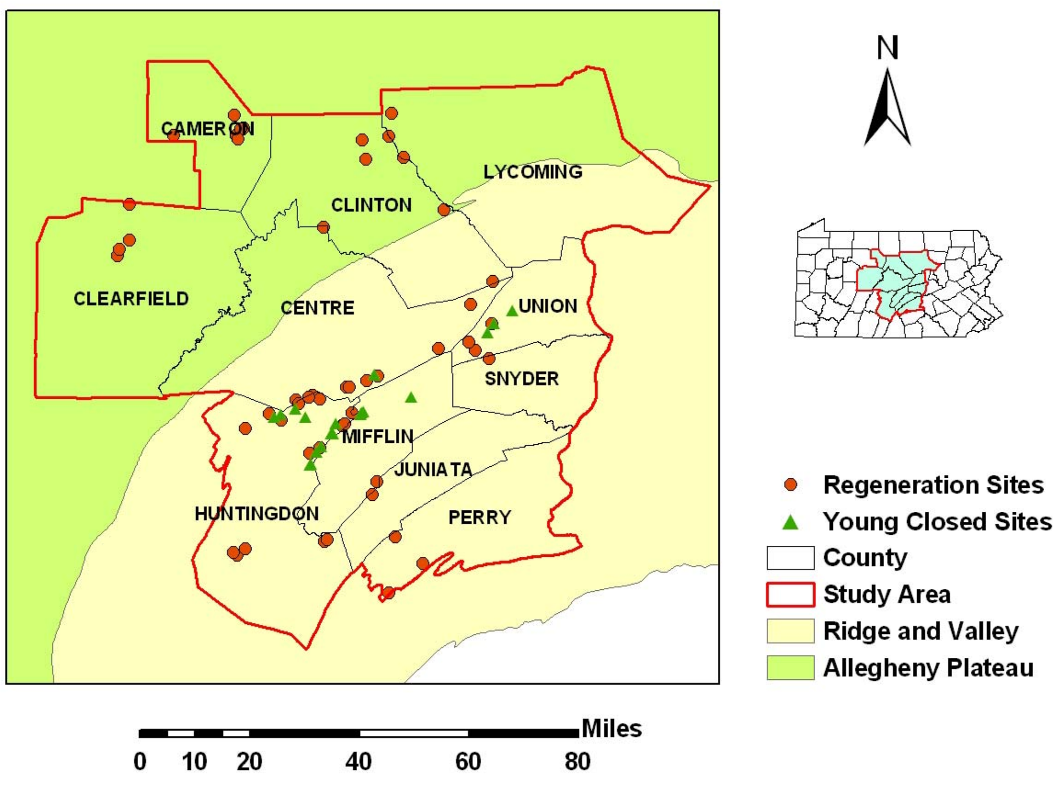



Figure 2.1 Distribution of research sites in the Allegheny Plateau and Ridge and Valley physiographical provinces of Pennsylvania.

### *Climate, physiography, and soil*

The climate in the study area is hot continental with warm summers and cold winters. Within the study area, average annual temperature ranges from 46 to 52°F, with mean January temperature of 24 to 28°F and mean July temperature of 68 to 74°F. The variation of temperature is primarily controlled by latitude and topography. On average, temperature in Ridge and Valley is about 2°F higher than on the Allegheny Plateau. Like temperature, average annual precipitation in the study area is influenced by the topography. Average annual precipitation ranges from 38 to 42 inches. The Ridge and Valley area is relatively drier than the Allegheny Plateau because of the “rain shadow” effect of the plateau (Cuff et al. 1989). Average annual snowfall ranges from 40 to 60 inches in the Ridge and Valley, and 60 to 70 inches on the Plateau. The length of growing season ranges from 120 to 140 days in the northwest, and 140 to 180 days in the southeast section of the study area.

Landscape is diverse in the study area. Elevation of study sites ranges from 850 ft in the Ridge and Valley to 2,250 ft on the Allegheny Plateau. The landforms in Ridge and Valley region are simply parallel sandstone ridges and limestone or shale valleys eroded from the folded rock. Most of the ridges stand a consistent 800 to 1,200 feet above the major valleys (Cuff et al. 1989). The topography of the Allegheny Plateau appears to be more flat. The Allegheny Plateau is an area of rolling uplands cut by deep, steep stream valleys. The Allegheny Plateau can be broken into six subregions according to differences in the height of the land or its erosional history. All of the mixed-oak stands included in this study on the Allegheny Plateau are located on the Mountainous High Plateau (Deep Valley) subregion. Soils of study area in both provinces are mature soils derived from sandstone, siltstone, and shale, and represent diverse soil series and associations.

### *Forest history*

Based on Bailey’s (1994) ecoregion map, the study area is in the Central Hardwood Region. Oak forests are the dominant natural vegetation in the Ridge and Valley region, and then transition into Allegheny hardwoods moving from south to north on the Allegheny Plateau (Bailey et al. 1994; Stout 1991). The predominant oaks are northern red oak (*Quercus rubra* L.), chestnut oak (*Q. montana* Willd.), white oak (*Q. alba* L.), black oak (*Q. velutina* Lam.), and scarlet oak (*Q. coccinea* Muenchh.). Other tree species such as red maple (*Acer rubrum* L.), hickories (*Carya* spp.), black birch (*Betula lenta* L.), blackgum (*Nyssa sylvatica* Marsh), flowering dogwood (*Cornus florida* L.), and eastern white pine (*Pinus strobus* L.) can often be found co-occurring in the mixed-oak stands.

Similar to the history given by Hicks (1997) for the Central Hardwood Region, the utilization and exploitation of forests in this study area has passed through various historical phases. Before European settlement, native peoples practiced extensive burning to improve habitat for game and to aid in land clearing for agriculture (Pyne 1982). After the first settlement in Pennsylvania in 1638, human impacts on the forest expanded and intensified. Demand for forest products and land for crops expanded and intensified. By the early 1900s, virtually all of the virgin timberland in Pennsylvania had been cut and most of it burned over by fires hot enough to consume much of the organic matter in the forest soils (Pennsylvania Bureau of Forestry 1975). Another dramatic event that occurred in the study region, as in adjacent regions, is the chestnut blight in the early 1900s. Chestnut (*Castanea dentata* (Marsh.) Borkh) was the most common tree in Pennsylvania, and was found in most parts of the state and on diverse soils and at all elevations. The event itself was a catastrophic disaster in forest history, but it increased the relative proportion and importance of oaks throughout the region (Johnson et al. 2002) and provided opportunities for other species such as red maple to invade in the forest (Vandermast et al. 2002). Since the 1930s and earlier, large areas of forest land and abandoned agricultural land have been purchased by the government within the Central Hardwood Region (Hicks 1997). Forest management has been carefully regulated on state and federal lands. The forest has re-grown to present the secondary-forest we see today.

## Data Sources

Four sets of data were used in this study: 1) the Pennsylvania Oak Regeneration Assessment database, 2) crown closure on-set dataset, 3) open-growing tree crown size dataset, and 4) stump sprouts crown size dataset. The Pennsylvania Oak Regeneration Assessment database is the main data source, and most of the analysis in this research is based on this database. Different data collection procedures were used in different datasets.

### *The Pennsylvania oak regeneration assessment database*

This database includes information from 52 mixed-oak stands on a total area of 2,386 acres across the Allegheny Plateau and Ridge and Valley physiographic provinces, measured from 1996 through 2003. Figure 2.1 shows the distribution of these stands (circled points). Seventeen stands are located on the Allegheny Plateau and 35 stands in the Ridge and Valley physiographic province. In each stand, depending on the size of the harvest site, 15 to 30 plots with a radius of 26.3 feet (20th-acre plots) were spaced systematically in a square grid to represent the whole stand. Four subplots with a radius of 3.72 feet (milacre plots), were established within each plot at 16.5 feet from the 20th-acre plot center along each cardinal direction (Figure 2.2). In total, data from 5,732 subplots were included in this study.

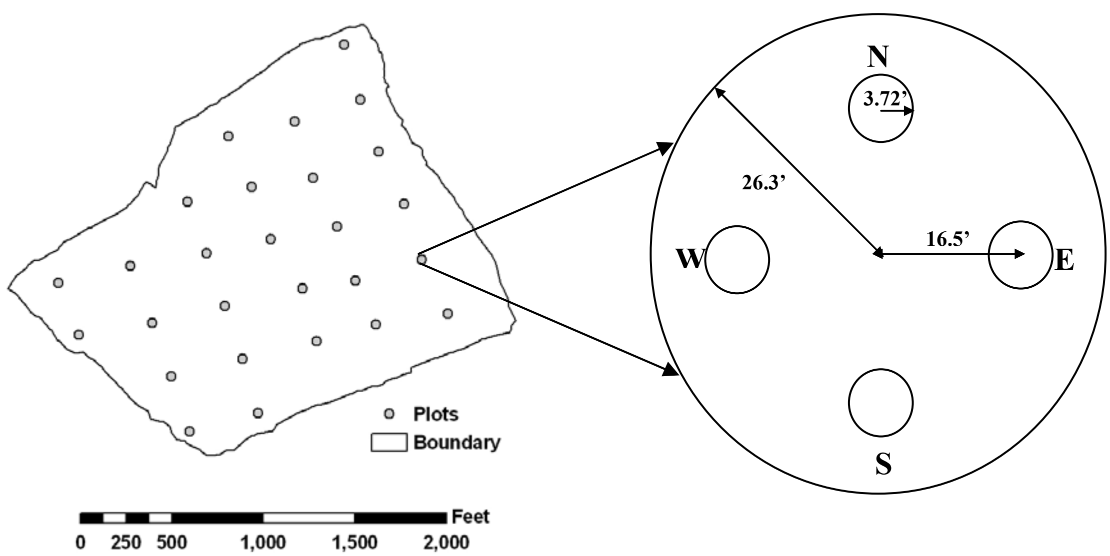


Figure 2.2 Layout of plots within a typical stand and of subplots within each plot.

All the stands were measured approximately one year prior to harvest (00 measurements), 33 stands have been re-measured one year after harvest (01 measurements), 16 stands have been re-measured four years after harvest (04 measurements), eight stands have been re-measured five years after harvest (05 measurements), and four stands have been measured again six years after harvest (06 measurements). Biotic and abiotic factors were recorded at stand, plot, and subplot level. The following is the list of factors measured in the field survey:

- Stand scale: elevation, slope position, slope aspect, and site index;
- Plot scale: slope position, slope aspect, slope shape (sum of percentage slope uphill, downhill, and at 90º to aspect, slope percentage, exposure angle (the angle between the visible east horizon and west horizon), and overstory tree diameter and species;
- Subplot scale: regeneration counts by height classes (eight height classes were used (<2 in, 2.0 - 6.0 in, 6.1 in - 1.0 ft, 1.1 - 2.0 ft, 2.1 - 3.0 ft, 3.1 - 4.0 ft, 4.1 - 5.0 ft, and > 5.0 ft)) and by tree species, dominant oak and non-oak regeneration stems (species, origin, height class, basal diameter, and DBH); percentage ground surface cover (in class of five percent) in stratum zero and percentage vegetation cover in stratum one (five feet to ground surface) and stratum two (from five to 20 feet) by different species; micro-topography (mound, slope, pit, or flat); closest canopy tree (species, diameter, distance, and azimuth); largest canopy tree (species, diameter, distance, and azimuth); and closest stump (species, stump diameter and height, distance, azimuth, and sprouts).

Fencing and/or herbicide treatments were applied or planned to apply in some of the stands. Treatments were based upon the forester's management objectives for each stand and were not experimentally controlled. The primary objective of the treatments was to establish and/or release desirable regeneration. In total, 12 stands were in the fencing and herbicide treatment group, 27 stands were in the fencing treatment group, one stand was in the herbicide treatment group, and 11 stands were in the no fencing or herbicide group. Since the fencing and herbicide treatment were applied between the 00 and 01 measurements, data from the 00 measurements represent the natural stand condition before harvest, fencing, and/or herbicide treatment are applied.

### *Crown closure onset dataset*

Fifteen mixed-oak stands with stand ages of 6 to 12 years were included in this dataset (Figure 2.1, triangle points). These stands were intentionally chosen to represent crown-closure conditions. Depending on the size of the stand, 15 to 30 plots with a radius of 7.4 ft (four milacre plots) were spaced systematically in a square grid to represent the whole stand. In total, 504 plots were included in this database. On each plot, species, height, and DBH were recorded for each stem that occurred in measured plots. Total crown occupancy was estimated. Stratum one non-tree vegetation cover was also recorded.

### *Open-growing tree crown size dataset*

Based upon abundance and availability, 576 open-growing trees were measured in this dataset, which includes 81 red maples, 97 black birches, 38 black gums, 92 white oaks, 125 chestnut oaks, 134 northern red oaks, and 9 black oaks. These trees were taken from stands that were 4 to 10 years old. For each tree, species, height, stem DBH, and crow diameter were recorded. In order to have best crown size estimation, crown diameters were measured in four directions: longest dimensions of the crown, and 45, 90, and 135 degrees off the longest dimension through the center.

### *Stump sprouts crown size dataset*

Two subsets of data were collected for crown size of stump sprouts. The first subset was for four- to six-year-old stump sprouts and the second subset was for twenty-year-old stump sprouts. Six stands were included in the first subset and nine stands were included in the second subset. Transects instead of fixed plots were used to collect stump data. Species, number of sprouts, height and DBH of the dominant sprout, and crown diameter were recorded for stumps in the first subset. One hundred and sixty one stumps were measured in this subset, which includes 41 red maple, 12 white oak, 59 chestnut oak, and 49 northern red oak stumps. Species, number of sprouts (a single sprout is a separate, vertical stem arising directly from the stump and forking no higher than two inches from its origin), DBH of each sprout, and crown diameter were recorded for in the second subset. A total number of 383 stump sprouts were measured, which includes 30 red maple, 93 white oak, 146 chestnut oak, and 114 northern red oak stumps.

# Chapter 3

# Composition and Distribution of Mixed-oak Stands in the Central Appalachians

*If you know the enemy and know yourself, your victory will not stand in doubt (知己知彼，胜乃不殆).*

Sun Zi (孙子)

*The Art of War* (孙子兵法)

***Abstract:*** Vegetation structure of 52 mature mixed-oak stands was analyzed and described. Red maple was the most abundant species in the overstory across the study area. Northern red oak was the most abundant oak species on the Allegheny Plateau physiographic province, while chestnut oak was the most abundant oak species in the Ridge and Valley provinces. Blueberry was the most abundant non-tree species, with an average forest floor coverage of nine percent for all the study area. Hayscented fern was the second most abundant non-tree species. It was more abundant on the Allegheny Plateau, where it covered an average of 22 percent of the forest floor. Mountain-laurel and huckleberry were the next two most common non-tree vegetation species in the understory. Species composition and density of advance regeneration varied from stand to stand. Red maple was the most abundant species of advance regeneration and had high density in almost all stands. With few exceptions, advance regeneration of all oak species was low both in size and density. A comparison of overstory tree and advance regeneration importance value indicated a putative trend that red maple increases its dominance from the Allegheny Plateau to the Ridge and Valley, black birch increases its dominance from the Ridge and Valley to the Allegheny Plateau, while white oak and chestnut oak were losing their dominance

in both physiographic provinces, but especially on the Allegheny Plateau. Cluster analysis based on importance values of overstory vegetation, understory vegetation, and advance regeneration of all the 52 stands indicated that there are two subtypes of forest in the study area: a red maple – northern red oak – hayscented fern subtype and a red maple – chestnut oak – blueberry subtype.

## Introduction

The study of vegetation structure has been a subject of major interest for decades by those wishing to understand and perhaps manage the ecological provinces that shape forests. The structure of vegetation is described as: the vertical arrangement of species (stratification); the horizontal arrangement of species (spatial distribution); and the compositional characteristics such as presence, abundance, and size. Forest vegetation stratification as a method for describing forest was proposed by Davis and Richards (1933, 1934), who constructed profile diagrams of tropical forest. The vertical arrangement of mixed-oak forests in the central Appalachians is relatively simple. The marked stratification of vegetation is mainly composed of two layers: an overstory canopy tree layer and an understory herb, shrub, and regeneration layer. In this chapter, vegetation composition and distribution will be analyzed within each of these strata.

Throughout eastern Northern America, natural regeneration of oaks is often difficult to obtain even where oaks are dominant components in the overstory before harvest. Observation suggests that red maple (*Acer rubrum* L.) is becoming increasingly dominant in stands that have historically been dominated by oak species (*Quercus* spp.), especially following harvest (Abrams 1998, Smith and Vankat 1991, Nowacki et al. 1990). The reasons for this historically novel phenomenon are unclear, but may involve relatively recent changes in deer densities and fire frequencies, as well as the virtual disappearance of American chestnut (*Castanea dentata* (Marsh.) Borkh) as a significant component of many of these stands. We know even less about how to manage or reverse the process.

Although the problem of oak regeneration is widespread both geographically and by species, there is no apparent universal solution. Our understanding is in part hindered by a lack of quantitative, descriptive information about the process in stands where it is occurring. The major purpose of this chapter is to provide baseline information on the species composition and structure of the upland mixed-oak forest in central Appalachians.

## Methodology

### *Study area*

The study area is located in Pennsylvania (latitude 40°13' to 41°46' N, and longitude 77°12' to 78°36' W). It crosses the Allegheny Plateau and Ridge and Valley physiographic provinces, which separate distinct ecoregions (Cuff et al. 1989). Soils in both provinces in the stand represented in this study are derived from sandstone, siltstone and shale and are typically well drained and support moderately productive forests. Stand elevations range from 800 ft above sea level in the Ridge and Valley province to 2,250 ft on the Allegheny Plateau. Precipitation, temperature, and length of growing season vary with latitude and topography. Mean annual precipitation ranges from 38 to 45 inches and mean annual temperature ranges from 46 to 52 °F. The length of growing season ranges from 120 to 140 days in the northwest, and 140 to 180 days in the southeast.

### *Data collection*

Pre-treatment (harvest, fencing, or herbicide) data from the 52 mature mixed-oak stands in the study area were used in this chapter to study the natural composition and distribution of this mixed-oak forest type. Depending on stand size, 15 to 30 permanent plots with a radius of 26.3 ft (0.05-acre) were systematically installed in a square grid to represent the whole stand. Four permanent subplots with a radius of 3.72 ft (0.001-acre) were established within each plot at a fixed distance from plot center. In total, 5,730 subplots were established in the study area.

On each plot, species and DBH of all overstory trees (≥ 2 in in DBH) were recorded. On each subplot, non-tree vegetation cover was estimated in five percent increment by species or species group; tree seedlings (< 2.0 inch in DBH) were recorded by species and height class (<2.0 in, 2.0 – 6.0 in, 6.1 in – 1.0 ft, 1.1 - 2.0 ft, 2.1 - 3.0 ft, 3.1 - 4.0 ft, 4.1 - 5.0 ft, and > 5.0 ft).

### *Data analysis*

Different variables were used to describe vegetation abundance in different strata. Average density, basal area, and occurrence frequency were used for mature trees in the overstory; average vegetation cover percentage and occurrence frequency were used for non-tree vegetation in the understory; and average density, cumulative height, and occurrence frequency were used for advance tree regeneration. In addition, a composite variable, importance value (IV) was also computed to describe the relative vegetation abundance for each stand. The IV for each species was calculated on the basis of three quantities: relative density (*rDens*), relative dominance (*rDom*), and relative frequency (*rFreq*) (Cottam and Curtis 1956, Mueller-Dombois and Ellenberg, 1974; Kershaw and Looney, 1985). Species dominance values were calculated based on different attributes for overstory trees, non-tree vegetation, and tree regeneration. For overstory tree species, basal area was used to calculate dominance. For non-tree vegetation, total percentage cover was used to calculate dominance. For tree regeneration, cumulative height was used to calculate dominance. Cumulative height of a given species is derived by adding the height of all the individuals of that species on the surveyed plot. The formulas used to calculate IV are listed as follows:

$$rDens\ (\%) = \frac{\text{Number of individuals of species “x”}}{\text{Total number of individuals of all species}} \text{ X } 100 \quad [3.1]$$

$$rFreq\ (\%) = \frac{\text{Occurrence frequency of species “x”}}{\text{Sum of occurrence frequency of all species}} \text{ X } 100 \quad [3.2]$$

$$rDom\ (\%) = \frac{\text{Dominance value of species “x”}}{\text{Sum of dominance values of all species}} \text{ X } 100 \quad [3.3]$$

$$IV = rDens + rFreq + rDom \quad [3.4]$$

Therefore, the maximum IVs for overstory and regeneration tree species are 300 percent. For non-tree vegetation, since percentage cover by species was the only estimated variable on each subplot, IV for non-tree vegetation was calculated only based on relative dominance and relative frequency. Hence, the maximum IV for all the non-tree vegetation species is 200 percent.

Average density, basal area, occurrence frequency, and IV were calculated for the three most abundant overstory non-oak species (red maple, blackgum [*Nyssa sylvatica* Marsh], and black birch [*Betula lenta* L.]) and three most abundant oak species (white oak [*Q. alba* L.], chestnut oak [*Q. montana* Willd.], and northern red oak [*Q. rubra* L.]) within each stand, within each physiographic province, and across the study area. To obtain a clearer view of size distribution, these six overstory tree species were grouped by DBH size classes. To identify the regional distribution pattern, the IVs of the six overstory species were superimposed on the physiographic map of the study region. In order to have a better idea about how these species were distributed in the two physiographic provinces, analysis of variance was also carried out for the two physiographic provinces.

Marquis (1994) proposed a criterion that if over 30 percent of the plots on the stand had over 30 percent cover then the competing vegetation is considered problematic. Following Marquis's criterion, a heavy cover plot was defined as a plot with over 30 percent cover of a given species, and heavy cover frequency was defined as the total number of heavy cover plots divided by the total number of plots. Average cover percentage, occurrence frequency, heavy cover frequency, and IV were calculated for the four most abundant non-tree species: blueberry, hayscented fern, mountain-laurel, and huckleberry within each stand, within each physiographic province, and across the study area. IVs for the top four non-tree vegetation species for each stand were mapped, and analysis of variance was carried out for the two physiographic provinces.

To facilitate investigation of the relationship between overstory trees and understory regeneration that will be discussed in Chapter 5, I focus here only on red maple, blackgum, black birch, white oak, chestnut oak, and northern red oak advance regeneration. Average density, cumulative height, occurrence frequency, and IV for advance regeneration were calculated within each stand, within each physiographic province, and across the study area. Because size is an important attribute of advance regeneration, the average density of advance regeneration that had over 10 percent occurrence frequency was calculated for each species by height classes.

As a common tool in community analysis, cluster analysis or clustering was applied in this study. The aim of cluster analysis is to classify sampling units into groups of stands that have similar attributes. Since stand is the minimum management unit, stand level attributes were used in the analysis instead of plot- or subplot-level attributes. In order to achieve the best result from cluster analysis, the maximum information should be included using a minimum number of variables (McCune and Grace 2002). Hence, IV as the composite variable of density, dominance, and frequency was used in the cluster analysis. Species used in the analysis included the top three non-oak and top three oak species in the overstory, the top four non-tree understory vegetation species or species groups, and the six advance regeneration species corresponding to the major non-oak and oak species in the overstory. Hierarchical clustering with Ward's linkage method was used to carry out the analysis (Ward 1963).

## Results

### *Overstory tree composition and distribution*

The composition of the overstory layer was quite diverse in the study area. Forty four tree species were identified on the sample plots across the study area (Table 3.1). On average, the overstory was composed of 232 trees per acre with a basal area of 107 square feet per acre. Red maple by IV was the most abundant species across the study area. It had a regional average density of 94 stems per acre and occurrence frequency over 90 percent on all the sampled plots. Northern red oak and chestnut oak by IV were the second and third most abundant overstory tree species. Northern red oak had the largest mean basal area (29 ft$^2$ per acre) among all the species. Both oak species occurred on about half of the sampled plots. The regional average density for chestnut oak and northern red oak is about 30 and 21 stems per acre, respectively. Blackgum and black birch by IV were the second and

Table 3.1. List of species and their average density, basal area, occurrence frequency, and importance value of overstory trees on the sampled plots.

| **Common Name** | **Scientific Name** | **Dens. (stems/acre)** | **BA ($ft^2$/acre)** | **Freq. (%)** | **IV (%)** |
|---|---|---|---|---|---|
| Red maple | *Acer rubrum* | 94.09 | 22.01 | 90.2 | 85.49 |
| Northern red oak | *Quercus rubra* | 21.41 | 29.21 | 49.9 | 49.95 |
| Chestnut oak | *Quercus montana* | 29.92 | 22.96 | 51.7 | 48.28 |
| White oak | *Quercus alba* | 12.83 | 10.67 | 31.8 | 24.05 |
| Blackgum | *Nyssa sylvatica* | 21.17 | 3.33 | 25.0 | 18.99 |
| Black oak | *Quercus velutina* | 5.41 | 6.44 | 18.5 | 13.34 |
| Black birch | *Betula lenta* | 9.50 | 2.04 | 17.2 | 10.63 |
| Eastern white pine | *Pinus strobus* | 11.27 | 1.62 | 12.7 | 9.80 |
| Pignut hickory | *Carya glabra* | 3.68 | 1.29 | 12.8 | 6.25 |
| Scarlet oak | *Quercus coccinea* | 2.48 | 2.81 | 8.0 | 5.85 |
| Flowering dogwood | *Cornus florida* | 2.47 | 0.16 | 7.9 | 3.34 |
| Juneberries | *Amelanchier* spp. | 2.16 | 0.21 | 8.1 | 3.31 |
| Sassafras | *Sassafras albidum* | 2.30 | 0.39 | 6.9 | 3.22 |
| Sugar maple | *Acer saccharum* | 2.68 | 0.60 | 4.7 | 2.99 |
| Striped maple | *Acer pennsylvanicum* | 2.02 | 0.11 | 3.8 | 1.99 |
| American beech | *Fagus grandifolia* | 1.41 | 0.22 | 3.1 | 1.64 |
| Tulip-tree | *Liriodendron tulipifera* | 0.75 | 0.91 | 1.6 | 1.61 |
| Eastern hemlock | *Tsuga canadensis* | 0.91 | 0.27 | 2.9 | 1.41 |
| Mockernut hickory | *Carya tomentosa* | 0.50 | 0.19 | 2.0 | 0.94 |
| Black locust | *Robinia pseudoacacia* | 0.77 | 0.14 | 1.7 | 0.91 |
| Cucumber | *Magnolia acuminata* | 0.32 | 0.22 | 1.3 | 0.68 |
| Hophornbeam | *Ostrya virginiana* | 0.54 | 0.05 | 1.4 | 0.66 |
| Pitch pine | *Pinus rigida* | 0.22 | 0.22 | 1.0 | 0.59 |
| Shagbark hickory | *Carya ovata* | 0.29 | 0.10 | 1.3 | 0.56 |
| White ash | *Fraxinus americana* | 0.28 | 0.13 | 1.1 | 0.54 |
| Basswood | *Tilia americana* | 0.18 | 0.17 | 0.7 | 0.43 |
| Black cherry | *Prunus serotina* | 0.14 | 0.16 | 0.6 | 0.38 |
| Norway spruce | *Picea abies* | 0.47 | 0.02 | 0.5 | 0.35 |
| Paper birch | *Betula papyrifera* | 0.17 | 0.14 | 0.4 | 0.32 |
| Hickory | *Carya* spp. | 0.25 | 0.05 | 0.6 | 0.30 |
| Bigtooth aspen | *Populus grandidentata* | 0.14 | 0.12 | 0.3 | 0.27 |
| American chestnut | *Castanea dentata* | 0.14 | 0.01 | 0.4 | 0.18 |
| Bitternut hickory | *Carya cordiformis* | 0.06 | 0.05 | 0.2 | 0.13 |
| Butternut | *Juglans cinerea* | 0.04 | 0.05 | 0.2 | 0.12 |
| Hawthorn | *Crataegus* spp. | 0.07 | 0.00 | 0.3 | 0.11 |
| Yellow birch | *Betula alleghaniensis* | 0.06 | 0.03 | 0.2 | 0.10 |
| Tree-of-heaven | *Ailanthus altissima* | 0.04 | 0.01 | 0.2 | 0.08 |
| Virginia pine | *Pinus virginiana* | 0.06 | 0.03 | 0.1 | 0.07 |
| Slippery elm | *Ulmus rubra* | 0.04 | 0.00 | 0.1 | 0.04 |
| Birch | *Betula* spp. | 0.03 | 0.01 | 0.1 | 0.04 |
| Table-Mountain pine | *Pinus pungens* | 0.01 | 0.00 | 0.1 | 0.03 |
| American elm | *Ulmus americana* | 0.01 | 0.00 | 0.1 | 0.03 |

third most abundant non-oak species (IVs of 19 percent and 11 percent, respectively). White oak by IV was the third most abundant oak species and occurred on about one third of all surveyed plots. Overall, only 10 of the 44 species had IVs over five percent. All five oak species (i.e., northern red oak, chestnut oak, white oak, black oak [*Q. velutina* Lam.], and scarlet oak [*Q. coccinia* Muenchh.]) that occurred on the surveyed plots were ranked in the top ten. The other two non-oak species included in the top ten were pignut hickory (*Carya glabra* Mill.) and eastern white pine (*Pinus strobes* L.). In the rest of this section, analysis will only focus on the top three abundant oak species (red oak, chestnut oak, and white oak) and top three non-oak species (red maple, blackgum, and black birch).

Besides abundance, size is another important property of vegetation composition. On the surveyed plots, non-oak species had a smaller average diameter than the oak species. The average diameters at breast height for red maple, blackgum, and black birch were 5.8, 4.8, and 5.3 inches, respectively; while for northern red oak, chestnut oak, and white oak, the mean diameters were 15.0, 11.2, and 11.5 inches, respectively. DBH size distributions of the six principal overstory tree species on the surveyed plots across the study area are shown in Figures 3.1 and 3.2. The three non-oak species each had a reverse “J” distribution (Figure 3.1). On the other hand, all three oak species had a uni-modal normal distribution with relatively few small or very large trees. These patterns were present within each of the stands under study. Therefore, the size distribution patterns of major non-oak and oak species are universal within the study region.

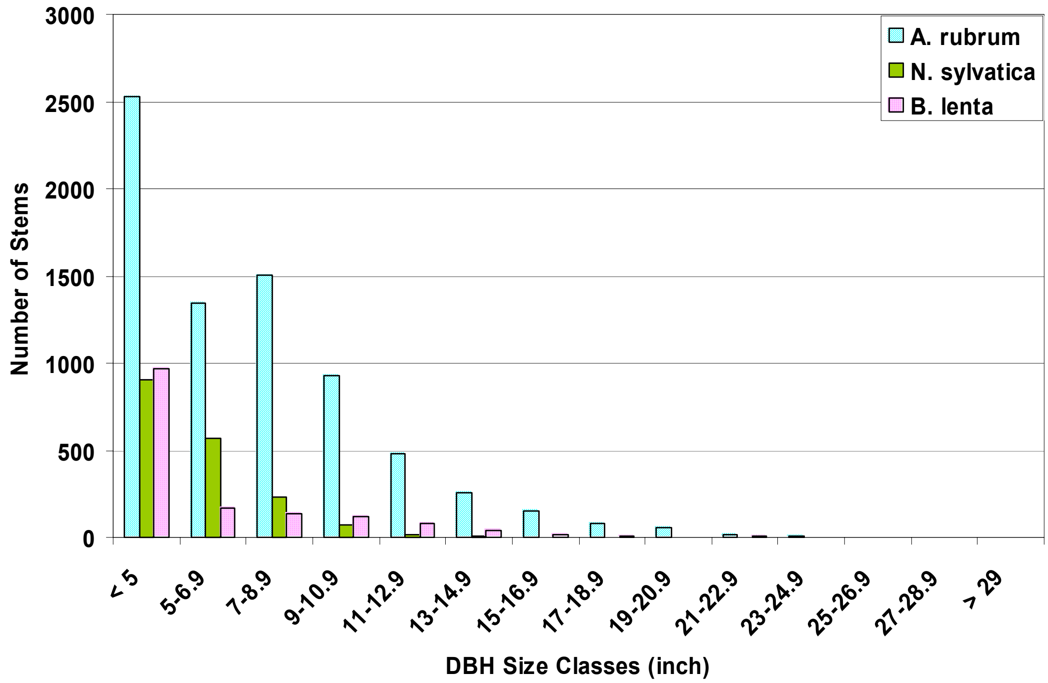



Figure 3.1. Size distributions of overstory red maple, blackgum, and black birch.

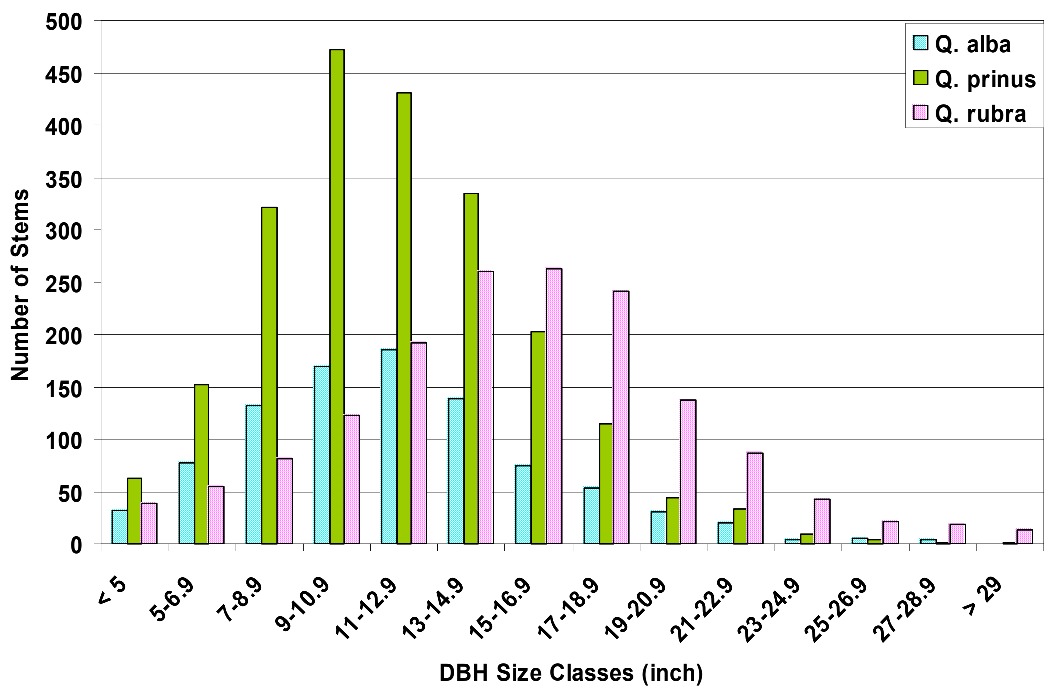



Figure 3.2. Size distributions of overstory white oak, chestnut oak, and red oak.

Average density, basal area, occurrence frequency, and IV were calculated for the three major oak and three major non-oak species for each of the 52 stands (Appendices A1, A2, A3, and A4). Not surprisingly, there was considerable variation among the stands for each species. Large differences among stands were apparent in the density, basal area, frequency, and importance value of red maple. Except for one stand, over 50 percent of the plots in each stand had at least one red maple. About two-thirds of the stands had over 90 percent red maple occurrence frequency. For black birch, 37 percent of the stands did not have a single stem, 46 percent of stands had a density less than 20 stems per acre, while eight percent of stands had a density over 50 stems per acre. Variation among stands for blackgum was also great. Twenty five percent of the stands did not have blackgum. By contrast, two stands had blackgum density greater than or equal to 100 stems per acre, and importance values over 70 percent.

For white oak, 92 percent of the stands had at least one white oak, and the IV ranged from as low as one to 128 percent. In those stands with white oak, 58 percent of stands had average white oak density of less than 10 stems per acre, 25 percent of the stands had average density between 10 and 30 stems per acre, and 17 percent of stands had average density between 31 and 59 stems per acre. All the surveyed stands had at least one chestnut oak and one red oak. The IV for chestnut oak ranged from two to 146 percent. Twenty nine percent of stands had average chestnut oak density of less than 10 stems per acre, and 31 percent of stands had average density between 10 and 30 stems per acre. The maximum chestnut oak stand density was as high as 133 stems per acre. Red oak had the largest variation among stands in terms of both basal area and IV. Average basal area for red oak ranged from one to 92 square feet per acre, and IV ranged from three to 140 percent. Even if all the oak species are taken as a group, variations are still big among the stands. Total oak basal area ranged from 34 to 110 square feet per acre, IV ranged from 70 to 223 percent.

By superimposing the IVs of the six overstory species on the physiographic map of the study region, some regional distribution patterns can be clearly identified (Figure 3.3). Means of density, basal area, occurrence frequency, and IV were different in each of the physiographic provinces (Table 3.2). Red maple was more

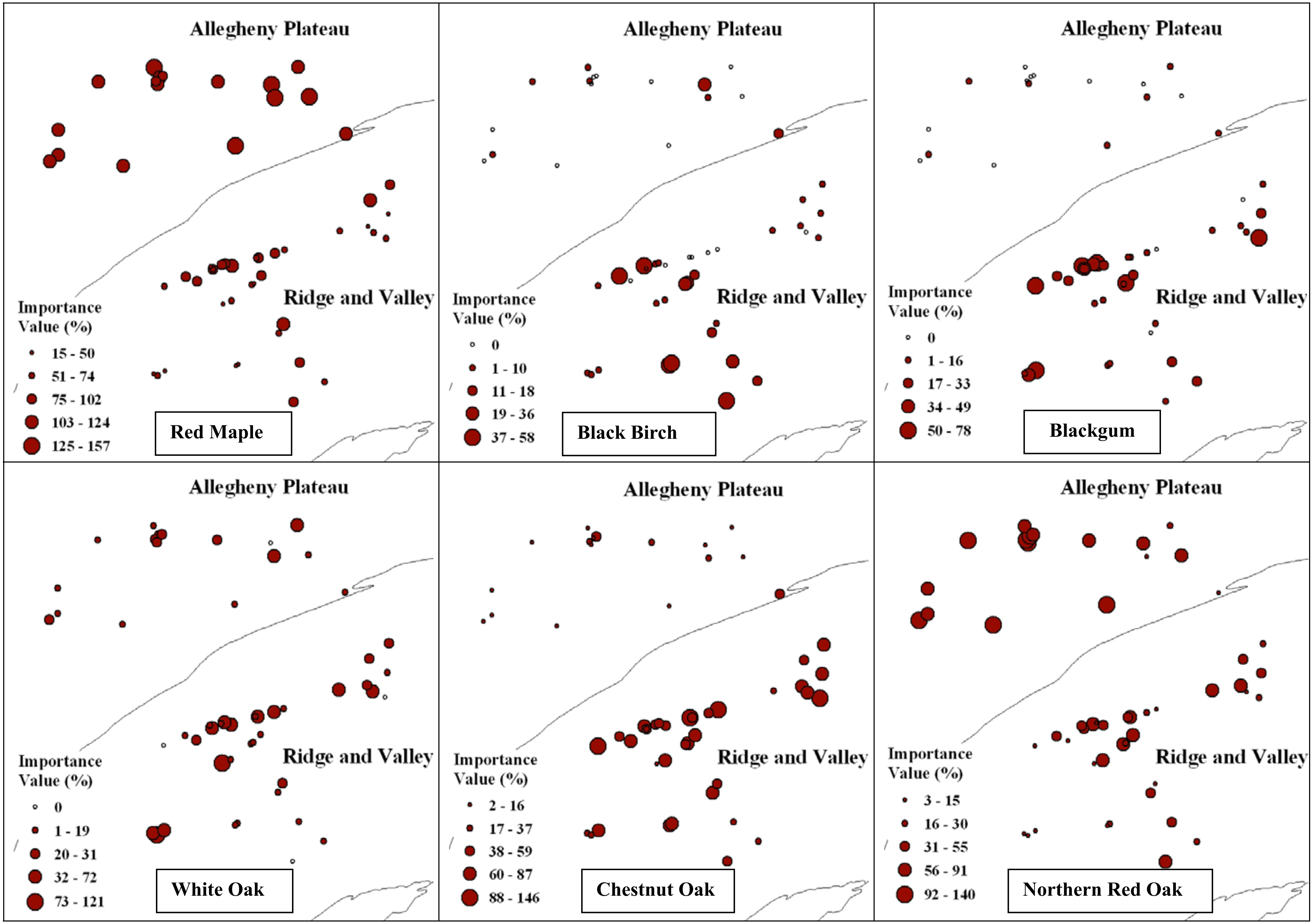


Figure 3.3. Regional distribution of importance value of overstory tree species by stand.

abundant on the Allegheny Plateau than in the Ridge and Valley (average IV of 123 and 69 percent, respectively, $p < 0.001$). All stands on the Allegheny Plateau had red maple IVs over 100 percent. In contrast to red maple, blackgum and black birch were more abundant in the Ridge and Valley. The IVs of blackgum and black birch were both less than five percent on the Allegheny Plateau, and had average densities around three stems per acre. White oak had a fair distribution across the study area. Although the mean IV for white oak was higher in the Ridge and Valley (28 percent) than on the Allegheny Plateau (20 percent), the difference was not significant ($p = 0.24$). Chestnut oak was much more abundant in the Ridge and Valley than on the Allegheny Plateau (average IV of 63 and 16 percent, respectively, $p < 0.001$). Northern red oak was more abundant on the Allegheny Plateau than in the Ridge and Valley (average IV of 82 and 35 percent, respectively, $p < 0.001$).

Table 3.2. Average density, basal area, frequency, and importance value of major overstory oak and non-oak species by physiographic province. (* means of same species in the same category are different in two provinces at $p < 0.05$, ** at $p < 0.01$)

| Physiographic province | Species | Density (stems/acre) | Basal Area ($ft^2$/acre) | Frequency (%) | Importance Value (%) |
|---|---|---|---|---|---|
| Allegheny Plateau (n=17) | Red Maple | 119.8** | 33.9** | 96.2* | 123** |
| | Black Birch | 2.9* | 0.5* | 7.1* | 4* |
| | Blackgum | 2.8** | 0.5** | 3.8** | 3** |
| | White Oak | 8.9 | 6.8 | 26.7 | 20 |
| | Chestnut Oak | 7.6** | 5.7** | 20.4** | 16** |
| | N. Red Oak | 31.7** | 47.4** | 65.2** | 82** |
| Ridge and Valley (n=35) | Red Maple | 79.1 | 14.9 | 86.6 | 69 |
| | Black Birch | 12.9 | 2.9 | 22.4 | 13 |
| | Blackgum | 29.2 | 4.5 | 35.3 | 25 |
| | White Oak | 15.2 | 13.1 | 35.8 | 28 |
| | Chestnut Oak | 39.9 | 31.1 | 67.4 | 63 |
| | N. Red Oak | 15.5 | 19.2 | 41.7 | 35 |

### *Understory non-tree vegetation composition and distribution*

Composition of understory non-tree vegetation was almost as diverse as the composition of the canopy. In total, there were 36 non-tree species or species groups in the understory. Average percentage cover, occurrence frequency, and IV of all the species are tabulated in Table 3.3. As mentioned earlier, IVs for non-tree vegetation were calculated only based on relative dominance and relative frequency, so the maximum IV for all non-tree species is 200 percent.

Table 3.3. List of species or species group and their average cover, occurrence frequency, and importance value for understory non-tree vegetation.

| Common Name | Science Name | Cover (%) | Freq. (%) | IV (%) |
|---|---|---|---|---|
| Blueberry | *Vaccinium* spp. | 9.28 | 68.92 | 49.21 |
| Hayscented fern | *Dennstaedtia punctilobula* | 8.61 | 24.59 | 32.97 |
| Mountain-laurel | *Kalmia latifolia* | 7.32 | 27.47 | 30.16 |
| Huckleberry | *Gaylussacia baccata* | 4.60 | 21.68 | 20.38 |
| Forbs | - | 0.28 | 41.80 | 14.28 |
| Teaberry | *Gaultheria procumbens* | 0.13 | 34.33 | 11.46 |
| Witch-hazel | *Hamamelis virginiana* | 1.54 | 18.29 | 10.38 |
| Grasses | - | 0.70 | 19.04 | 8.18 |
| Bracken fern | *Pteridium aquilinum* | 1.02 | 11.12 | 6.55 |
| Sedges | - | 0.30 | 15.57 | 5.90 |
| Greenbrier | *Smilax* spp. | 0.04 | 4.45 | 1.55 |
| Other ferns | - | 0.18 | 1.76 | 1.08 |
| Grape | *Vitis* spp. | 0.01 | 3.18 | 1.05 |
| Rubus | *Rubus* spp. | 0.07 | 2.39 | 0.96 |
| Viburnum | *Viburnum* spp. | 0.02 | 2.76 | 0.96 |
| Partridgeberry | *Mitchella repens* | 0.00 | 2.43 | 0.79 |
| Black raspberry | *Rubus occidentalis* | 0.05 | 1.83 | 0.74 |
| Blackberry | *Rubus alleghaniensis* | 0.03 | 1.95 | 0.72 |
| Virginia creeper | *Parthenocissus quinquefolia* | 0.01 | 1.90 | 0.64 |
| Clubmoss | *Lycopodium* spp. | 0.04 | 1.27 | 0.52 |
| New York fern | *Thelpteris novaboracensis* | 0.05 | 0.33 | 0.26 |
| Barberry | *Berberis* spp. | 0.02 | 0.38 | 0.19 |
| Spicebush | *Lindera benzoin* | 0.00 | 0.44 | 0.14 |
| American holly | *Ilex opaca*. | 0.00 | 0.44 | 0.14 |
| Rhododendron | *Rhododendron* spp. | 0.00 | 0.44 | 0.14 |
| Sweet-fern | *Comptonia peregrina* | 0.03 | 0.14 | 0.13 |
| Scrub oak | *Quercus ilicifolia* | 0.01 | 0.21 | 0.11 |
| Hercules' club | *Aralia* spp. | 0.02 | 0.16 | 0.10 |
| Striped pipsissewa | *Chimaphila maculata* | 0.00 | 0.24 | 0.08 |
| Rose | *Rosa* spp. | 0.00 | 0.19 | 0.06 |
| Poison ivy | *Toxicodendron radicans* | 0.00 | 0.19 | 0.06 |
| American elder | *Sambucus* spp. | 0.00 | 0.09 | 0.03 |
| Buckthorn | *Rhamnus* spp. | 0.00 | 0.07 | 0.02 |
| American hazel | *Corylus americana* | 0.00 | 0.05 | 0.02 |
| Holly | *Ilex* spp. | 0.00 | 0.03 | 0.01 |
| Ninebark | *Physocarpus opulifolius* | 0.00 | 0.02 | 0.01 |

Blueberry by IV was the most abundant understory species category. On average, it covered about 9.3 percent of the entire surveyed forest floor. Its occurrence frequency was also high with over two-thirds of all 5,730 sampled subplots having at least some blueberry cover. The second most abundant species by IV was hayscented fern. About 8.6 percent of the surveyed forest floor was covered with hayscented fern, which was found on almost one of every four subplots. Mountain-laurel (*Kalmia latifolia* L.) and huckleberry (*Gaylussacia baccata* (Wangh.) Koch) were the next two most abundant species, with IVs of 30 and 20 percent, respectively. Forbs, grasses, and teaberry (*Gaultheria procumbens* L.) had a common attribute, which was that they were widely distributed but had small cover percentages. Overall, 44 percent of non-tree vegetation species or species groups had occurrence frequencies less than one percent, and about 83 percent of the species or species groups had average cover less than one percent. The understory non-tree vegetation was dominated by a few species or species groups.

Average cover percentage, occurrence frequency, heavy cover frequency, and IV are tabulated in Appendices B1 and B2 for each stand for the four most abundant non-tree species: blueberry, hayscented fern, mountain-laurel, and huckleberry. These four non-tree species had large variations in abundance and occurrence among the stands. Seventeen percent of the stands did not have a single stem of hayscented fern on measured plots; while about ten percent of stands had over 30 percent average fern cover and occurrence frequencies of over 75 percent. Based on Marquis's standard, seventeen percent of the stands had fern cover at or above the problematic level. Mountain-laurel occurred in 77 percent of the stands, and its IV was as high as 100 in some stands. There were four stands out the 52 that had over 30 percent of plots covered with heavy mountain-laurel. Huckleberry and blueberry played different roles in tree regeneration, which will be further discussed in Chapter 5. Two-thirds of the stands had at least some huckleberry, and 12 percent of the stands had over 50 percent of the forest floor covered with huckleberry. Blueberry, as the most abundant non-tree vegetation, occurred in all of the surveyed stands. It was also widely distributed within each stand. Nearly 80 percent of the stands had blueberry cover on over half of their plots.

Regional distributions of IVs for the top four non-tree vegetation species are mapped for the two physiographic provinces in Figure 3.4. The means of average cover, occurrence frequency, heavy cover frequency, and IV for the top four species are also provided for each region (Table 3.4). Thirteen of the 17 Allegheny Plateau stands had hayscented fern IVs over 15 percent. On average, half of all the sampled plots had fern cover, and the mean cover was over 20 percent, which indicates that

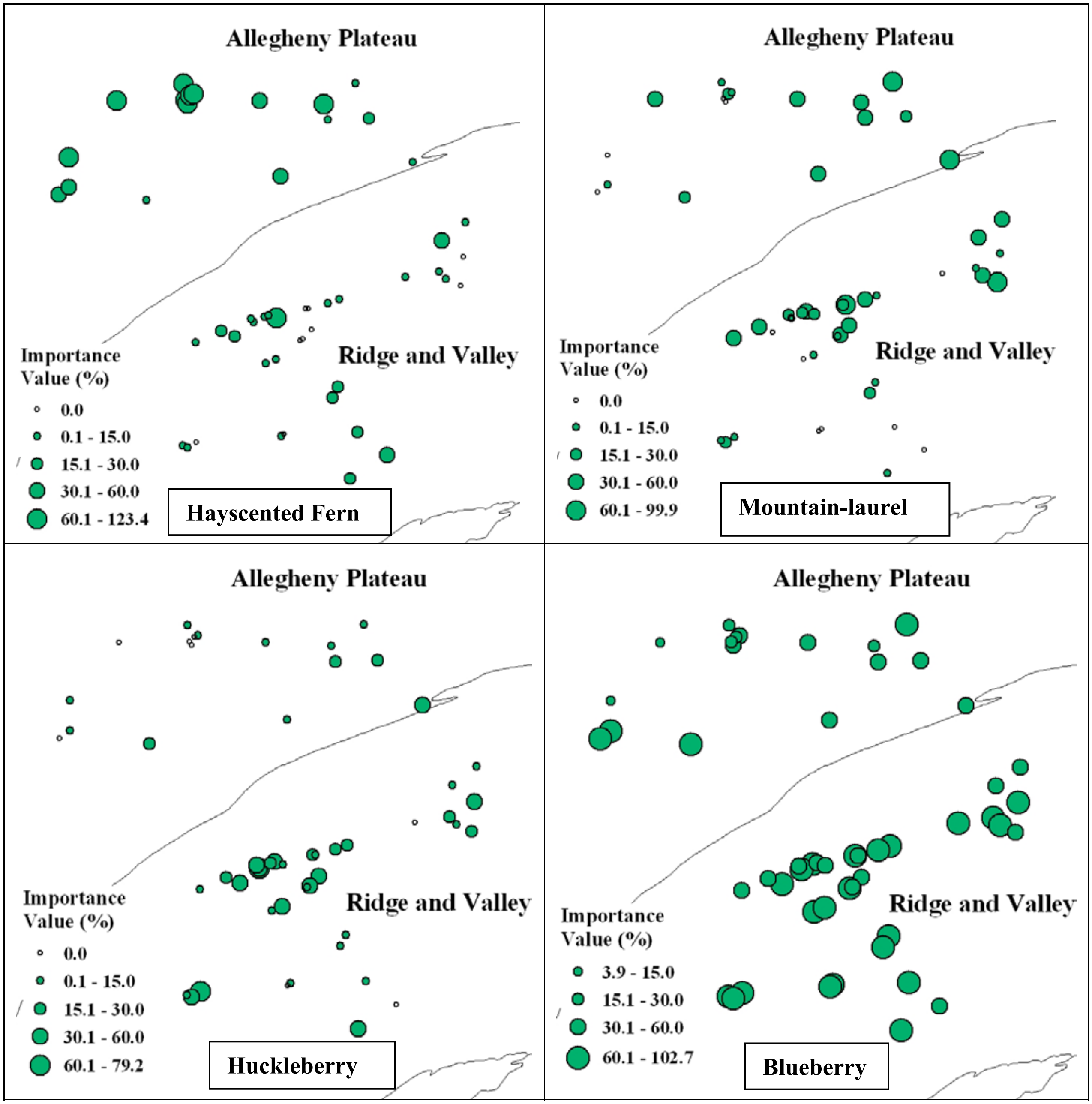



Figure 3.4. Regional distribution of importance value of non-tree vegetation by species and by stand.

those plots that did have ferns were fairly well covered. Ferns were less abundant on most of the stands in the Ridge and Valley province. The mean IV of hayscented fern was significantly less in the Ridge and Valley than on the Plateau (11 and 59, respectively, $p < 0.001$). The distribution of mountain-laurel did not have as clear a pattern as hayscented fern, and mean IVs for the two regions were not significantly different ($p = 0.34$). In both regions, some stands did not have mountain-laurel on measured plots, while some stands had large amounts. Huckleberry and blueberry were both more abundant in the Ridge and Valley than on the Allegheny Plateau. Blueberry average cover was almost two times higher in the Ridge and Valley than on the Plateau, and IV was significantly higher in the Ridge and Valley province ($p < 0.001$).

Table 3.4. Average vegetation cover, occurrence frequency, frequency of heavy cover subplots, and importance value of major understory tree by physiographic province. (* means of same species in the same category are different in two provinces at $p < 0.05$, ** at $p < 0.01$)

| Physiographic province | Species | Cover (%) | Freq. (%) | >30 Freq. (%) | IV (%) |
|---|---|---|---|---|---|
| Allegheny Plateau (n=17) | Hayscented Fern | 19.5** | 50.4** | 29.8** | 59.1** |
| | Mountain-laurel | 11.2 | 31.9 | 17.5 | 28.1 |
| | Huckleberry | 2.1* | 12.7* | 2.6 | 8.4** |
| | Blueberry | 6.1* | 60.0 | 4.7** | 43.3** |
| Ridge and Valley (n=35) | Hayscented Fern | 2.8 | 11.0 | 3.9 | 11.3 |
| | Mountain-laurel | 5.8 | 25.5 | 8.3 | 21.1 |
| | Huckleberry | 5.9 | 26.1 | 8.4 | 22.5 |
| | Blueberry | 11.0 | 74.2 | 13.4 | 70.7 |

### *Advance regeneration composition and distribution*

Advance regeneration, also known as pre-harvest reproduction, is an important source of regeneration for the development of the next stand after major disturbances, especially for oak species. Accordingly, the composition and distribution pattern of advance regeneration has a significant impact on the composition and distribution pattern of the future stand (Oliver and Larson 1996). A total of 49 species or species groups of tree regeneration was identified on all the sampled plots in the study area (Table 3.5). Compared to the mature overstory, there were slightly more tree species or species groups in the understory regeneration.

Table 3.5. List of species or species groups and their average density, cumulative height, occurrence frequency, and importance value of tree regeneration.

| Common Name | Scientific Name | Dens. (stems/acre) | Cum. Ht. (feet/acre) | Freq. (%) | IV (%) |
|---|---|---|---|---|---|
| Red maple | *Acer rubrum* | 24638.5 | 9277.1 | 93.0 | 160.52 |
| Northern red oak | *Quercus rubra* | 3298.9 | 1460.9 | 45.7 | 33.60 |
| Chestnut oak | *Quercus montana* | 2484.1 | 1713.4 | 28.9 | 27.00 |
| Juneberries | *Amelanchier* spp. | 855.5 | 451.8 | 23.3 | 12.85 |
| White oak | *Quercus alba* | 700.3 | 473.4 | 12.6 | 8.88 |
| Striped maple | *Acer pennsylvanicum* | 415.5 | 504.7 | 12.3 | 8.33 |
| Black birch | *Betula lenta* | 478.5 | 428.5 | 11.8 | 7.87 |
| Black oak | *Quercus velutina* | 392.1 | 254.1 | 14.8 | 7.42 |
| Sassafras | *Sassafras albidum* | 307.3 | 166.1 | 11.0 | 5.48 |
| Blackgum | *Nyssa sylvatica* | 253.2 | 126.3 | 10.0 | 4.74 |
| Black cherry | *Prunus serotina* | 275.7 | 128.2 | 9.7 | 4.72 |
| Eastern white pine | *Pinus strobus* | 62.5 | 159.4 | 3.5 | 2.34 |
| Scarlet oak | *Quercus coccinea* | 94.2 | 87.2 | 4.1 | 2.16 |
| Pignut hickory | *Carya glabra* | 78.7 | 41.6 | 5.0 | 2.11 |
| Tulip-tree | *Liriodendron tulipifera* | 110.5 | 22.0 | 3.8 | 1.69 |
| Sugar maple | *Acer saccharum* | 115.2 | 50.2 | 3.0 | 1.61 |
| White ash | *Fraxinus americana* | 86.2 | 43.3 | 3.0 | 1.49 |
| Hophornbeam | *Ostrya virginiana* | 71.4 | 91.7 | 2.0 | 1.43 |
| Hickory | *Carya* spp. | 36.1 | 20.1 | 1.8 | 0.80 |
| Hawthorn | *Crataegus* spp. | 20.1 | 10.2 | 1.3 | 0.55 |
| American beech | *Fagus grandifolia* | 21.1 | 39.7 | 0.7 | 0.55 |
| Black locust | *Robinia pseudoacacia* | 16.9 | 29.4 | 0.9 | 0.53 |
| Flowering dogwood | *Cornus florida* | 14.3 | 9.7 | 1.0 | 0.41 |
| Pin cherry | *Prunus pensylvanica* | 14.3 | 5.2 | 0.8 | 0.34 |
| Eastern hemlock | *Tsuga canadensis* | 8.9 | 9.1 | 0.8 | 0.33 |
| Cucumbertree | *Magnolia acuminata* | 8.9 | 3.1 | 0.7 | 0.28 |
| American chestnut | *Castanea dentata* | 8.4 | 19.4 | 0.4 | 0.27 |
| Mockernut hickory | *Carya tomentosa* | 7.7 | 4.5 | 0.6 | 0.25 |
| Hornbeam | *Carpinus caroliniana* | 7.5 | 19.7 | 0.2 | 0.21 |
| Shagbark hickory | *Carya ovata* | 3.1 | 3.5 | 0.3 | 0.13 |
| Yellow birch | *Betula alleghaniensis* | 5.8 | 1.9 | 0.3 | 0.12 |
| Norway spruce | *Picea abies* | 1.4 | 9.6 | 0.1 | 0.11 |
| Birch | *Betula* spp. | 5.2 | 1.6 | 0.2 | 0.10 |
| Tree-of-heaven | *Ailanthus altissima* | 3.7 | 4.9 | 0.2 | 0.10 |
| Basswood | *Tilia americana* | 2.4 | 0.9 | 0.2 | 0.09 |
| Cherry | *Prunus* spp. | 1.4 | 0.5 | 0.1 | 0.05 |
| Ash | *Fraxinus* spp. | 2.6 | 0.7 | 0.1 | 0.03 |
| Spruce | *Picea spp* | 0.7 | 0.2 | 0.1 | 0.03 |
| American elm | *Ulmus americana* | 1.6 | 0.3 | 0.1 | 0.02 |
| Sumac | *Rhus spp* | 0.5 | 0.5 | 0.0 | 0.02 |
| Bitternut hickory | *Carya cordiformis* | 0.2 | 1.3 | 0.0 | 0.01 |
| Norway maple | *Acer platanoides* | 0.5 | 0.2 | 0.0 | 0.01 |
| Black walnut | *Juglans nigra* | 0.2 | 0.3 | 0.0 | 0.01 |
| Paper birch | *Betula papyrifera* | 0.2 | 0.3 | 0.0 | 0.01 |
| Red pine | *Pinus resinosa* | 0.3 | 0.1 | 0.0 | 0.01 |
| Dogwood | *Cornus* spp. | 0.2 | 0.1 | 0.0 | 0.01 |
| Choke cherry | *Prunus virginiana* | 0.2 | 0.1 | 0.0 | 0.01 |
| Honeylocust | *Gleditsia triacanthos* | 0.2 | 0.1 | 0.0 | 0.01 |
| Bigtooth aspen | *Populus grandidentata* | 0.2 | 0.0 | 0.0 | 0.01 |

The advance regeneration was heavily dominated by red maple (161 percent average IV). This species had a very high average density (25,400 stems per acre) and occurrence frequency (93 percent) compared to other regeneration species. The average height of red maple seedlings was about 4 inches. Northern red oak by IV was the second most abundant species of advance regeneration. The average density of northern red oak seedlings across the study area was 3,400 stems per acre with occurrence frequency of nearly 46 percent. The size of northern red oak advance regeneration was not great either, but on average northern red oak was about one inch taller than red maple. Chestnut oak was the third most abundant species of advance regeneration. It occurred on nearly one-third of the plots and had average density approaching 2,500 stems per acre across study area. Interestingly, juneberry (*Amelanchier* spp.) advance regeneration ranked fourth in the understory although it ranked 12th in the overstory. This is probably because juneberry is a small tree and hardly reaches beyond the mid- or lower part of the canopy. White oak was the fifth most abundant advance regeneration with average density of 700 stems per acre. Four pine species occurred in the overstory of these stands, but only eastern white pine and red pine were recorded in the advance regeneration. Overall, 77 percent of the species occurred on less than five percent of surveyed plots, and close to 50 percent of advance regeneration species had average densities less than 10 stems per acre. In other words, advance regeneration was dominated by a few species.

Because size is an important attribute of advance regeneration, the average density of advance regeneration that had over 10 percent occurrence frequency was calculated for each species by height classes (Table 3.6). It is obvious that most of the regeneration was small. For each species listed in Table 3.6, over half of the advance regeneration was six inches or less in height. The percentage of red maple seedlings in the lowest height class was as high as 88 percent. Not including the over five-foot height class, density decreases as the height class increases for all the species (reverse "J" size distribution). There were no notable accumulations of large advance oak regeneration except for chestnut oak. The overall density of striped maple, an oak regeneration competitor, was relatively low, but its density in the large height classes was right next to chestnut oak and much higher than the other oak species.

Table 3.6. Advance regeneration density by height class and by species.

| Species | Height Classes | | | | | | |
|---|---|---|---|---|---|---|---|
| | 0-0.5' | 0.5-1' | 1-2' | 2-3' | 3-4' | 4-5' | 5'+ |
| *Acer rubrum* | 21714 | 1865 | 718 | 179 | 54 | 29 | 80 |
| *Quercus rubra* | 2602 | 640 | 40 | 6 | 3 | 2 | 6 |
| *Quercus montana* | 1379 | 715 | 248 | 62 | 27 | 17 | 36 |
| *Amelanchier* spp. | 607 | 165 | 53 | 16 | 7 | 2 | 6 |
| *Quercus alba* | 387 | 199 | 76 | 21 | 7 | 2 | 7 |
| *Betula lenta* | 312 | 58 | 52 | 24 | 5 | 2 | 25 |
| *Quercus velutina* | 239 | 99 | 34 | 10 | 4 | 2 | 5 |
| *Acer pennsylvanicum* | 231 | 60 | 44 | 28 | 13 | 11 | 28 |
| *Prunus serotina* | 208 | 38 | 6 | 5 | 1 | 1 | 2 |
| *Sassafras albidum* | 204 | 79 | 20 | 2 | 0 | 1 | 1 |
| *Nyssa sylvatica* | 187 | 52 | 12 | 1 | 0 | 0 | 1 |

Average density, cumulative height, occurrence frequency, and IV for advance regeneration in each stand are provided to investigate the variation among stands (Appendices C1, C2, C3, and C4). Clearly, there were variations both in species composition and overall stand density. In some stands such as 9718 (stand ID of the Pennsylvania Oak Regeneration Assessment Project), the total regeneration was only about 4,000 seedlings per acre. Even red maple density was as low as 2,000 stems per acre. At the other extreme, some stands were crowded with advance regeneration, and one (9910) had an average advance regeneration density of nearly 97,000 stems per acre. For most stands, advance oak regeneration occurrence frequency was lower than that in the overstory. Eight percent of the stands had none or less than one percent occurrence frequency of white oak in the overstory, but 17 percent of stands had none or less than one percent of white oak occurrence frequency in the understory. Likewise, the complete absence of chestnut oak on measured plots soared from zero percent of stands for the overstory to 13 percent of stands for the understory. The occurrence frequency of northern red oak was similar in the overstory and advance regeneration classes.

Regional distribution of advance regeneration for red maple, black birch, blackgum, white oak, chestnut oak, and northern red oak are shown in Figure 3.5.

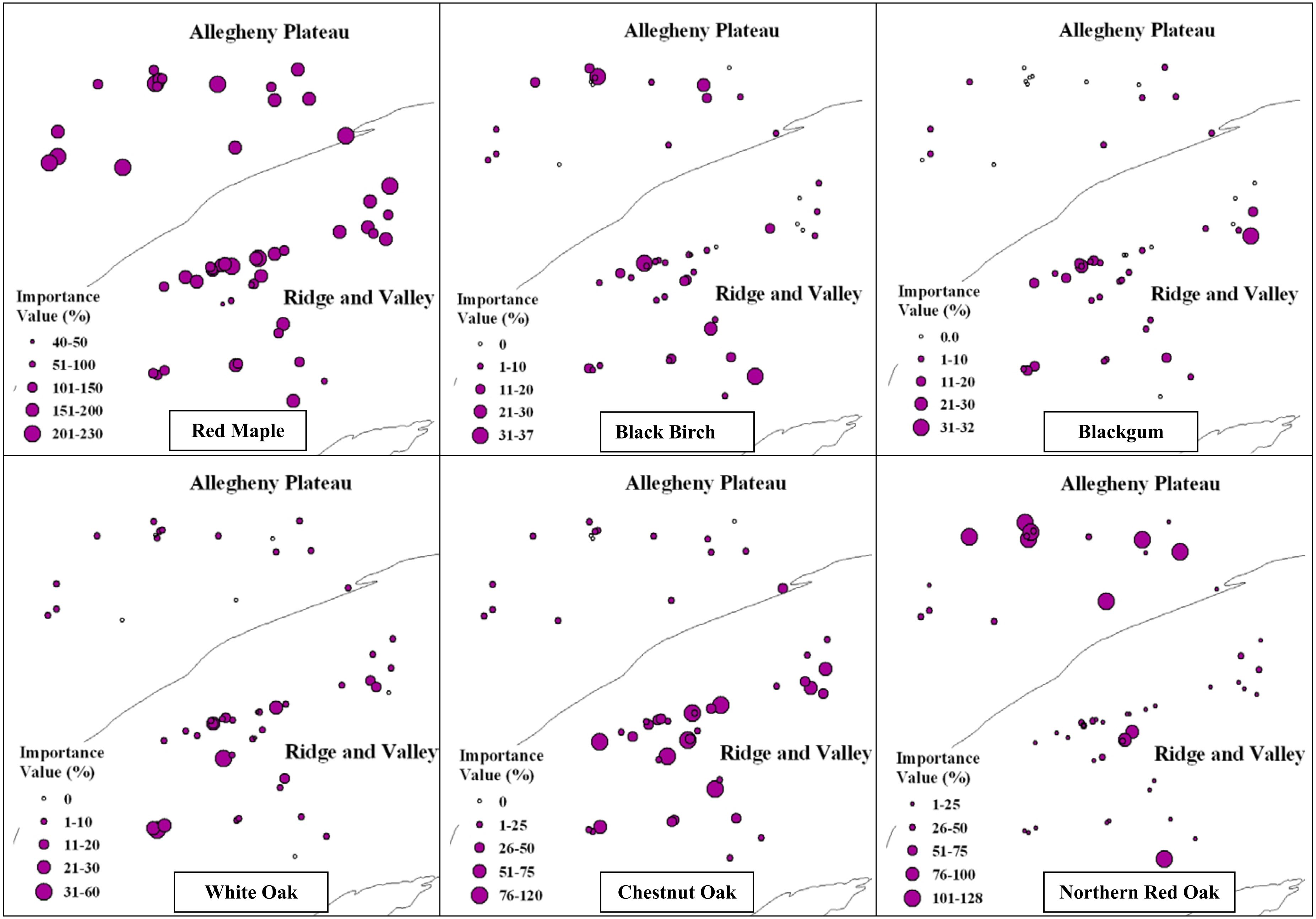



Figure 3.5. Regional distribution of importance value of advance regeneration by species and by stand.

Means of advance regeneration density, cumulative height, occurrence frequency, and IV are tabulated for stands on the Allegheny Plateau and the Ridge and Valley physiographic provinces (Table 3.7). Distribution patterns of advance regeneration were similar to those observed for overstory trees. The average IV for red maple was higher on the Allegheny Plateau (172 percent) than in the Ridge and Valley (150 percent); however, the difference is not significant (p = 0.07). Compared to overstory distribution, red maple dominance was higher in the advance regeneration class. The difference was greater in the Ridge and Valley (IV 69 to 150 percent) than on the Allegheny Plateau (IV 123 to 171 percent).

Table 3.7. Average density, cumulative height, frequency, and importance values of six oak and non-oak regeneration species by physiographic province. (* means of same species in the same category are different in two provinces at p < 0.05, ** at p < 0.01)

| Physiographic province | Species | Density (stems/milacre) | Cum. Ht. ($ft^2$/milacre) | Frequency (%) | Importance Value (%) |
|---|---|---|---|---|---|
| Allegheny Plateau (n=17) | Red Maple | 29.81 | 10.71 | 91.2 | 171.9 |
| | Black Birch | 0.36 | 0.43 | 8.6 | 7.4 |
| | Black-gum | 0.02** | 0.01** | 1.2** | 0.6** |
| | White Oak | 0.10 | 0.05 | 3.7* | 2.1* |
| | Chestnut Oak | 0.22** | 0.15* | 6.2** | 4.1** |
| | N. Red Oak | 7.15** | 2.96** | 61.3** | 64.1** |
| Ridge and Valley (n=35) | Red Maple | 22.13 | 8.49 | 93.3 | 150.4 |
| | Black Birch | 0.54 | 0.46 | 13.8 | 7.9 |
| | Black-gum | 0.36 | 0.18 | 14.0 | 6.7 |
| | White Oak | 0.99 | 0.77 | 17.8 | 10.0 |
| | Chestnut Oak | 3.58 | 2.83 | 40.8 | 41.1 |
| | N. Red Oak | 1.43 | 0.72 | 38.5 | 24.4 |

Black birch, by contrast, was more abundant in the Ridge and Valley (IV 7.9 percent) than on the Allegheny Plateau (IV 7.4 percent). There was no significant difference in advance regeneration (p = 0.86), but there was a significant difference for overstory trees (p = 0.04). Black birch is a pioneer species, and advance regeneration is relatively unimportant because the main regeneration appears after overstory removal. The distribution pattern for blackgum was about same for both the overstory and advance regeneration; the Ridge and Valley had more blackgum than the Allegheny Plateau.

Both white oak and chestnut oak advance regeneration were more abundant in the Ridge and Valley than on the Allegheny Plateau. The average white oak IV for advance regeneration was about five times higher in the Ridge and Valley (p = 0.02). Compared to the overstory, average white oak seedling IV dropped in both provinces, but the drop rate was much sharper on the Plateau (90 percent drop) compared to the Ridge and Valley (64 percent drop). Similarly, chestnut oak advance regeneration was more abundant in the Ridge and Valley. The decreasing of IV of chestnut oak from overstory tree to regeneration was much faster on the Allegheny Plateau. In contrast, advance regeneration of northern red oak was more abundant on the Allegheny Plateau and the distribution pattern was similar to the overstory trees of its own kind.

### *Stand classification*

Species distribution analysis for overstory trees, understory non-tree vegetation, and advance regeneration indicated that the composition of mixed-oak stands varies considerably within the study region. From the stand management point of view, it would be helpful to distinguish different stand types in order to facilitate decision making. The dendrogram from the cluster analysis is presented in Figure 3.6. The procedure divided all the 52 stands into two major clusters, the majority of stands in Cluster I are located on the Allegheny Plateau, and virtually all stands in Cluster II are in the Ridge and Valley. Five Ridge and Valley stands are classed in Cluster I, and only one Allegheny Plateau stand is classed in Cluster II.

Average IVs of non-tree vegetation, overstory tree, and advance regeneration are shown for each cluster in Figure 3.7. Cluster I was dominated by red maple and northern red oak both in the overstory and in advance regeneration and by hayscented fern (and to a lesser degree by blueberry and mountain-laurel) in the understory vegetation. Cluster II was dominated by red maple and chestnut oak both in the overstory and in advance regeneration, and by blueberry in the understory vegetation. Therefore, Cluster I can be described as *red maple – northern red oak – hayscented fern* subtype, and Cluster II can be described as *red maple – chestnut oak – blueberry* subtype.

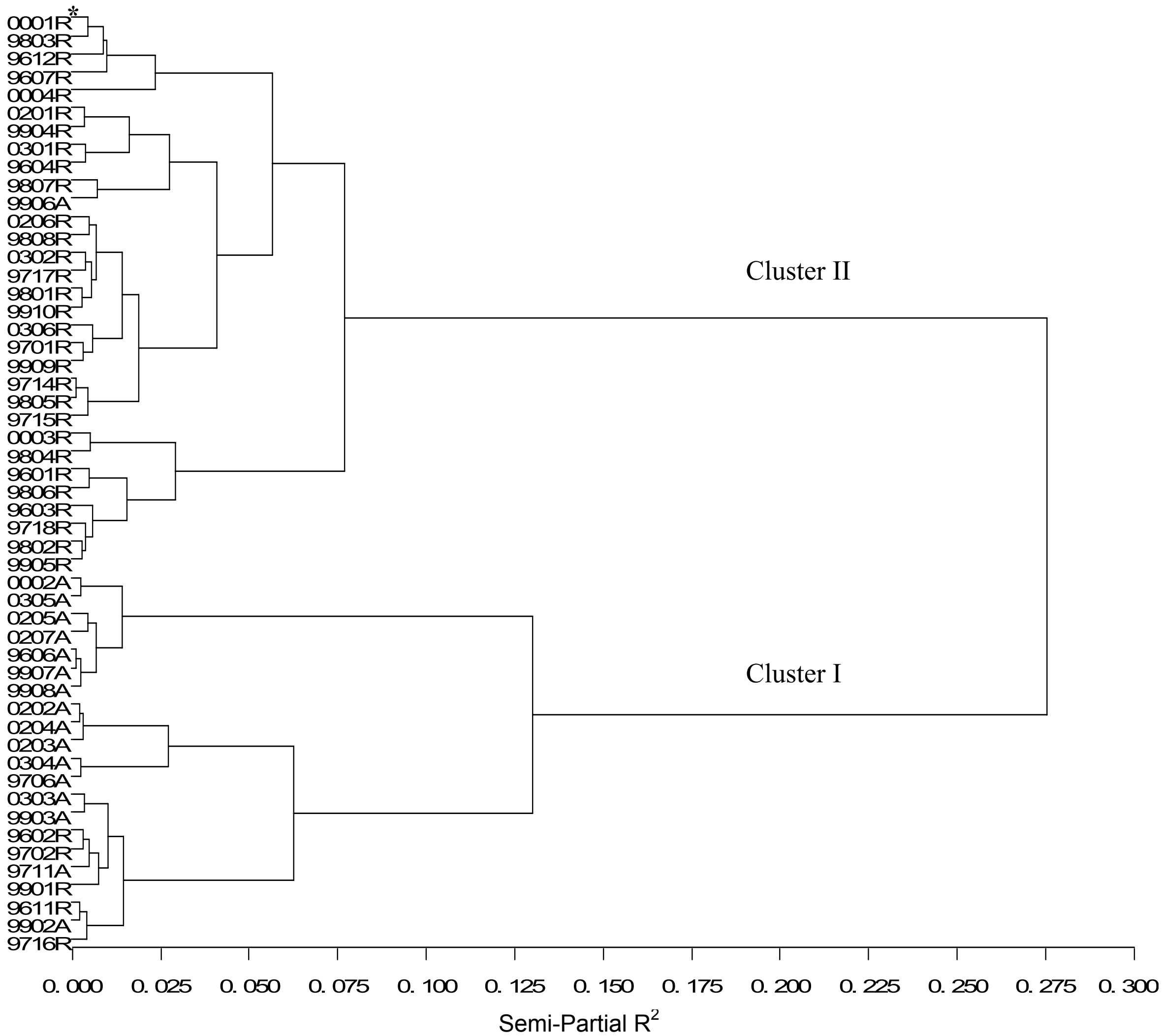



Figure 3.6. Dendrogram of hierarchical cluster analysis based on Ward's linkage method.

* A – the Allegheny Plateau stands; R – the Ridge and Valley stands.

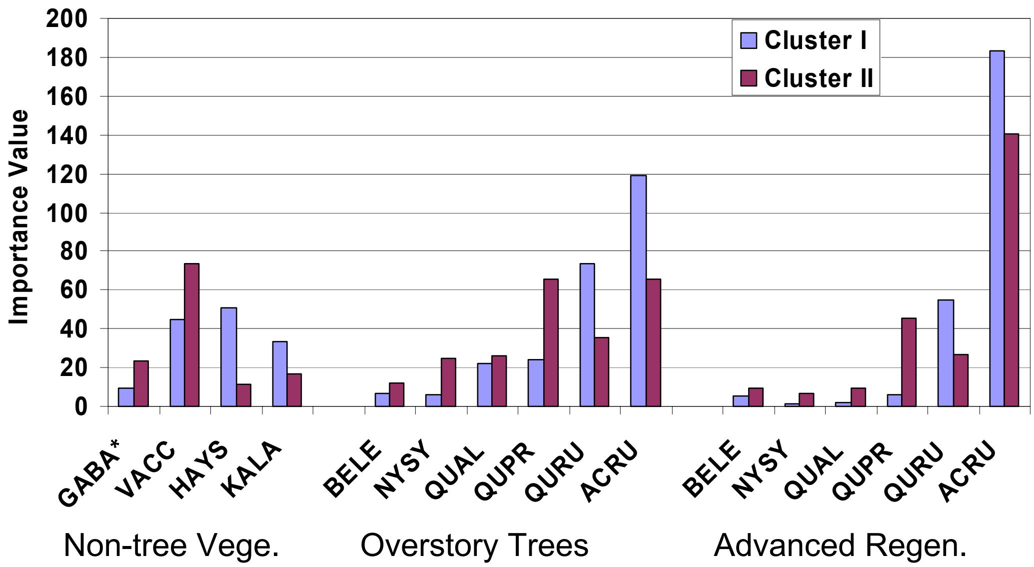



Figure 3.7. Average importance value of non-tree vegetation, overstory trees, and advance regeneration for each cluster.
* Four-letter species code: GABA – huckleberry, VACC – blueberry, HAYS – hayscented fern, KALA – mountain laurel, ACRU – red maple, BELE – black birch, NYSY – blackgum, QUAL – white oak, QUPR – chestnut oak, QURU – northern red oak.

## Discussion

The results indicated that red maple was the most abundant tree species both in the overstory and in the advance regeneration across the study area. By comparing the IVs of red maple in the overstory and in the advance regeneration, the trend was clearly shown that red maple was increasing its abundance in both of the physiographic provinces. Red maple was more abundant on the Allegheny Plateau; however, the increasing rate of occurrence was much higher in the Ridge and Valley (2.2 times) than on the Allegheny Plateau (1.4 times), which suggests a trend that red maple is increasing its abundance from the Allegheny Plateau to the Ridge and Valley. Although not all the advance red maple regeneration can survive and carry on to the new stand after overstory removal, it seems likely that red maple will expand its dominance if no major disturbance occurs. What is more, with the high abundance of red maple in the overstory, red maple can easily recover after a major disturbance such as overstory removal. Red maple stumps sprout vigorously, and the sprouts have a high survival rate (Walters and Yawney 1990). As found also by Abrams

(1998) and McWilliams (2004), red maple appears to be increasing its abundance in the stands represented by our study.

Development trends for black birch and blackgum were not obvious by comparing their abundance of overstory tree and advance regeneration. Black birch is a pioneer species, and its advance reproduction is not an important source for stand development after overstory removal. However, it can have tremendous regeneration potential after overstory removal if a seed source is available. In the new inventory report for Pennsylvania's forests, McWilliams et al. (2004) found large amounts of black birch in the 2-inch DBH class across Pennsylvania.

All three major oak species appeared to be losing their relative abundance based upon comparison of the oak IVs in the overstory and advance regeneration. Among the three oak species, white oak had the sharpest rate of drop in IV, especially on the Plateau. In some stands on the Allegheny Plateau, white oak had no presence as a component of advance regeneration although it was present in the overstory. As mentioned earlier, advance regeneration is especially important to the regeneration of oaks. Advance regeneration for all the oak species had a reverse "J" size distribution. Most of the advance oak regeneration is in the < 6 in height class and there are very few seedlings reaching the > 5 ft height class. Overstory oaks all had a uni-modal normal distribution in size structure. By linking the size structure of advance regeneration and overstory trees, it is obvious that there is a severe bottleneck for the oak species between seedling and overstory tree (i.e., limited number of seedlings can grow into sapling stage) as found in the other studies (Crow 1988, Nowacki et al. 1990, Abrams 2003).

Interestingly, overstory tree size distribution of all three non-oak species had a reverse "J" distribution, while all three oak species had a uni-modal normal distribution. If we assume that there is a one to one positive relationship between tree diameter and age, then we can conclude that the populations of three non-oak species are persistent, and the populations of three oak species are declining. The non-oak species will replace the oak species in the future if no major disturbances occur. However, based on the stand history, each stand included in this study was developed either from a clearcut or an abandoned old field. It is possible that both the oak and non-oak species were established at the same time and had similar ages. If that is the case, then the two different distribution patterns could have arisen if the oak species out-competed the non-oak species during stand development process, resulting larger average diameters. Most of the non-oak species were suppressed and remained in the small size classes with only occasional exceptions. Unfortunately, I do not have age structure data for the overstory trees; therefore, no definite conclusion can be drawn to explain the two different distribution patterns.

Both the analysis of variance on overstory mature tree, understory non-tree vegetation type, and advance regeneration for the two physiographic province and overall cluster analysis indicate that there are two distinct forest subtypes: *red maple – northern red oak – hayscented fern* subtype, and *red maple – chestnut oak – blueberry* subtype. Different strategies should be applied when managing stands in these two different subtypes.

# Chapter 4

# Cumulative Height -- A Composite Variable to Measure Tree Seedling Populations

*It is common sense to take a method and try it; if it fails, admit it frankly and try another. But above all, try something.*

Franklin D. Roosevelt

***Abstract*:** Cumulative height, a composite measure of seedling size and density, is proposed for describing seedling populations in the early-stage of stand development. Cumulative height is analogous to other forest measurements, such as basal area, that incorporate both size and density into a single value. Data from 33 mixed-oak stands (3,452 subplots) were used to compare the utility of seedling density, average height, and cumulative height for examining patterns of stand development. Comparisons of coefficients of determination ($r^2$) indicate that cumulative height produces more robust models for describing the early development of red maple and oak than do density and average height. Comparisons between expected oak densities derived from a regeneration model and densities, mean heights, and cumulative heights of advance oak regeneration indicate that cumulative height may efficiently describe oak regeneration potential in advance of harvest.

## Introduction

Increasing interest in hardwood regeneration, particularly in eastern mixed-oak stands in North America, has created a need to better understand changes in tree seedling populations shortly before and after timber harvests. Forest managers who rely on natural regeneration to restock stands after overstory removals are often interested in controlling the size, density, and composition of advance regeneration because failure to obtain adequate and prompt regeneration of desired species can leave a stand unproductive for many years. Accurate measurements of regeneration potential are essential to the development of sound silvicultural prescriptions. After harvest, a seemingly chaotic period of stand development begins. Young stands often contain a large number of species with a range of densities and sizes, and quantifying and predicting stand composition during this critical period of development is not straightforward.

Descriptive variables such as basal area (Avery and Burkhart 1994) and stocking (Gingrich 1967) incorporate measures of both tree size and density to efficiently describe overall stand conditions and the importance of individual species. However, these measurements are not applicable to stands that have not yet reached a minimum size (3 inch diameter at breast height (DBH)). Seedling height and density are readily measured, but the interpretation of these two variables is not obvious. Is a treatment successful if it decreases seedling density, but increases average height? How does one quantify the importance of a new regeneration cohort that increases density but decreases mean height due to the addition of many small seedlings?

In this chapter, I argue that cumulative height, a composite measure of seedling size and density, is a useful approach for describing seedling populations before harvest and shortly after harvest. Cumulative height is defined as the total height of all the individuals of a species or species group per unit area. Mean plot cumulative height is calculated from plot data as:

$$CumHt = \left(\sum_{i=0}^{m}\sum_{j=0}^{n} h_{ij}\right) / m \qquad [4.1]$$

where $h_{ij}$ is the height of *j*th seedling on *i*th plot, *n* is number of seedlings on plot *i*, and *m* is the number of sample plots.

The objective of this chapter is to demonstrate that cumulative height more predictably describes patterns of stand development than seedling density and height. The size and density of advance oak regeneration have been used to model the development of oaks after harvest (Loftis 1990b, 1993). Analysis will show that cumulative height of advance oak regeneration more closely matches predicted future oak stocking than regeneration density or average height alone.

## Methodology

Data were collected in 33 mixed-oak stands in Pennsylvania. Depending on stand size, 15 to 30 permanent plots with a radius of 26.3 ft (20th-acre) were systematically installed in a square grid to represent the whole stand. Four permanent subplots with a radius of 3.72 ft (milacre) were established within each plot at a fixed distance from plot center. In total, 3,452 subplots were established in the study area. On each subplot, tree seedlings (< 2 in in DBH) were recorded by species and height class. Stands were measured approximately one year before harvest (00 measurements), and re-measured one year after harvest (01 measurements). Sixteen stands were re-measured four years after harvest (04 measurements) and eight stands were re-measured five years after harvest (05 measurements). All stands included in this study had overstory removals after the first measurement (30 to 95 percent of basal area removed). Fencing and/or herbicide treatments were also applied in some cases.

Mean cumulative heights (eq. 4.1), mean densities, and mean heights of oak (*Quercus* spp.) and red maple (*Acer rubrum* L.) regeneration were calculated for each stand and measurement period. The three methods for quantifying regeneration were compared by fitting linear regression models between measurement periods. For example, mean oak cumulative height one year after harvest was regressed on mean oak cumulative height one year before harvest. The regression model is as follows,

$$y_{latter} = \alpha \cdot y_{former} \qquad [4.2]$$

where $y_{former}$ stands for attributes of the former measurements, $y_{latter}$ stands for attributes of subsequent measurements, and $\alpha$ is a regression coefficient. The model intercept was set at zero because most stands had a clearcut or heavy shelterwood, and no significant new regeneration cohorts were expected. Three stands that had large seed crops between the pre-harvest and post-harvest measurements were excluded from the oak analysis because they were strong outliers regardless of the measurement method. Linear regression analysis was also used to compare regeneration one and four years after harvest and four and five years after harvest. Coefficients of determination ($r^2$) were compared to identify the measurement that most consistently characterized patterns of stand development.

Expected oak densities 20 yrs after harvest were calculated for each stand based on pre-harvest advance oak regeneration using the individual stem probability approach described by Loftis (1990b, 1993), assuming site index 70. Under this approach, the density of advance oak regeneration in a given size class is multiplied by the size class probability of success (i.e., the probability of becoming a dominant or codominant stem 20 yrs after harvest). Expected densities are then summed across size classes. The original probability equation (Loftis 1990b) was based on data from northern red oak (*Quercus rubra* L.) and uses basal diameter as an independent variable. The equation was fitted to all oak as a species group for the purpose of illustrating differences between regeneration measurements. Basal diameters are estimated from individual stem height using a deterministic relationship derived from measurements on 2240 stems ($Basal\ Diameter = 0.033 + 0.094 \cdot Height$, $r^2 = 0.84$). Linear regression analysis was used to compare 20-yr expected oak densities against mean regeneration density, height, and cumulative height.

## Results

Regression coefficients ($\alpha$) and coefficients of determination ($r^2$) for linear regression models comparing mean density, mean height, and mean cumulative height between measurement periods are listed in Table 4.1. In all cases, cumulative height exhibited the strongest correlations between measurement periods based on coefficients of determination. Changes in regeneration populations were most variable between pre-harvest (00) and one-year post-harvest (01) measurements. Coefficients of determination were negative for red maple density and oak mean height indicating very poor model fits. As regression coefficients ($\alpha$) show, red maple density generally decreased while mean height increased. Oak density and mean height both generally decreased. Cumulative height decreased for both oaks and red maple, but there was a moderately strong and statistically significant relationship between 00 and 01 cumulative height for both species.

Regeneration development was more predictable between subsequent post-harvest measurements. Oak and red maple densities generally remained unchanged ($\alpha \approx 1.0$) between 01 and 04 and 04 and 05 measurements, and mean heights and cumulative heights generally increased. Both oak and red maple had relative annual rates of increase in cumulative height of about 1.25 (1.95 over 4 yrs). A plot of oak cumulative height one and four years after harvest (Figure 4.1) indicates that variation in the rate of cumulative height growth among stands was relatively small, despite the range of overstory and understory treatments. Coefficients of determination for cumulative height indicate highly deterministic models ($r^2 \geq 0.95$ in three of four models). Other measures of regeneration were less deterministic and only one of the eight models had a coefficient of determination greater than 0.80.

Table 4.1. Regression coefficient ($\alpha$) and coefficient of determination ($r^2$) of regression models of stand density, average height, and cumulative height for red maple and oak species. 00: one year before harvest; 01: one year after harvest; 04: four years after harvest; 05: five years after harvest.

| **Species** | **Models** | **Dens.** | | **Avg. Ht.** | | **Cum. Ht.** | |
|---|---|---|---|---|---|---|---|
| | | $\alpha$ | $r^2$ | $\alpha$ | $r^2$ | $\alpha$ | $r^2$ |
| Red maple | 00 vs. 01 (n = 33) | 0.45 | -0.13 | 1.17 | 0.40 | 0.88 | 0.64 |
| | 01 vs. 04 (n = 16) | 1.09 | 0.57 | 2.17 | 0.55 | 1.97 | 0.75 |
| | 04 vs. 05 (n = 8) | 1.06 | 0.51 | 1.37 | 0.52 | 1.26 | 0.98 |
| Oak spp. | 00 vs. 01 (n = 29) | 0.61 | 0.37 | 0.83 | -0.05 | 0.68 | 0.53 |
| | 01 vs. 04 (n = 16) | 0.94 | 0.50 | 2.04 | 0.83 | 1.93 | 0.95 |
| | 04 vs. 05 (n = 8) | 0.98 | -0.37 | 1.17 | 0.78 | 1.26 | 0.96 |

Linear regressions of expected oak density two decades after overstory removal on advance oak regeneration density, mean height, and cumulative height are plotted in Figure 4.2. Clear relationships are evident between expected densities and all three measures of advance regeneration. However, cumulative height captures virtually all the variation in expected oak density ($r^2 = 0.97$), while density and mean height alone only capture around one-half of the variation ($r^2 = 0.58$ and 0.46, respectively).

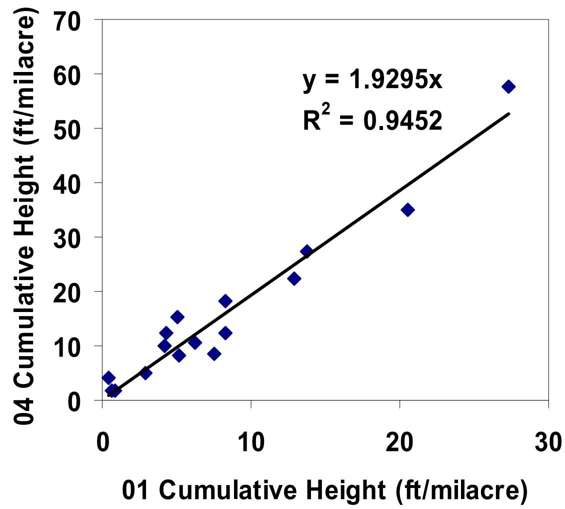



Figure 4.1. Regression of oak cumulative height one and four years after overstory removal for 16 mixed-oak stands (the annual rate of change is approximately $1.93^{1/3} \approx 1.25$).

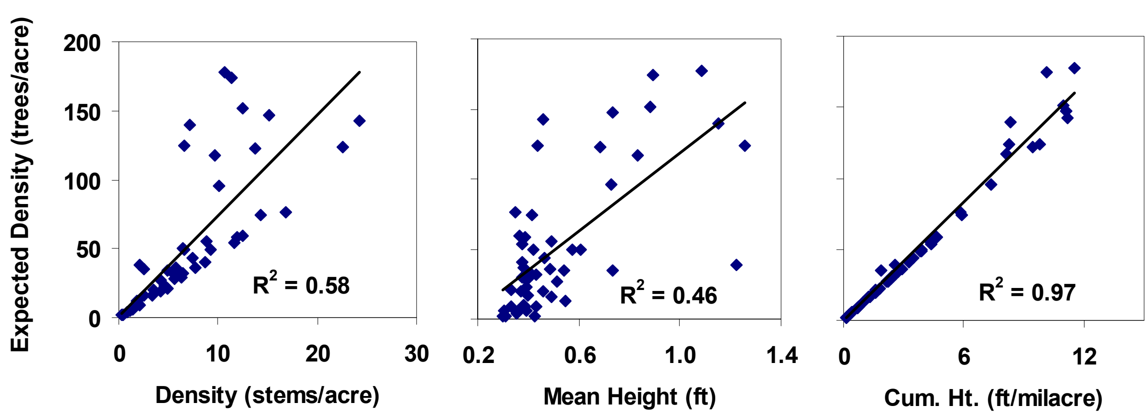



Figure 4.2. Regression of expected oak densities 20 years after overstory removal against pre-harvest regeneration density (left), mean height (middle) and cumulative height (right), from models in Loftis (1990b).

## Discussion and conclusions

Early stand development following major disturbances is a chaotic period characterized by rapid changes in tree density and size. This period is poorly understood compared to other stages of development due, in part, to the difficulty of measuring the relative potential among different species for future site occupancy. Our results indicate that cumulative height is a promising variable for measuring the relative prevalence of a species at a given stage of development and its ability to persist into future stages. Cumulative height is a more comprehensive measure of the condition of a regeneration cohort than density or average height alone because it incorporates both of those important parameters. Simple measures of tree size (e.g., height and diameter) have been used to develop highly deterministic equations for biomass estimates (Tritton and Hornbeck 1982, Ter-Mikaelian and Korzukhin 1997). By measuring both size and density, cumulative height indirectly measures biomass per unit area of a given species or species group. After recovering from an overstory removal, biomass typically increases monotonically during early stand development, regardless of density and species change (Barnes et al. 1998, White et al. 2004). Because the stands in this study had generally not reached crown closure, competition among seedlings was minimal, allowing cumulative height to increase for all species. Patterns will change with the onset of competition, and cumulative height per unit area will eventually reach a peak and then decrease.

It is possible that cumulative seedling basal diameter or basal area might serve as well or better than cumulative height. However, a large proportion of the seedlings in the early stage of stand development has not yet reached a minimum size to have a measurement of DBH, and it is more time-consuming to measure seedling basal diameter. It has been shown that the sum of the merchantable height is more highly correlated with volume or biomass than basal area in an established stand (Wiant and Zeide 1979, Myers 1985, Bailes and Brooks 2004). Therefore, it is also possible that in the stand regeneration stage, cumulative height might serve better to measure the relative prevalence of a species and its ability to persist into future stages than cumulative basal diameter or basal area.

Other researchers should explore the use of cumulative height for describing seedling populations. Cumulative height may be useful for efficiently summarizing seedling population responses to experimental treatments (e.g., prescribed fire or herbicide). In our analyses, cumulative height change was somewhat unstable after stand harvest and accompanying treatments, probably reflecting a range of responses to varying treatments.  However, subsequent development of regeneration cohorts was highly predictable using cumulative height.  The high level of predictability suggests change in cumulative height within the first several years after treatment is relatively independent of site factors.  In addition, cumulative height efficiently summarizes the advance regeneration attributes (size and density) used to model post-harvest oak regeneration development (Loftis 1993).  As the properties of cumulative height are explored, its applications and limitations will be better understood.

# Chapter 5

# Relationships between Advance Regeneration and Biotic and Abiotic Factors

*“Species that live in compliance with the law live forever…….”*

Daniel Quinn
*Ishmael*

***Abstract:*** Relationships between advance tree regeneration and biotic and abiotic factors were investigated in 52 mature mixed-oak stands in the central Appalachians. Four regeneration species: red maple, white oak, chestnut oak, and northern red oak, two biotic factors: non-tree vegetation and canopy composition, and two abiotic factors: soil series and topographic variables were used in this study. Analyses were carried out separately for two physiographic provinces. Associations with tree regeneration were found for all biotic and abiotic factors both in the partial models and the full models. Red maple is abundant on most of the sites, but high red maple abundance is commonly associated with moist, north-facing slopes with no or low cover of mountain-laurel and hayscented fern. Regeneration of the three oak species is greatly favored by the abundance of overstory trees of their own kind. White oak regeneration is most abundant on south-facing, gentle, lower slopes with soils in the Buchanan series. Chestnut oak is more common on south-facing, steep upper slopes with stony soils. There is also a positive association between chestnut oak and huckleberry cover classes. Northern red oak is more abundant on north-facing, moist sites with Hazleton soil, and is associated with low levels of mountain-laurel and hayscented fern.

## Introduction

Abundance of tree regeneration in the mixed-oak forest may be affected by both biotic and abiotic factors at stand or landscape scales. For abiotic factors, these may include soil and topographic heterogeneity. For example, differences in water-holding capacity, drainage, and nutrient supply apparently limit growth of some species but not others (Kimmins 1987). Observational studies have shown that abiotic factors such as soil series and landform have strong influence on the composition of hardwood forests (Robles et al. 1976, Honeycutt et al. 1982, Host et al. 1987). Experimental studies also have shown that seedlings in the mixed-oak forest have pronounced response to abiotic factor manipulations such as prescribed fire, soil scarification, and fertilization (Grayney 1982, Brose and VanLear 1997, Ward and Gluck 1999, Zaczek 2002, Adams and Rieske 2003).

For biotic factors, species interaction including negative or positive associations can affect both regeneration establishment and survival, which in turn affect future forest composition. In the mixed-oak forests of the central Appalachians, dense ground covers of blueberry (*Vaccinium* spp.), hayscented fern (*Dennstaedtia punctilobula* (Michaux) Moore), and other non-tree species can interfere with the development of advance oak regeneration (Allen and Bowersox 1989, Steiner and Joyce 1999, Horsley et al. 1992). Overstory trees, another important class of biotic factors, play a twofold role in the establishment and survival of regeneration. They provide the necessary seed source for the new cohort, but they also reduce the understory light level and compete for underground resources that are important to tree regeneration.

As a common problem throughout eastern Northern America, natural regeneration of oaks is often difficult to obtain even where oaks are the dominant components in the overstory before harvest. The major causes of regeneration difficulty may change from site to site and region to region. Because of this variability, we need to view "the oak regeneration problem" as having both local and regional aspects (Lorimer 1992). As Crow (1988) has pointed out for northern red oak, specific prescriptions for local conditions are needed to supplement general guidelines for regenerating oak. Although we know that all biotic and abiotic factors can influence tree regeneration, and we have had good, general descriptions of species site preferences for a long time, specific regional knowledge of associations between tree regeneration and biotic and abiotic factors is needed to help to achieve better oak regeneration.

In addition, studies have shown that juvenile and adult tree abundance respond differently to environmental gradients (Nowacki et al. 1990, Goebel and Hix 1996, Collins and Carson 2004). Patches with different regeneration composition and abundance are often observed within a stand where the overstory adult trees are relatively uniform. Common knowledge of species site preferences for adult trees might not be suitable for seedlings in the regeneration stage. A few studies (Bowersox 1972, Gribko et al. 2002, Collins and Carson 2004) have investigated the influences of both biotic and abiotic factors on regeneration in mixed-oak forests in the central Appalachians. Inclusive regional knowledge of the relationships between regeneration abundance and biotic and abiotic factors can help a resource manager to maintain a healthy, diverse, and compositionally stable forest system.

## Methodology

### *Data collection*

Data from 52 mature mixed-oak stands across the Allegheny Plateau and the Ridge and Valley physiographic provinces in the central Appalachians are the focus of this chapter. Depending on stand size, 15 to 30 permanent plots with a radius of 26.3 ft (0.05 acres) were systematically installed in a square grid to represent the whole stand. Four permanent subplots with a radius of 3.72 ft (0.001 arce) were established within each plot at a 16.7 ft distance on the cardinal axes from plot center. In total, 1,433 plots (5,732 subplots) were established in the study stands.

On each subplot, tree seedlings (< 2.0 inch in DBH) were recorded by species and height class (eight height classes were used (<2 in, 2.0 - 6.0 in, 6.1 in - 1.0 ft, 1.1 - 2.0 ft, 2.1 - 3.0 ft, 3.1 - 4.0 ft, 4.1 - 5.0 ft, and > 5.0 ft)). Biotic and abiotic conditions were also recorded at the stand, plot, and subplot scale. The following variables were measured in the field survey:

- Stand scale: slope position, and slope aspect;

- Plot scale: slope shape (sum of percentage slope uphill, down hill, and at 90º to aspect), slope percentage, exposure angle (the angle between the visible east horizon and west horizon), slope aspect, and DBH of all overstory trees (≥ 2.0 inch in DBH) by species.
- Subplot scale: cover percentage (in class of five percent) of non-tree vegetation by species or species group.

Soil type and elevation for each plot were also obtained by superimposing the coordinates of each sampled plot onto the National Soil Information System (NASIS) (USDA 2003) and onto the 30 meter resolution National Elevation Dataset (NED) (USGS 2003).

### *Data analysis*

Since the Allegheny Plateau and the Ridge and Valley physiographic provinces have different regeneration composition based on the results of Chapter 3, analyses of the relationship between tree regeneration and biotic and abiotic factors were carried out separately for each province. Red maple (*Acer rubrum* L.), the most abundant advance regeneration species, and three oak species (white oak [*Quercus alba* L.], chestnut oak [*Q. montana* Willd.], and northern red oak [*Q. rubra* L.]) were included in this study. Two classes of biotic factors: non-tree vegetation and overstory trees, and two classes of abiotic factors: soil series and topographic variables were studied for their relationships with advance regeneration. First, partial models that only include one class of biotic or abiotic factors as the independent variable were applied, and then full models were fit using the significant variables derived from the partial models.

Cumulative height, a composite measure of size and density, was used as an index of regeneration abundance. Cumulative height is defined as the total height of all the individuals of a species or species group (such as *Carya* species) per unit area. The relationships between regeneration abundance and non-tree vegetation were tested at the subplot scale since information for advance regeneration and non-tree vegetation were both available at the subplot scale. The four most abundant non-tree vegetation categories: hayscented fern, mountain-laurel (*Kalmia latifolia* L.), huckleberry (*Gaylussacia baccata* (Wangh.) Koch), and blueberry were selected for inclusion in the analysis. Percentage cover by these four categories of vegetation was defined by four classes: none, low (1 to 10 percent cover), moderate (11 to 30 percent), and heavy (over 30 percent). The heavy class reflects the threshold level of competing vegetation considered problematic by Marquis (1994). Analysis of variance was used and means of cumulative height in each cover class were compared using Duncan's multiple range tests (Neter et al. 1996).

The relationship between regeneration abundance and overstory trees was studied at the 0.05-acre plot scale. Average cumulative height was calculated based on the associated four subplots. Basal area of overstory tree species or species groups was also calculated for each plot. To minimize the complexity and maximize the degrees of freedom, only the three most abundant non-oak overstory species (red maple, blackgum [*Nyssa sylvatica* Marsh.], and black birch [*Betula lenta* L.]) and three oak species (white oak, chestnut oak, and northern red oak) were included in the analysis. Another variable, basal area of other species (BAOT), was created for each regeneration species to assess the crowdness of overstory species not of its own kind. For example, BAOT for red maple regeneration is calculated by subtracting overstory red maple basal area from the total basal area on a given plot. Multiple linear regressions were applied by setting average cumulative height per acre of a given species as the response variable and basal area per acre of overstory tree species as the independent variables. Backward stepwise elimination procedure was applied to achieve the best-fit models.

Since there was a total number of 74 different soil types on the surveyed stands, analysis of variance using all the soil types was not possible. To facilitate the analysis and to minimize errors induced by map resolution, soil types were grouped into soil series or associations. Soil series or associations that occurred on fewer than three percent of the surveyed plots or in fewer than two stands were excluded from the analysis. Analysis of variance was used and means of cumulative height in each soil series were compared using Duncan's multiple range tests.

Mixed models were applied to study the relationship between regeneration abundance and topographic variables. Slope aspect, $\theta$ ,is a circular variable, and attention must be given to its periodic nature during model building. In this analysis, the effect of aspect was modeled through a linear combination of the two variables $\sin\theta$ (which measures east-west effects) and $\cos\theta$ (which measures north-south effects). Slope percent (SL), slope shape (SH), $\sin\theta$ (AX), $\cos\theta$ (AY), exposure angle (EX), and elevation (EL) were set as numerical independent variables, slope position (PO) was set as categorical independent variable, and average plot cumulative height was set as the response variable. Backward stepwise elimination procedure was applied to achieve the best fit models. Because 16 out of the 17 stands on the Allegheny Plateau had the same slope position, this variable was not included in the Allegheny Plateau models.

Finally, full models for the four regeneration species were developed at the plot scale by pooling all significant biotic and abiotic factors derived from the partial models. Mixed models were applied in model building. Multicollinearity was checked between the independent variables before fitting the models. To simplify the analysis, no interaction terms were included.

## Results

### *Advance regeneration abundance vs. non-tree vegetation*

Associations between non-tree vegetation cover class and advance tree regeneration abundance were found in both physiographic provinces (Figure 5.1). Red maple regeneration abundance was significantly influenced by the abundance of all the four non-tree vegetation categories in the Ridge and Valley, and was significantly influenced by the abundance of huckleberry, mountain-laurel, and hayscented fern on the Allegheny Plateau. In both provinces, red maple regeneration abundance was significantly lower under heavy cover of mountain-laurel and hayscented fern.

White oak regeneration abundance was significantly influenced by the abundance of all four non-tree vegetation categories in the Ridge and Valley, but no significant association was found on the Allegheny Plateau. White oak regeneration

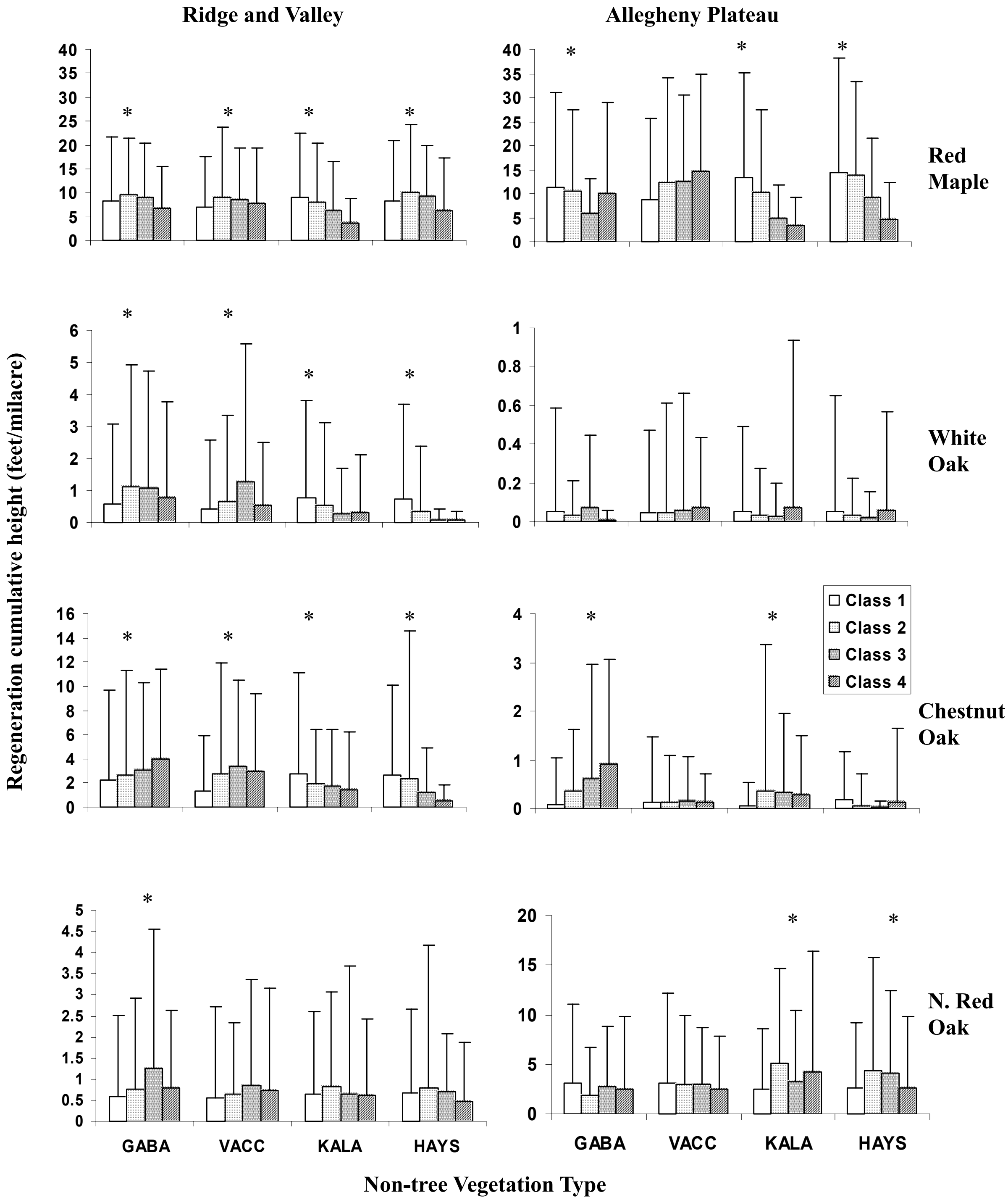



Figure 5.1. Mean and stand deviation of advanced regeneration abundance of four tree species, as expressed by cumulative height per milacre, under different cover classes (Class 1: no cover; Class 2: 1-10 percent; Class 3: 11-30 percent; Class 4: >30 percent) of four non-tree vegetation species (GABA: huckleberry, VACC: blueberry, KALA: mountain-laurel, and HAYS: hayscented fern) in the Ridge and Valley (left column) and the Allegheny Plateau (right column) physiographic provinces;
* association between regeneration abundance and cover abundance is significant ($p<0.05$).

was significantly higher when associated with low to moderate cover of huckleberry or moderate cover of blueberry, and was significantly lower when associated with moderate to heavy cover of mountain-laurel or hayscented fern.

Chestnut oak regeneration abundance was significantly influenced by the abundance of all four non-tree vegetation categories in the Ridge and Valley, and was significantly influenced by the abundance of huckleberry and mountain-laurel on the Allegheny Plateau. Consistent associations of chestnut oak regeneration and huckleberry and cover were found across the physiographic provinces. Chestnut oak regeneration abundance increased monotonically as huckleberry cover thickened, and chestnut oak regeneration abundance was significantly higher when associated with heavy huckleberry cover.

Significant association between northern red oak regeneration and huckleberry abundance was found in the Ridge and Valley. Northern red oak abundance was significantly higher with moderate cover of huckleberry. While on the Allegheny Plateau, northern red oak regeneration abundance was significantly affected by mountain-laurel and hayscented fern abundance. Northern red oak regeneration was most abundant with moderate with low mountain-laurel or hayscented fern cover.

### *Advance regeneration abundance vs. overstory trees*

Variables of overstory trees that entered into the multiple linear regression models are listed in Table 5.1. Red maple, blackgum, and black birch, as individual species, were not entered into the final models, which indicated that they did not significantly influence regeneration abundance of the four species in either physiographic province. Relationships between red maple regeneration abundance and overstory trees were different in different regions. Red maple regeneration was neither affected by overstory trees of its own species nor by the total basal area not of its own kind. Red maple had negative associations with chestnut oak and northern red oak in the Ridge and Valley, but positive association with northern red oak on the Allegheny Plateau physiographic province. This is hard to explain. It is possible that other underlying factors might drive these associations. Hence, the overstory tree associations were not included in the final full models for red maple regeneration.

All three oak species had positive associations with overstory trees of their own species, and negative associations with total basal area not of their own kind (Table 5.1). In other words, their regeneration cumulative height increased as the total basal area of their own kind increased, and decreased as the total basal area in species other than their own increased. This trend held for all the three oak species in both provinces.

Table 5.1. Relationship between advance regeneration abundance and basal area of overstory tree species (OT: other species not of its own kind). “0” means no significant association, “+” means positive association, and “-” means negative association between advance regeneration abundance and basal area of overstory trees (* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$).

| Physiographic Provinces | Regeneration Species | Association with Overstory Species | | | |
|---|---|---|---|---|---|
| | | White Oak | Chestnut Oak | N. Red Oak | OT |
| Ridge and Valley | Red maple | 0 | -*** | -*** | 0 |
| | White oak | +*** | 0 | 0 | -*** |
| | Chestnut oak | 0 | +*** | 0 | -*** |
| | N. red oak | 0 | 0 | +*** | -** |
| Allegheny Plateau | Red maple | 0 | 0 | +*** | 0 |
| | White oak | +** | 0 | 0 | -* |
| | Chestnut oak | 0 | +*** | 0 | -* |
| | N. red oak | 0 | 0 | +*** | -* |

### *Advance regeneration abundance vs. soil types*

Surveyed plots in the Ridge and Valley physiographic province fell on 42 different soil types in 15 soil series and three soil associations. Six soil series and one soil association each occurred with a frequency greater than three percent and occurred on more than two stands. On the Allegheny Plateau, 32 different soil types were identified on the surveyed plots. They can be grouped into eight soil series and two soil associations. Four soil series occurred with a frequency greater than three percent and occurred on more than two stands. Properties of these major soil series are listed in Appendix D.

Regeneration abundance for different soil series is shown in Table 5.2. Since the two provinces only share one common soil series (the Hazleton series), no direct comparisons can be made between the provinces. In the Ridge and Valley province,

Table 5.2. Average cumulative height (AvgCH) and occurrence frequency (percent of plots with AvgCH >0) of four regeneration species on common soil series or associations in the Ridge and Valley and Allegheny Plateau physiographic provinces. (n – number of plots; N – number of stands)

| Physiographic Province | Soil Series or Associations | Red Maple | | White Oak | | Chestnut Oak | | N. Red Oak | |
|---|---|---|---|---|---|---|---|---|---|
| | | AvgCH (ft/milacre) | Freq. (%) | AvgCH (ft/milacre) | Freq. (%) | AvgCH (ft/milacre) | Freq. (%) | AvgCH (ft/milacre) | Freq. (%) |
| Ridge and Valley | Berks (n = 37*, N = 4) | $3.01^{d**}$ | 100 | $0.03^{b}$ | 14 | $0.09^{c}$ | 8 | $0.12^{c}$ | 59 |
| | Buchanan (n = 114, N = 12) | $8.21^{bc}$ | 100 | $1.33^{a}$ | 51 | $2.48^{b}$ | 65 | $0.66^{bc}$ | 60 |
| | Hazleton (n = 61, N = 5) | $5.57^{cd}$ | 100 | $0.03^{b}$ | 3 | $1.87^{bc}$ | 59 | $1.67^{a}$ | 72 |
| | Hazleton-Dekalb (n = 141, N = 13) | $11.92^{ab}$ | 99 | $0.35^{b}$ | 30 | $4.80^{a}$ | 79 | $0.88^{ab}$ | 79 |
| | Laidig (n = 309, N = 18) | $6.36^{cd}$ | 99 | $0.25^{b}$ | 26 | $2.02^{bc}$ | 71 | $0.49^{bc}$ | 71 |
| | Meckesville (n = 60, N = 3) | $11.07^{ab}$ | 100 | $0.01^{b}$ | 10 | $2.87^{ab}$ | 82 | $0.54^{bc}$ | 57 |
| | Ungers (n = 33, N = 3) | $12.43^{a}$ | 100 | $0.55^{b}$ | 58 | $1.71^{bc}$ | 58 | $0.42^{bc}$ | 73 |
| Allegheny Plateau | Clymer (n = 130, N = 9) | $11.34^{ab}$ | 99 | $0.02^{b}$ | 10 | $0.05^{b}$ | 12 | $3.04^{a}$ | 82 |
| | Cookport (n = 120, N = 9) | $14.69^{a}$ | 99 | $0.02^{b}$ | 13 | $0.24^{a}$ | 18 | $2.02^{a}$ | 87 |
| | Hazleton (n = 99, N = 7) | $7.26^{b}$ | 99 | $0.04^{b}$ | 8 | $0.05^{b}$ | 10 | $3.59^{a}$ | 96 |
| | Wharton (n = 54, N = 3) | $11.50^{ab}$ | 100 | $0.15^{a}$ | 33 | $0.06^{b}$ | 13 | $0.14^{b}$ | 61 |

* Statistical tests were based on plots.

** Mean cumulative height within the same column in each province not sharing same letters are significantly different at $P < 0.05$.

red maple occurred on almost all the surveyed plots. Its average cumulative height was the highest on the Ungers series, followed by the Hazleton-Dekalb association and the Meckesville series, and was the lowest on the Berks series. White oak had a low occurrence frequency overall. Although white oak occurrence frequency was the highest on the Ungers soil, its average cumulative height was significantly higher on the Buchanan soil than the other soil series. Chestnut oak regeneration had the highest average cumulative height on the Hazleton-Dekalb association, followed by the Meckesville series. It had the lowest occurrence frequency and average cumulative height on the Berks series. Northern red oak had relatively similar occurrence frequency on all the soil series. Its average cumulative height was the highest on the Hazleton series, followed by the Hazleton-Dekalb association, and had the lowest cumulative height on the Berks series. Although each species was most abundant on different soil series, all four species had their poorest regeneration on the Berks series.

On the Allegheny Plateau, red maple regeneration abundance was highest on the Cookport series, followed by the Wharton and the Clymer series. Both white oak and chestnut oak had low average cumulative height and occurrence frequency on all the soil series. White oak had some regeneration on the Wharton series, and virtually none on the other three soil series. Chestnut oak had some regeneration on the Cookport series, and virtually none on the other three soil series. Northern red oak regeneration was lowest on the Wharton series both in average cumulative height and occurrence frequency, and no significant differences of average cumulative height were found among the other soil series.

### ***Advance regeneration abundance vs. topographic factors***

Relationships between regeneration abundance and topographic factors were more complicated than other biotic or abiotic factors. Results derived from the mixed models are presented in Table 5.3 for numerical topographic variables in both physiographic provinces, and in Table 5.4 for the categorical factor slope position, in the Ridge and Valley.

Table 5.3. Relationships between advance regeneration abundance and numerical topographic factors (SL: slope percent, SH: slope shape, AX: sin$\theta$, AY: cos$\theta$, where $\theta$ is the slope aspect, EX: exposure angle, and EL: elevation) in the Ridge and Valley and Allegheny Plateau physiographic provinces. "0" means no significant association, "+" means positive association, and "-" means negative association ($p < 0.05$).

| Physiographic Provinces | Regeneration Species | Association with Topographic Factors | | | | | |
|---|---|---|---|---|---|---|---|
| | | SL | SH | AX | AY | EX | EL |
| Ridge and Valley | Red maple | 0 | 0 | 0 | + | 0 | 0 |
| | White oak | - | 0 | 0 | - | + | - |
| | Chestnut oak | + | 0 | 0 | - | 0 | 0 |
| | N. red oak | 0 | 0 | 0 | + | - | + |
| Allegheny Plateau | Red maple | 0 | 0 | 0 | + | - | + |
| | White oak | 0 | + | 0 | - | 0 | 0 |
| | Chestnut oak | + | 0 | 0 | 0 | 0 | 0 |
| | N. red oak | 0 | 0 | - | 0 | 0 | 0 |

In the Ridge and Valley, red maple regeneration was most abundant on bottoms or lower slopes with a north-facing aspect (positive association with cos $\theta$). Abundant white oak regeneration was associated with the low elevation, valley bottom gentle slopes with a south facing aspect. Abundant chestnut oak regeneration was also associated with south-facing slopes, but it was more commonly associated with steep slopes and upper slope position. Northern red oak was found more abundant on the north-facing slope with a relative small exposure angle, and was more commonly associated with high elevation ridge top, upper slope positions, or benches.

On the Plateau region, red maple regeneration was more commonly associated with north-facing slopes, small exposure angles, and high elevations. Abundant white oak regeneration was associated with concave slope shape and a south-facing slope aspect. Chestnut oak regeneration was more abundant on steeper slopes, and northern red oak regeneration was more abundant on west-facing slopes. Although different association patterns were identified across provinces, they still share some similarity. In both provinces, red maple positively associated with north-facing slopes, white oak positively associated with south-facing slopes, and chestnut oak positively associated with steeper slope percents.

Table 5.4. Regeneration abundance of red maple, white oak, chestnut oak, and northern red oak on different slope position (1: ridge top, 2: upper slope, 3: mid slope, 4: lower slope, 5: bench, and 7: bottom) in the Ridge and Valley physiographic province.

| Slope | Average Cumulative Height (ft/milacre) | | | |
|---|---|---|---|---|
| Position | Red Maple | White Oak | Chestnut Oak | N. Red Oak |
| 1 (n = 79) | 7.72 $^{b*}$ | 0.00 $^{c}$ | 0.38 $^{c}$ | 1.22 $^{ab}$ |
| 2 (n = 130) | 5.36 $^{b}$ | 0.12 $^{c}$ | 4.65 $^{a}$ | 1.43 $^{a}$ |
| 3 (n = 401) | 7.40 $^{b}$ | 0.78 $^{b}$ | 2.13 $^{bc}$ | 0.34 $^{c}$ |
| 4 (n = 126) | 11.15 $^{a}$ | 0.51 $^{bc}$ | 2.89 $^{b}$ | 0.22 $^{c}$ |
| 5 (n = 77) | 11.05 $^{a}$ | 0.53 $^{bc}$ | 1.54 $^{bc}$ | 1.15 $^{ab}$ |
| 7 (n = 45) | 12.37 $^{a}$ | 2.44 $^{a}$ | 1.44 $^{bc}$ | 0.96 $^{b}$ |

* Mean cumulative height within the same column not sharing same letters are significantly different at $P < 0.05$.

### *Full model of advance regeneration with biotic and abiotic factors*

Biotic and abiotic factors included in the full models for red maple and three oak species are listed in Table 5.5. Full models provide a comprehensive view of the association between regeneration abundance and biotic and abiotic factors. Full models for the three oak regeneration species were relatively similar among the species and between the two physiographic provinces. Regardless of provinces, oak regeneration was favored by the abundance of overstory trees of its own kind and was significantly related to soil series. Models for red maple regeneration were least consistent, except that in both regions red maple decreased in abundance as mountain-laurel cover increased.

In the Ridge and Valley region, slope aspect and position were the other two factors that had significant associations with regeneration abundance, except slope position for white oak. Both chestnut oak and northern red oak abundance decreased as the total basal area for species not of their own kind increased. Chestnut oak regeneration abundance was positively associated with huckleberry cover classes.

Models for the Allegheny Plateau were relatively simpler than for the Ridge and Valley region. Regeneration of three species was favored by the abundance of overstory trees of its own kind, but not significantly influenced by of its own kind. Soil was the only abiotic factor that was significantly association with the regeneration abundance of chestnut oak and northern red oak.

Table 5.5. Biotic and abiotic factors (non-tree vegetation cover [GABA: huckleberry, VACC: blueberry, KALA: mountain-laurel, and HAYS: hayscented fern], basal area of mature overstory trees [BAQA: white oak basal area, BAQM: chestnut oak basal area, BAQR: northern red oak basal area, and BAOT: basal area of trees not of its own species]), soil series or association [SS], and topographic factors [PO: slope position, SL: slope percent, SH: slope shape, AX: sin $\theta$, AY: cos $\theta$, where $\theta$ is the slope aspect, EX: exposure angle, and EL: elevation]) that significantly associated with regeneration abundance of red maple, white oak, chestnut oak, and northern red oak ($p < 0.05$). (For numerical factors, "+" means positive association and "-" means negative association)

| Physiographic Provinces | Regeneration Species | Influential Factors (p <0.05) | |
|---|---|---|---|
| | | Biotic | Abiotic |
| Ridge and Valley | Red maple | KALA, VACC | SS, AY $^+$, PO |
| | White oak | BAQA $^+$ | SS, AY $^-$, SL$^-$ |
| | Chestnut oak | BAQM $^+$, BAOT $^-$, GABA, KALA | SS, AY $^-$, PO |
| | N. red oak | BAQR $^+$, BAOT $^-$ | SS, AY $^+$, PO, EL$^+$ |
| Allegheny Plateau | Red maple | KALA, HAYS | EX $^-$, EL$^+$ |
| | White oak | BAQA $^+$ | SS, SH $^+$ |
| | Chestnut oak | BAQM $^+$, GABA | SS |
| | N. red oak | BAQR $^+$, HAYS, KALA | SS |

## Discussion

As the causes of oak regeneration failure vary from species to species and from region to region, the association between tree regeneration and biotic and abiotic factors also varied from species to species and region to region. Non-tree vegetation had a significant influence on tree regeneration for most species in both provinces. Plots with moderate blueberry and huckleberry cover had the highest or second highest white oak regeneration abundance, and plots with heavy huckleberry cover and moderate blueberry cover had the highest chestnut oak regeneration abundance in both regions. The result matches the former findings that good white oak and chestnut oak regeneration was normally associated with blueberry and huckleberry cover (Bowersox 1972, Northrup 2003). Rogers (1974) pointed out that heath communities dominated by blueberry and huckleberry have an affinity for infertile sites with well-drained acidic soils. The affinity of some oaks for similar environmental conditions may at least partially explain why regeneration of white oak and chestnut oak was associated with blueberry and huckleberry. Blueberry and huckleberry cover had an average height of about two feet on our surveyed plots. Moderate to heavy cover of this low shrub layer might have reduced deer predation on acorns and small seedlings facilitating the establishment of oak regeneration.

Regeneration of all species was inhibited to some degree by the presence of moderate to heavy cover of mountain-laurel and hayscented fern. This trend did not hold for white oak regeneration on the Allegheny Plateau, because white oak regeneration on the Plateau is virtually non-existent. Competition from hayscented fern has been identified as an important factor contributing to the regeneration problem in Pennsylvania (McWilliams et al. 1995), and Steiner and Joyce (1999) demonstrated that oak seedlings would not grow through hayscented fern with a forest overstory even when protected from deer browsing. Hayscented fern in mixed-oak forest understories appears to suppress desirable tree seedlings by decreasing light quantity and quality beneath the herbaceous layer (Horsley 1993, George and Bazzaz 1999). Hayscented fern has been classified as a competitor species because of its ability to respond aggressively to sudden resource availability with vegetative expansion through rhizomes and sexual reproduction (Groninger and McCormick 1991, Hughes and Fahey 1991).

Mountain-laurel is another strong regeneration competitor because of its aggressive vegetative growth habit (Moser et al. 1996). Chapman (1950) reported that light levels underneath mountain-laurel canopies may only be about two percent of full sunlight. Although mountain-laurel has little effect on regeneration establishment, it does suppress the growth of small seedlings (Waterman et al. 1995). The competition from heavy cover of hayscented fern and/or mountain-laurel was so intense that even the relatively shade-tolerant red maple was greatly inhibited under these species in our study area.

The co-occurrence of northern red oak regeneration and low levels of hayscented fern and mountain-laurel is difficult to interpret. One possible explanation is that northern red oak can escape detection by deer under low fern or mountain laurel cover aiding its establishment, but neither white oak nor chestnut oak appears to be able to tolerate the competition and the shade cast by these competitive species.

The associations between overstory oak trees and understory oak regeneration were overwhelmingly consistent among the species and across the regions, even though oaks (primarily chestnut oak and northern red oak) composed more than 50 percent of the overstory basal area in every stand studied. Oak regeneration was favored by the presence of mature overstory trees of its own species within the same plot and was inhibited by other species. This association is mainly caused by the biological characteristics of oak species. Although small mammals and birds may disperse acorns long distances (Barnett 1977, Johnson and Adkisson 1986), the majority acorns merely fall to the ground and remain in the vicinity of the female parent. More adult oak trees produce more acorns, which likely germinate more oak seedlings. Another biological characteristic of oak is that their seedlings are intolerant of shade (Johnson et al. 2003), so increasing overstory crowdedness can reduce seedling establishment. Red maple fruits, on the other hand, are winged and dispersed by wind. Perhaps this explains the lack of association between red maple overstory and red maple regeneration. Red maple is a shade tolerate species (Walters and Yawney 1990), which helps it to establish regardless canopy density.

All four species had the least abundant regeneration on the Berks series in the Ridge and Valley. The Berks soil series consists of moderately deep soils that formed in shale and siltstone residuum with very low available water capacity (USDA 1993). Compared to the other six major soil series in the Ridge and Valley, the Berks series has the poorest available water capacity, and this may explains why all four species had the poorest regeneration on that series.

In the Ridge and Valley region, white oak regeneration abundance was significantly higher on the Buchanan series than elsewhere. The Buchanan series consists of deep, moderately well-drained soils that formed in sandstone, siltstone, and shale colluvium. It is often found on lower slopes along the base of mountains and in depressions at the heads of drainage-ways in mountains (USDA 1981). This agrees with the results of the topographic factor analysis that white oak was more abundant in valley bottoms or on gentle slopes. Similar results were also found by Honeycutt et al. (1982) in Eastern Kentucky where white oak grows best on the lower third of the slope position on soils with high nitrogen content. Chestnut oak was most abundant on the Hazleton-Dekalb association in the Ridge and Valley. Hazleton-Dekalb soils are characterized by steep slopes with stony surface (3 to 50 percent stone cover). This association between chestnut oak regeneration and Hazleton-Dekalb soil matches the results of the topographic factor analysis that chestnut oak is commonly associated with a steep, upper-slope position, where stony surfaces are common. This result agrees with the McQuilkin (1990) who described chestnut oak as occurring typically on dry upland sites such as ridge tops and upper slopes with shallow soils, south- and west-facing upper slopes, and sandy or rocky soils with low moisture-holding capacity. Because of the low occurrence of white oak and chestnut oak regeneration on the Plateau sites, associations of white oak and chestnut oak regeneration and soil series on the Allegheny Plateau are not straightforward to interpret.

Northern red oak had advance regeneration in greatest abundance on the Hazleton soils both in the Ridge and Valley and on the Allegheny Plateau. The Hazleton soil belongs to the loamy-skeletal soil family and has low to moderate available water capacity (USDA 1981, 1993). No clear explanation can be provided for the association between Hazleton soil and northern red oak regeneration. Red maple has relatively abundant regeneration on almost every soil series except the Berks series. One possible explanation of why red maple regenerates well on a variety of soil types is that red maple has low resource requirements and is a "super-generalist" that has characteristics of both early and late successional species (Abrams 1998).

As mentioned above, topographic factors and soil play important roles in the regeneration process. Although different factors were included in these models, they convey similar information. Low slope positions, gentle slopes, and low elevations are characteristics of the valley floor and are favored by white oak. South-facing slopes, large exposure angles, and concave slope shapes mean dry and sunny conditions and also are favored by white oak. Abundant chestnut oak regeneration was associated with south-facing and relatively steep upper slopes, while northern red oak was associated with moist, north-facing slopes. Although red maple regeneration can be found on any site, it was more often associated with moist north-facing slopes.

Since some factors are more influential than others, and some factors are interrelated with and can be presented through others, not all the resulting significant factors in the partial models were entered into the final full models. Soil series was definitely a factor influencing tree regeneration. It was significant in all models for all the species in both regions, except red maple on the Allegheny Plateau. Overstory composition was the other influential factor for oak regeneration. The more the overstory trees were of its own kind, the higher was the oak regeneration abundance. Different non-tree vegetation species had different associations with tree regeneration. The presence of huckleberry positively associated with chestnut oak regeneration abundance, while the dense cover of mountain-laurel and hayscented fern negatively associated with the regeneration of all species. Topographic factors such as slope position and aspect also greatly influenced regeneration abundance.

Obviously, some other factors such as deer browsing, seed crop fluctuation, and climatic stochastic variation are also very important to tree regeneration. These factors might completely change the regeneration patterns. Unfortunately, we do not have information available for these factors. Therefore, we need be careful when apply the above results to field management, and should compromise these results with other important factors if available. Nevertheless, this study provides regional specific knowledge of the biotic and abiotic advantages and limitations for tree regeneration.

In conclusion, red maple was commonly associated with moist north-facing slopes with no or low cover of mountain-laurel and hayscented fern. Regeneration of all three oak species was positively associated with the abundance of overstory trees of their own kind. White oak regeneration was most abundant on the south-facing gentle lower slope with the Buchanan soil series. Chestnut oak was more abundant on south-facing steep upper slopes with stony soils. It also positively associates with the huckleberry cover classes. In contrast to white oak and chestnut oak, northern red oak was more abundant on the north-facing moist site with loamy-skeletal soil and was commonly associated with low cover of mountain-laurel or hayscented fern.

# Chapter 6

# Early Stump Sprout Development in Regenerating Mixed-Oak Forests

*Life is like a box of chocolates; you never know what you're going to get.*

Forrest Gump

***Abstract:*** Stump sprouts play an important ecological and economic role in mixed-oak forest regeneration processes in the central Appalachians. The objectives of this study were to understand early stage stump sprout development and to investigate potential mechanisms associated with red maple and oak stump sprouts. Sprouting probability was high for red maple (92 percent), and moderate for oak species (48 to 72 percent) except white oak, which sprouted poorly (33 percent). Sprouting probabilities for all non-oak species were not significantly influenced by stump age or diameter. In contrast, sprouting probabilities for all oak species were significantly influenced by stump age and/or stump diameter. Survival probabilities were high for all species, and the differences between species were insignificant, except that blackgum had lower survival probability than other species. On average, red maple produced the tallest dominant sprouts, the largest number of sprouts per stump, and the largest sprout crown diameter among all the species. Among the oak species, white oak had the least number of stems per stump, the lowest height of dominant sprouts, and the smallest crown size. A potential strategy to reserve future growing space early in the development stage was discovered for red maple. For a stand with a typical overstory composition, the percentage of canopy occupied by sprouts was 18.4 for red maple and smaller than five for all oaks combined. Relatively high frequency in the overstory, high probability of sprouting and

survival, and fast height growth make red maple stump sprouts highly competitive in regenerating mixed-oak stands.

## Introduction

Stump sprouts have long been an important source of tree regeneration after harvest in central hardwood forest (Smith 1986, Martin and Tritton 1991). Stump sprouts can be an important source of regeneration because they can easily outgrow competition and avoid other difficulties associated with the more limited site resources available to smaller, seed-origin regeneration (Johnson et al. 2002). Large amounts of research have been devoted to factors affecting stump sprouting potential and sprout growth and mortality. Stump sprouting potential may be related to parent tree diameter and age, site quality, and/or season of cutting (Solomon and Blum 1967, Johnson 1977, Miller and Phillips 1984, Weigel and Johnson, 1998), and sprout mortality and growth rate may be influenced by stump diameter and age and site quality (McIntyre 1936, Johnson 1977, Ross et al. 1986, Dey 1991).

Research attention has been attracted to the development of oak (*Quercus* spp.) stump sprouts because natural oak regeneration is hard to obtain throughout the central hardwood region, even when oak is the major component in the overstory before harvest (Abrams 1992, Crow 1988). Although red maple (*Acer rubrum* L.) is becoming an important forest component in much of the central hardwood forest region, less attention has been paid to red maple stump sprout development. One-third of the red maple trees had originated from stump sprouts in even-aged stands in Lower Michigan (Sakai et al. 1985), and red maple stump sprouts can be highly competitive (Palik and Pregitzer 1992). Because interspecific competition is thought to be a primary factor responsible for the reduced ability of oak regeneration (Crow 1988, Lorimer 1993), a better understanding is needed of the relative role of red maple sprouts and oak sprouts in the regeneration process after harvest. In this chapter, stump sprouts of major oak and non-oak species from one, four, five, and twenty years after harvest were examined to understand their sprout probability, survivorship, growth rate, and space occupancy.

## Methodology

### *Data collection*

Three sets of data were used to develop this chapter. The first data set is from the Pennsylvania Oak Regeneration Assessment Project (see Chapter 2). Stump measurements were collected on 28 harvested mixed-oak stands in the central Appalachians. All 28 stands were measured one growing season after harvest, 11 of the 28 stands were re-measured four years after harvest, and 8 of the 11 stands were measured again five years after harvest. Depending on stand size, 15 to 30 permanent plots with a radius of 26.3 ft (0.05 acres) were systematically installed in a square grid to represent the whole stand. Four permanent subplots with a radius of 3.72 ft (0.001 acre) were established within each plot at a fixed distance from plot center. For each subplot, the stump closest to the subplot center was selected and the same stump was relocated in the sequential surveys. Species, stump diameter (average of the longest and shortest axes), stump height, and stump age (age of the tree at the time of harvest) were recorded. If the stump had sprouted, the number of sprouts along with the height and basal diameter of the dominant sprout were also recorded. A single sprout was defined as a separate, vertical stem arising directly from the stump and forking no higher than two inches from its origin. Site index and month of harvest of each stand were also recorded.

The second and third data sets include stump information collected from four- to six-year-old and approximate twenty-year-old mixed-oak stands, respectively. Six stands were included in the second data set and nine stands were in the third data set. Transects instead of fixed plots were used to collect stump data. Species, number of sprouts, height and DBH of the dominant sprout, and crown diameter were recorded for stumps included in the second data set, and species, number of sprouts, DBH of each sprout, and crown diameter were recorded for stumps included in the third data set. In order to have a better crown size estimation, crown diameters were measured in four directions: longest dimensions of the crown, and 45, 90, and 135 degrees off the longest dimension through the center.

### *Data analysis*

Analyses were focused on the three most abundant non-oak species (red maple, black birch [*Betula lenta* L.], and blackgum [*Nyssa sylvatica* Marsh]) and the four most abundant oak species (white oak [*Quercus alba* L.], chestnut oak [*Q. montana* Willd.], northern red oak [*Q. rubra* L.], and black oak [*Q. velutina* Lam.]). Percentage of stumps with one or more sprouts one year after harvest and survival probability four years and five years after harvest for each stand were summarized by species for each stand. Average sprouting frequency and survival percentages were then calculated by species using stands that had at least five stumps of a given species. Logistic regression was used to analyze the relationships between sprouting percentage and stump diameter, stump age, time of harvest, and site index. Analysis of variance was carried out to evaluate the differences among means of different species.

The average number of sprouts per stump and mean height and basal diameter of the dominant sprout were calculated for each species one, four, and five years after harvest. Height and basal diameter yearly relative growth rate between one and four years after harvest were calculated based on data from the 11 stands that have been measured through four years after harvest, and the relative growth rates between four and five years were calculated based on data from the 8 stands that have been measured through five years after harvest. Relationships between height of the dominant sprout and total crown diameter of the four- to six-year-old sprouts were analyzed using linear regression. Crown area was calculated for each species at age twenty.

Lastly, stump sprouting cover percentages by species were estimated for a hypothetical stand. Average densities of overstory species derived from Chapter 3 were used to represent the overstory composition of an average stand before harvest. Density of sprouts after harvest was then calculated for each species by multiplying overstory density by sprouting probability and survival probability. Based on the relationship between height of the dominant sprout and crown area, crown areas were estimated for sprouts with average height four or five years after harvest. Total crown area for each species then derived by multiplying sprout density by average crown area.

## Results

### *Stump sprouting probability*

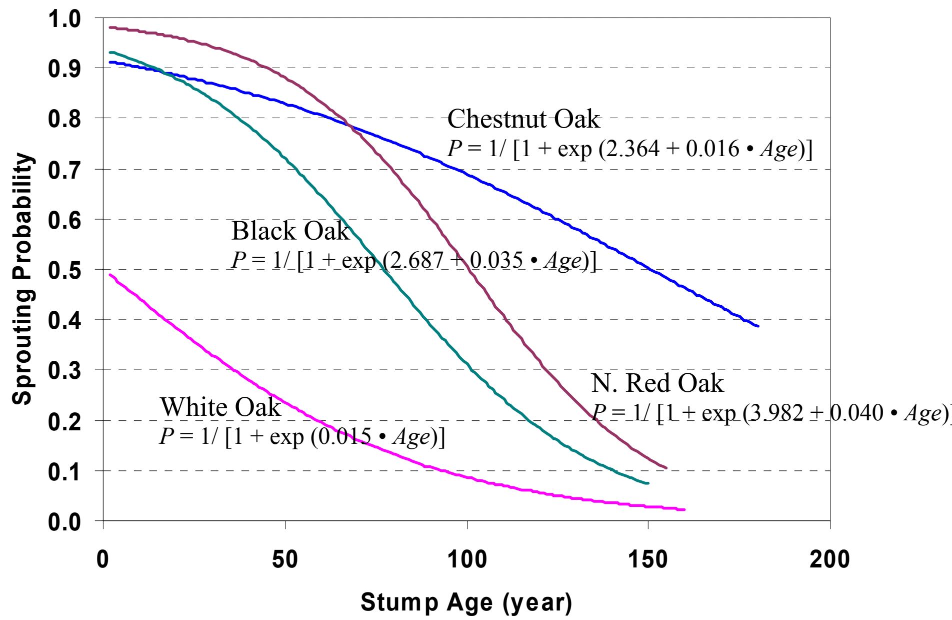
Average sprouting frequencies one year after harvest are shown in Table 6.1. Red maple had the highest sprouting frequency (92 percent), and blackgum had the second highest stump sprouting frequency (84 percent). Among the four oak species, chestnut oak sprouting frequency was the highest (72 percent), followed by northern red oak (59 percent) and black oak (48 percent). Average sprouting frequency for black birch and white oak were the lowest among all the species (34 and 33 percent, respectively).

Table 6.1. Sprouting frequency one year (01) after overstory removal, and sprout survival probability, relative height growth rate (RHGR), and relative basal diameter growth rate (RBGR) of the dominant sprout between one and four years (04) and between four and five years (05) after harvest.

| Species | Sprouting Prob. (%) | Survival Prob. (%) | | RHGR ($year^{-1}$) | | RBGR ($year^{-1}$) | |
|---|---|---|---|---|---|---|---|
| | 01 | 01-04 | 04-05 | 01-04 | 04-05 | 01-04 | 04-05 |
| Red maple | 92 [a*] | 90 [a] | 98 [a] | 1.32 [a] | 1.27 [a] | 1.34 [ab] | 1.18 [a] |
| Black birch | 34 [e] | - | - | - | - | - | - |
| Blackgum | 84 [ab] | 77 [b] | - | 1.36 [a] | - | 1.38 [ab] | - |
| White oak | 33 [e] | 80 [ab] | 91 [a] | 1.28 [a] | 1.26 [a] | 1.32 [b] | 1.40 [a] |
| Chestnut oak | 72 [bc] | 96 [a] | 96 [a] | 1.36 [a] | 1.20 [a] | 1.39 [ab] | 1.57 [a] |
| N. red oak | 59 [cd] | 86 [ab] | 100 [a] | 1.30 [a] | 1.26 [a] | 1.34 [ab] | 1.09 [a] |
| Black oak | 48 [de] | 82 [ab] | - | 1.37 [a] | - | 1.43 [a] | - |

* Means in the same column not sharing the same letter are significantly different from each other at $p < 0.05$.

There was no correlation between sprouting probability and site index or harvest time. Results of logistic regressions indicated that neither stump diameter nor stump age had a significant influence on sprouting probability of any non-oak species. However, significant relationships ($p < 0.01$) were found between stump age and sprouting probability for all oak species, and between stump diameter and sprouting probability for white oak, chestnut oak, and black oak (Figure 6.1). Chestnut oak,



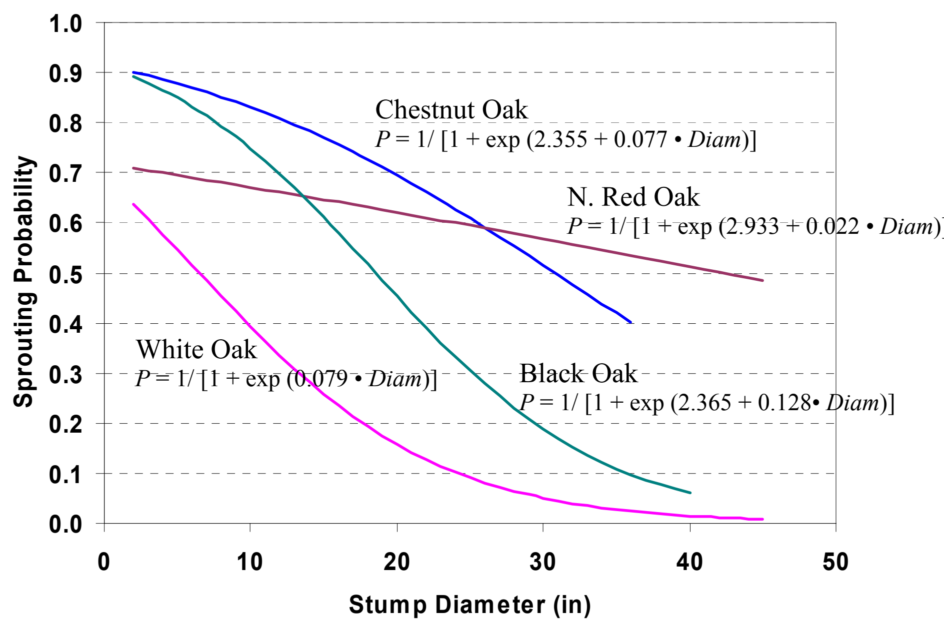




Figure 6.1. Estimated sprouting probability (*P*, the probability that a stump will have at least one living sprout one year after harvest) in relation to stump age (*Age*) and stump diameter (*Diam*). Relationships between sprouting probability and stump age and stump diameter were all significant ($p < 0.01$), except northern red oak sprouting probability with stump diameter.

northern red oak, and black oak had similar sprouting probabilities if the trees from whose stumps the sprouts originated were young, but northern red oak and black oak had reduced their sprouting probabilities quickly as stump age increased and declined to only about 10 percent at age 150. Chestnut oak still had about 50 percent sprouting probability at age 150. White oak had the lowest sprouting probability at all stump ages compared to other oak species. It had almost no sprouting probability at age 150. Among chestnut oak, black oak, and white oak, chestnut oak always had the highest sprouting probability if stump diameters of the three species were the same. Both black oak and white oak had less than 10 percent sprouting probability when the stump diameter reached 40 inches. The relationship between northern red oak sprouting probability and stump diameter was insignificant ($p > 0.05$). After using a backward stepwise selection procedure, only stump diameter or stump age was included in the final models for the four oak species. Sprouting probabilities of white oak and black oak were best predicted with stump diameter, and sprouting probabilities of chestnut oak and northern red oak were best predicted with stump age.

### *Stump sprouting development after harvest*

Number of sprouts per stump, height and basal diameter of the dominant sprout for each stump one, four, and five years after overstory removal are summarized in Tables 6.2, 6.3, and 6.4. One growing season after harvest, red maple and chestnut oak had significantly higher numbers of sprouts per stump (22 and 20, respectively) than other species after one growing season, and the number of sprouts per stump for the other species was similar (11 to 14). Chestnut oak has the largest variation in number of sprouts per stump. Mean heights for the dominant sprout for red maple, chestnut oak, northern red oak, and black oak were not significantly different after one growing season; however, mean height for red maple was the tallest (4.1 ft). Mean height for white oak dominant sprouts (2.4 ft) was significantly lower than for other oak species. Mean basal diameter for the dominant sprout of red maple, chestnut oak, northern red oak, and black oak were not significantly different after one growing season; black oak on average had the largest basal diameter (0.5 in). White oak had the smallest basal diameter (0.3 in) among all the oak species. On average, black birch stumps had the lowest number of sprouts per stump (11) and smallest dominant sprout both in height (2.6 ft) and in basal diameter (0.2 in) after one growing season.

Table 6.2. Average number of sprouts per stump and average height and basal diameter of the dominant sprout per stump after one growing season by species.

| | | Total Sprouts per stump | | Dom. Ht (feet) | | Dom. Ba. Diam.(inch) | |
|---|---|---|---|---|---|---|---|
| **Species** | | **AVG.** | **StDev** | **AVG.** | **StDev** | **AVG.** | **StDev** |
| Red maple | (n = 744) | 21.9 [a] | 18.3 | 4.1 [a] | 3.0 | 0.45 [ab] | 0.30 |
| Black birch | (n = 16) | 10.7 [b] | 12.7 | 2.6 [c] | 2.8 | 0.21 [d] | 0.13 |
| Blackgum | (n = 152) | 10.6 [b] | 10.5 | 3.0 [bc] | 2.0 | 0.35 [bc] | 0.21 |
| White oak | (n = 48) | 13.2 [b] | 12.8 | 2.4 [c] | 1.5 | 0.28 [cd] | 0.18 |
| Chestnut oak | (n = 358) | 20.7 [a] | 20.6 | 3.9 [ab] | 2.4 | 0.45 [ab] | 0.28 |
| N. red oak | (n = 201) | 14.2 [b] | 16.9 | 3.7 [ab] | 2.2 | 0.42 [ab] | 0.24 |
| Black oak | (n = 59) | 12.2 [b] | 12.3 | 3.9 [ab] | 2.4 | 0.46 [a] | 0.26 |

Table 6.3. Average number of sprouts per stump and average height and basal diameter of the dominant sprout per stump after four growing seasons by species.

| **Species** | | Total Sprouts per stump | | Dom. Ht (feet) | | Dom. Ba. Diam.(inch) | |
|---|---|---|---|---|---|---|---|
| | | **AVG.** | **StDev** | **AVG.** | **StDev** | **AVG.** | **StDev** |
| Red maple | (n = 246) | 16.9 [a] | 10.0 | 13.8 [a] | 4.5 | 1.49 [b] | 0.58 |
| Blackgum | (n = 53) | 8.7 [c] | 5.5 | 9.0 [c] | 4.6 | 1.09 [cd] | 0.63 |
| White oak | (n = 12) | 8.6 [c] | 6.5 | 7.0 [d] | 3.3 | 0.83 [d] | 0.49 |
| Chestnut oak | (n = 176) | 13.2 [ab] | 8.2 | 10.9 [bc] | 4.5 | 1.42 [b] | 0.69 |
| N. red oak | (n = 76) | 13.7 [a] | 8.3 | 11.2 [b] | 3.6 | 1.37 [bc] | 0.52 |
| Black oak | (n = 27) | 9.3 [bc] | 4.9 | 12.2 [ab] | 3.8 | 1.77 [a] | 0.71 |

Table 6.4. Average number of sprouts per stump and average height and basal diameter of the dominant sprout per stump after five growing seasons by species.

| **Species** | | Total Sprouts per stump | | Dom. Ht (feet) | | Dom. Ba. Diam.(inch) | |
|---|---|---|---|---|---|---|---|
| | | **AVG.** | **StDev** | **AVG.** | **StDev** | **AVG.** | **StDev** |
| Red maple | (n = 92) | 10.2 [a] | 5.7 | 15.7 [a] | 4.1 | 1.68 [a] | 0.53 |
| White oak | (n = 10) | 4.9 [b] | 1.4 | 10.1 [c] | 2.8 | 1.40 [a] | 0.53 |
| Chestnut oak | (n = 82) | 9.4 [a] | 4.4 | 12.0 [b] | 3.4 | 1.82 [a] | 2.04 |
| N. red oak | (n = 52) | 7.8 [a] | 4.7 | 11.6 [b] | 4.4 | 1.39 [a] | 0.72 |

Four years after harvest, red maple still had the highest average number of sprouts per stump (17), followed by northern red oak (14) and chestnut oak (13). Dominant sprouts were also tallest on average for red maple (13.8 ft), and its sprouts had the second largest average basal diameter (1.5 in). Among the four oak species, chestnut oak and northern red oak typically had more sprouts per stump than the other two oak species after four growing seasons, and black oak on average had the largest dominant sprout both in height (12.2 ft) and in basal diameter (1.8 in). Compared to the other oak species, white oak stump sprouts retained its bottom position of number of sprouts per stump (9), average height (7.0 ft), and basal diameter (0.8 in). Black birch stump sprouts are not described here because there were not enough stumps surveyed four years after harvest. Average height and basal diameter for the dominant blackgum sprouts were greater than for white oak but smaller than the other three oak species.

After five growing seasons, red maple retained its leading position in average number of sprouts per stump (10) and in average height of dominant sprout (15.7 ft). Among white oak, chestnut oak, and northern red oak, chestnut oak had the largest number of sprouts per stump (9), largest dominant sprout in average height (12.0 ft) and in basal diameter (1.8 in) after five growing seasons; while white oak had the lowest means in sprouts per stump (5), dominant sprout height (10.1 ft), and dominant sprout basal diameter (1.4 in).

Sprouting survival probability and height and basal diameter relative growth rate of the dominant sprout between one and four years and between four and five years after harvest are shown in Table 6.1. Red maple had the second highest survival probability between one and four years (90 percent) and four and five years after harvest (98 percent). Blackgum had the lowest survival probability among all the species in the period of one and four years after harvest. Among all the oak species, survival probabilities were not significantly different from each other. No survival probability was calculated for black birch because not enough black birch stumps were recorded after overstory removal. Relative height growth rates of the dominant sprouts were not significantly different among the species. Basal diameter relative growth rates were not significantly different either, except between black oak and white oak in the period of one to four years after harvest.

Data for stump sprouts approximately 20 years after overstory removal are summarized in Table 6.5. On average, red maple still had the highest number of sprouts per stump (5.0), and white oak had the lowest number of sprouts per stump (1.7). Northern red oak had a significantly larger crown diameter (17.0 ft) than other species. Chestnut oak had the largest basal area per stump sprout cluster (0.49 $ft^2$) among all the species. Average crown diameter and total basal area per stump sprout cluster for red maple were relatively smaller than all the oak species 20 years after overstory removal, even though red maple retained higher number of sprouts per stump.

Table 6.5. Average number of sprouts, crown diameter, and total basal area per stump 20 years after harvest by species.

| Species | | Total Sprouts (per stump) | | Crown Diameter (feet) | | Basal Area ($feet^2$) | |
|---|---|---|---|---|---|---|---|
| | | AVG. | StDev | AVG. | StDev | AVG. | StDev |
| Red maple | (n = 30) | 5.0 [a] | 1.8 | 11.7 [b] | 3.6 | 0.36 [b] | 0.17 |
| White oak | (n = 93) | 1.7 [c] | 0.9 | 12.4 [b] | 4.9 | 0.38 [b] | 0.34 |
| Chestnut oak | (n = 146) | 2.2 [b] | 1.1 | 13.5 [b] | 5.4 | 0.49 [a] | 0.36 |
| N. red oak | (n = 114) | 2.3 [b] | 1.3 | 17.0 [a] | 5.6 | 0.46 [ab] | 0.29 |

### *Coverage of stump sprouting*

Linear regression between crown diameter and height of the dominant sprout and number of sprouts per stump was investigated for stumps four to six years old from the second data set. The relationship between crown diameter and height of the dominant sprout is plotted in Figure 6.2. Not surprisingly, crown diameter was positively correlated with the height of the dominant sprout. Coefficients of the regression of crown diameter on height for different species were not significantly different from each other ($p > 0.05$). Only northern red oak had a significant positive correlation between crown diameter and number of sprouts per stump. A generalized model for all species is as follows:

$$CD = 0.738 \cdot HT \qquad [6.1]$$

where *CD* stands for crown diameter and *HT* stands for height of the dominant sprouts. The model explains 66 percent of the variation in crown diameter.

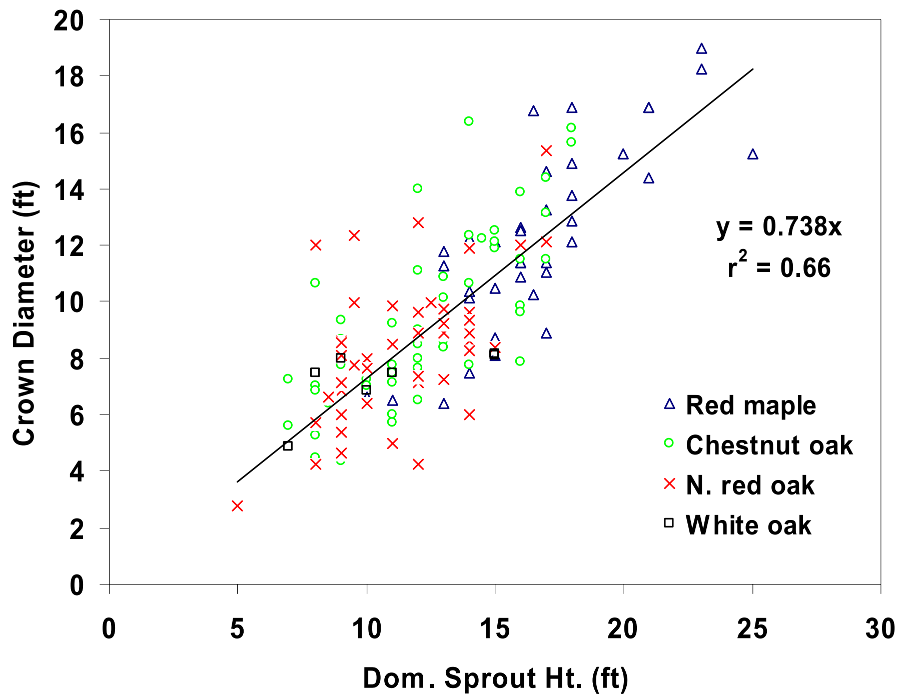



Figure 6.2. Relationships between crown diameter and height of the dominant sprout by species four to six years after harvest.

Using average overstory composition (species density and size) before harvest, sprouting and survival probabilities after harvest, average height of the dominant sprout, and the crown size and height relationship (eq. 6.5), total crown area of stump sprouts for each species was estimated at age four and age five (Table 6.6). The estimated cover percentage of red maple stump sprouts four years after harvest is 14.6 percent of the total area for a typical stand, which is much higher than the oak species. The estimated cover percentage of chestnut oak stump sprouts is highest among the oaks (2.4 percent), while covers for both white oak and northern red oak are less than two percent at age four. At age five, estimated red maple coverage increases to 18.4 percent, while all the three oak species have only a slight increase. Red maple covers 3.6 and 4.0 times more area than all the three oaks combined at age four and age five, respectively. The total basal area of an average stand is 107 $ft^2$. If assuming that percentage of crown cover of mature overstory tree is proportional to its basal area, then red maple trees cover 20.1 percent of an average stand before harvest. Therefore, five years after harvest, red maple stump sprouts can re-occupy over 90 percent of the space that have been used by their parent trees before harvest.

Table 6.6. Estimated sprouting density, crown area per stump, and total stump sprouting cover by species four (04) and five (05) years after harvest based on average overstory composition before harvest.

| Species | Pre-harvest Overstory | | Sprouting Dens. (stumps/acre) | | Crown Diam. (ft) | | Total Cover (%) | |
|---|---|---|---|---|---|---|---|---|
| | Dens. (stems/ acre) | BA ($ft^2$/acre) | 04 | 05 | 04 | 05 | 04 | 05 |
| Red maple | 94 | 22 | 78 | 76 | 10.2 | 11.6 | 14.6 | 18.4 |
| White oak | 13 | 11 | 3 | 3 | 6.7 | 7.5 | 0.3 | 0.3 |
| Chestnut oak | 30 | 23 | 21 | 20 | 8.1 | 8.9 | 2.4 | 2.8 |
| N. red oak | 21 | 29 | 11 | 11 | 8.3 | 8.6 | 1.3 | 1.4 |

Average crown diameters at age four, five, and twenty for each species are shown in Figure 6.3. Since stump size data for age four and five and for age twenty are from two different populations of stands, direct comparisons might not be appropriate. However, these crown size data at least provide some rough idea of stump sprout development patterns for different species. Red maple stumps had different crown development patterns than the three oak species. Crown diameter for red maple stump sprouts was greater than for oak species in the first several years after overstory removal, but was smaller at age twenty. The differences of crown diameters for red maple were within the one to two feet range at the three different ages used in this study, and red maple stump sprout crown diameters at age five were almost 99 percent of crown diameter at age twenty. However, crown diameters of all oak species at age five were much smaller than at age twenty. At age five, crown diameters of white oak, chestnut oak, and northern red oak stump were only 60, 65, and 50 percent of crown diameters at age twenty, respectively.

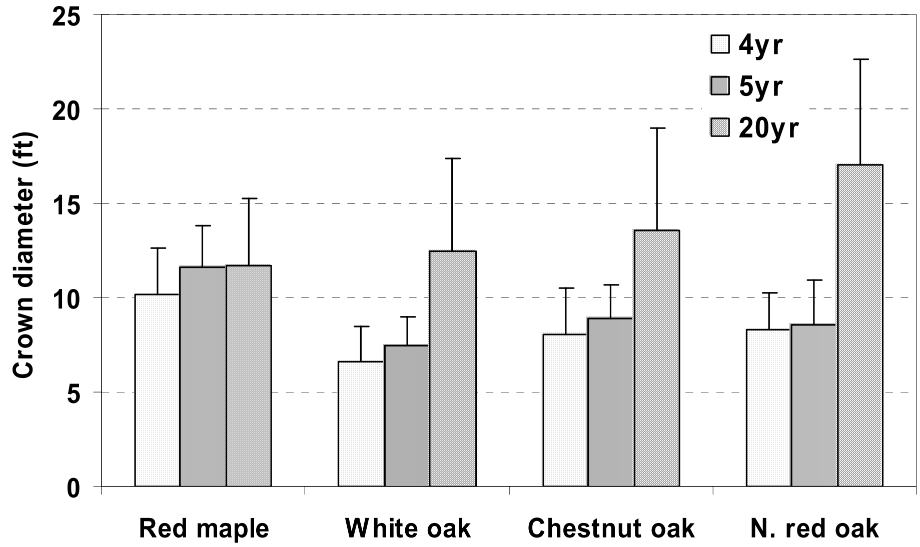



Figure 6.3. Mean and standard deviation of stump sprout crown diameter for red maple, white oak, chestnut oak, and northern red oak at age four, five, and twenty.

## Discussion

The frequency of oak stump sprouts varied by species, and was influenced by parent tree age and/or stump diameter. Young or small diameter trees were more likely produce stump sprouts. However, no significant correlation was found between the oak sprouting frequency and site quality or season of cutting. Previous studies have shown that the proportion of oak stumps that produce sprouts after trees are cut is inversely related to tree age and stump size (Roth and Hepting 1943, Church 1960, Wendel 1975, Weigel and Johnson 1998). Among the oak species, chestnut oak on average had the highest stump sprouting frequency, followed by northern red oak and black oak, and white oak stump sprouting frequency was the lowest. A similar order of stump sprouting frequency for the four oak species was reported by Weigel and Johnson (1988).

A remarkable percentage cover for red maple stump sprouts was estimated shortly after overstory removal. For a stand with a typical overstory composition before harvest, red maple stump sprouts can cover almost one-fifth of the stand area five years after a complete overstory removal, which is close to its coverage before harvest. The reasons for such a high level of coverage by red maple stump sprouts might be due to the following. Red maple has high overstory density before harvest, and it has the highest stump sprouting probability that is not significantly affected by stump age or diameter. Red maple responds to the harvest event quickly, and it has the tallest dominant sprout at least through age five. The other notable strategy for red maple is that each stump bears a large number of sprouts, which serves as a means of reserving space early in the stand development that it can continue to use as the stand develops. This space reservation strategy is clearly shown in Figure 6.3. Individual crown diameter for red maple stump sprouts at age four and five approximate crown diameter at age twenty, which indicates that red maple stump sprouts are highly effective at capturing space early in stand development and reserved enough space for future development .

Stump sprouts of all three oak species, in contrast, were not as robust as red maple at least in the first several years after overstory removal. Their stump sprouts did not display the space reservation strategy. Chestnut oak stump sprouts were most successful among all the oak species. However, because of its relatively lower overstory density, lower sprouting probability, and slower response to overstory removal than red maple, chestnut oak stump sprouts were not as dominant as red maple sprouts in the new stand. White oak stump sprouts struggled to survive. As shown in Figure 6.1, white oak sprouting probability decreased very fast as the overstory trees age and increase in size. Because white oak had the lowest overstory density, lowest average stump sprout probability, low number of sprouts per stump, and slowest growth response following overstory removal, its stump sprouts made a small contribution to the future stand.

Northern red oak stump sprouts had similar number of sprouts per stump and relative height growth rate as chestnut oak. However, since northern red oak sprouting probability was also highly influenced by stump age, its average sprouting probability was smaller than chestnut oak. Low overstory density along with low sprouting probability reduces the contribution of northern red oak stump sprouts to the new stand.

Although red maple stump sprouts had a fast response to overstory removal and had strong dominance in the first several years, this species lost its leading position 20 years after harvest with relative smaller average crown diameter and total basal area per stump compared to the oaks. Red maple had the highest number of sprouts per stump through the first 20 years of stand development. A high number of sprouts could help the clump of sprouts to occupy a large amount of space and avoid competition from other species, but it also could become a limiting factor after a certain stage of development. A high number of sprouts from the same stump can cause strong competition among the sprouts resulting in a limited amount of resources available to each individual sprout. This could be responsible for the less competitive position of red maple compared to oak stump sprouts twenty years after harvest.

In conclusion, red maple stump sprouting is a significant source of regeneration compared to stump sprouts of other species. Oak stump sprouts are not as competitive as red maple in the first several years after harvest, but they keep expanding their crown size at least through age twenty. Red maple stump sprouts captures a lot of growing space even at the early stage of stand development, which can establish their strong competitive position relative to other species. As recommend by Beck and Hooper (1986), if a larger oak component is desired, lessening competition from prolific sprouters such as red maple will be necessary.

# Chapter 7

# Development of Seed-origin Regeneration after Overstory Removal in Mixed-oak Forests

*A gigantic tree grows from a tiny shoot; a sky-high mansion rises from a handful of earth; a thousand-mile journey begins with a single step.*
(合抱之木，生于毫末；九层之台，起于累土；千里之行，始于足下)

Lao Zi (老子)
*Bible of Morals* (道德经)

***Abstract:*** Early-stage development of non-tree vegetation and seed origin regeneration are analyzed and described for 33 mixed-oak stands. Overstory removal and herbicide treatment reduced the frequency of plots with problematic heavy non-tree vegetation cover (> 30 percent). The reduction provides a "window of opportunity" for tree regeneration to establish and to grow beyond the herbaceous layer. Except for black birch, advance regeneration is the most important factor influencing regeneration abundance of most species after harvest. Small advance oak regeneration (< 1 ft) can grow into larger size classes (> 5 ft) after overstory removal. Blackgum and black birch had dramatic increases in density, occurrence frequency, and cumulative height after overstory removal, and their seedlings in a dominant position had a higher relative growth rate than other species. Red maple was the most abundant regeneration species both before and after harvest. The principal advantages of red maple regeneration are its ability to accumulate in large numbers prior to harvest and to carry these seedlings forward after overstory removal. Oak species had a slower response to overstory removal than the non-oak species in terms of cumulative height, and their seedlings in the dominant position also had a lower relative height growth rate. However both northern red oak and chestnut oak had greater increase in cumulative height growth rate between one and four years after harvest than did

red maple. Oak kept its occurrence frequency and level of dominance in cumulative height at least through four years after harvest.

## Introduction

Natural regeneration of oaks (*Quercus* spp.) is often difficult to obtain even where oaks are dominant components in the overstory before harvest. Forest managers who rely on natural regeneration to restock stands after overstory removal are often interested in controlling and manipulating the size, density, and composition of tree regeneration. Interest in methods for achieving better oak regeneration has created a need to better understand stand development after timber harvests.

Early-stage stand development is characterized by rapid tree growth and changes in species composition. The environment, growth pattern, and size of each plant change more dramatically during this stage than during any other period (Oliver and Larson 1996). Failure to obtain adequate and prompt regeneration of desired species can leave a stand unproductive for many years, cost excessive amounts to reclaim through artificial means, and severely limit the suitability of the stand for a wide range of forest values (Marquis and Twery 1992). However, monitoring and understanding early-stage stand development is difficult and challenging because young forest stands are often highly complex and exhibit seemingly unpredictable responses to a multitude of important factors.

In the mixed-oak forests in the central Appalachians, dense ground covers of blueberry (*Vaccinium* spp.), hayscented fern (*Dennstaedtia punctilobula* (Michaux) Moore), and other non-tree species can interfere with the development of oak regeneration (Allen and Bowersox 1989, Steiner and Joyce 1999, Horsley et al. 1992). Strong associations of advance regeneration abundance and non-tree vegetation were observed in Chapter 5. However, the relationship of non-tree vegetation and its influence on tree regeneration development in the early-stage stand development after overstory removal is unclear.

Observation suggests that red maple (*Acer rubrum* L.) is becoming increasingly dominant in stands that have historically been dominated by oak species, especially following harvest (Abrams 1998, Smith and Vankat 1991, Nowacki et al.

1990). Black birch (*Betula lenta* L.), also has raised some concerns because of its increasing dominance in young stands (McWilliams 2004). The reasons for these phenomena are unclear, but may involve relatively recent changes in deer densities and fire frequencies, as well as the virtual disappearance of American chestnut (*Castanea dentata* (Marsh.) Borkh) as a significant component in many of these stands (Pennsylvania Bureau of Forestry 1975). We know even less about how to manage or reverse these processes. Our understanding is in part hindered by a lack of quantitative, descriptive information about the species shift process in stands where it is occurring. The purpose of this chapter is to describe early-stage development of mixed-oak stands in the central Appalachians, where a transition to dominance by red maple and other non-oak species seems to be occurring with especial rapidity.

## Methodology

### *Data collection*

Data collected in 33 mixed-oak stands in Pennsylvania were used in this study. Depending on stand size, 15 to 30 permanent plots with a radius of 26.3 ft (20th-acre) were systematically installed in a square grid to represent the whole stand. Four permanent subplots with a radius of 3.72 ft (milacre) were established within each plot at a fixed distance from plot center. In total, 3,452 subplots were established in the study area. On each plot, species and DBH of all overstory trees (≥ 2 in in DBH) were recorded. On each subplot, non-tree vegetation cover percentage was estimated (in five percent increment) by species or species group; average height of the dominant non-tree vegetation was estimated; all tree seedlings (< 2 in in DBH) were recorded by species and height class; and one dominant oak and one dominant non-oak seedling were also recorded by species and height class. Stands were measured approximately one year before harvest (00 measurements), and re-measured one year after harvest (01 measurements). Sixteen stands were re-measured four years after harvest (04 measurements). All stands included in this study had overstory removals after the first measurement. Fencing and/or herbicide treatments were applied or planned to apply in some of the stands. Treatments were based upon the forester's management objectives for each stand and were not experimentally controlled. The primary objective of the treatments was to establish and/or release desirable regeneration. In total, 7 stands were in the fencing and herbicide treatment group, 15 stands were in the fencing treatment group, and 11 stands were in the no fencing or herbicide group. Fencing and herbicide treatments were applied between the 00 and 01 measurements.

### *Data analysis*

For each stand, average percentage cover, occurrence frequency, and heavy cover occurrence frequency (percent of plots with over 30 percent cover) were calculated for each non-tree species or species group. The four most abundant non-tree species: hayscented fern, mountain-laurel (*Kalmia latifolia* L.), blueberry, and huckleberry (*Gaylussacia baccata* (Wangh.) Koch) were included in this study. Blueberry and huckleberry, which are morphologically and functionally similar to each other, were grouped together as “low shrub” species. Linear regression models were fitted for percent cover, frequency, and heavy cover frequency between measurement periods. For example, hayscented fern occurrence frequency one year after harvest was regressed on hayscented fern occurrence frequency one year before harvest. The regression model is as follows,

$$y_{latter} = \alpha \cdot y_{former} \qquad [7.1]$$

where $y_{former}$ stands for attributes of the former measurements, $y_{latter}$ stands for attributes of subsequent measurements, and $\alpha$ is a regression coefficient. Average height and standard deviation for hayscented fern, mountain-laurel, and low shrub species were calculated at each survey period.

Regeneration development of the three most abundant oak species (northern red oak [*Q. rubra* L.], chestnut oak [*Q. montana* Willd.], and white oak [*Quercus alba* L.] and non-oak species (red maple, blackgum [*Nyssa sylvatica* Marsh], and black birch) was summarized by cumulative height. Cumulative height is defined as the total height of all the individuals of a species or species group per unit area. Linear regression models were fitted for cumulative height between measurement periods using the same model as shown in Equation 7.1. Only seed-origin regeneration was included in the analysis. In addition, three stands known to have had large acorn crops between the first and second measurements were not included in the regression analysis. In addition to cumulative height, regeneration density, regeneration size classes, and regeneration occurrence frequency were also summarized for the 16 stands that were measured four years after harvest.

Development of the dominant oak and non-oak seedling within each plot was analyzed for the 01 and 04 period of stand establishment. Only subplots with the same dominant oak and non-oak species in the two measurements were used. Total height growth and relative growth rate were calculated based on the heights of the dominant seedling on each subplot at one and four years after harvest assuming that the dominant seedlings were represented by the same plants during this period. Average absolute growth and relative growth rate were summarized by species and by the initial height class at one year after harvest.

The percentage of plots dominated by oak regeneration was calculated for each measurement period using two different criteria (cumulative height and maximum height). Cumulative height dominance was calculated as the percentage of subplots where oak cumulative height was greater than or equal to non-oak cumulative height. Maximum height dominance was calculated as the percentage of subplots where the largest stem of oak regeneration was larger than or equal to the largest stem of non-oak regeneration.

To investigate those factors affecting regeneration abundance after overstory removal a general linear model was applied using one-year-after-harvest cumulative height as the response variable. Herbicide and fencing treatment, non-tree vegetation abundance, percentage of basal area harvested, remaining basal area by species, and remaining total basal area were used as independent variables. Backward stepwise procedure was applied to find the best fit model.

## Results

### *Development of non-tree vegetation*

Different development patterns were found for hayscented fern and mountain-laurel according to whether the stands were herbicided or not (Figure 7.1). For the non-herbicided stands, average hayscented fern cover had increased only slightly

(1.04 times) one year after harvest. But its occurrence frequency had a significant increase (1.3 times). This was especially evident for those stands that had pre-harvest occurrence frequency less than 30 percent. There were seven stands that had virtually no hayscented fern before harvest, but had occurrence frequency of over 15 percent after harvest. However, the frequency of plots with over 30 percent fern cover remained almost the same before and after harvest in non-herbicided stands. For the herbicided stands, there was an obvious decrease in cover percentage, occurrence frequency, and heavy cover (>30 percent) occurrence frequency for hayscented fern. Regardless of previous coverage, average hayscented fern cover in herbicided stands was less than two percent after harvest, except one stand that had 10 percent fern cover after herbicide treatment (Appendix E). On average, occurrence frequency had a 42 percent drop, while heavy cover occurrence frequency had a dramatic 94 percent reduction.

Herbicide treatment affected average cover and heavy cover occurrence frequency reduction for mountain-laurel but not occurrence frequency. Mountain-laurel average cover decreased 65 and 77 percent one year after harvest for herbicided and un-herbicided stands, respectively. Heavy cover occurrence frequency of mountain-laurel also had a remarkable reduction. One year after harvest, average heavy cover occurrence frequency dropped 80 and 92 percent for un-herbicided and herbicided stands, respectively. However, no difference was observed between herbicided and un-herbicided stands for mountain-laurel occurrence frequency change. On average, mountain-laurel occurrence frequency dropped 11 percent one year after harvest for all the stands. Overall, mountain-laurel had the largest decrease in average cover, occurrence frequency, and heavy cover frequency among the three non-tree vegetation species or species groups one year after harvest. On average, low shrub cover decreased 31 percent, and heavy cover occurrence frequency decreased 41 percent one year after harvest compared to before harvest. Occurrence frequency remained almost the same.

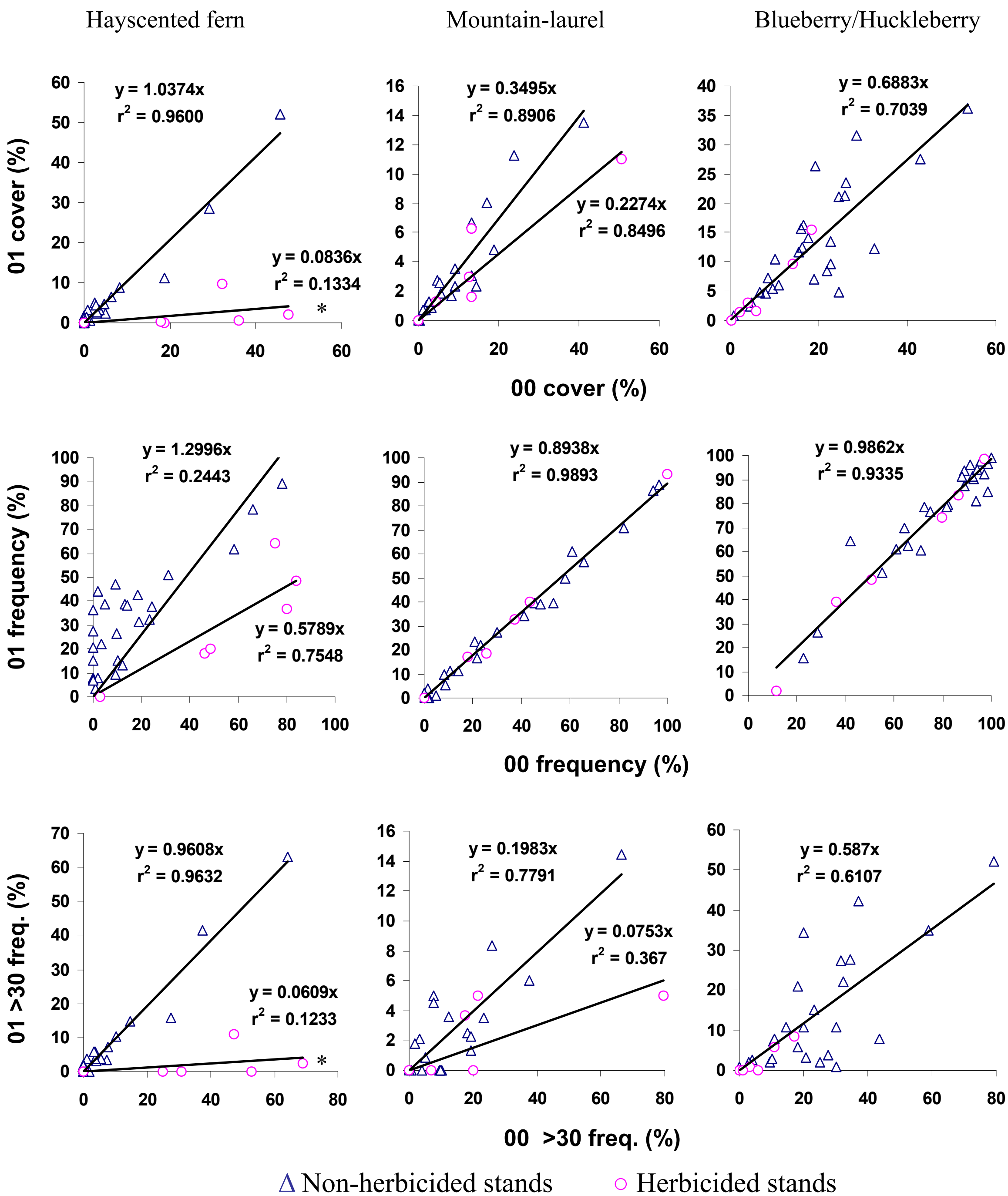



Figure 7.1. Development of average cover, occurrence frequency, and heavy cover (>30 percent) occurrence frequency of hayscented fern (left column), mountain-laurel (middle column), and low shrub species including huckleberry and blueberry (right column) before harvest (00) and one year after harvest (01) in 33 mixed-oak stands.

* Regression model is not significant ($p > 0.05$).

Development of hayscented fern was less predictable than mountain-laurel and low shrub species in the period between one- and four-year after harvest (Figure 7.2). Hayscented fern cover at year four was 0.54 times of that found at year one. However, four stands had virtually no fern at year one, but had over five percent cover at year four. Fern average occurrence frequency increased 1.23 times during this period. Except one stand, all 15 stands increased their fern occurrence frequency, which indicates fern expanded during this period, although its cover density decreased. Stands with less than 30 percent occurrence frequency had more expansion than stands that already had relatively higher occurrence frequency. Development of heavy cover occurrence frequency was similar to average cover for hayscented fern in this period.

Mountain-laurel lost cover percentage and heavy cover occurrence frequency, but slightly gained occurrence frequency in the period between one- and four-year after harvest. Its cover percentage decreased six percent, and its heavy cover occurrence frequency decreased 35 percent at the end of this period. However, the development trend for heavy cover occurrence frequency is rather weak ($r^2 = 0.076$). Its occurrence frequency had a slight gain on average (1.02 times) with a highly predictable development trend ($r^2 = 0.997$). The development pattern for the low shrub species group of blueberry and huckleberry was similar to mountain-laurel in the period between one- and four-year after harvest. At the end of this period, average cover and heavy cover occurrence lost 16 percent and 23 percent, respectively. Its occurrence frequency had a slight gain (1.04 times) with a highly predictable development trend ($r^2 = 0.971$).

Interesting development patterns were observed for non-tree vegetation height (Table 7.1). Hayscented fern increased its average height over time. It had an average height of 1.83 ft before harvest, and gained 0.17 ft one year after overstory removal. Its average height reached 2.66 four years after harvest, which is significantly taller than before and right after harvest. Mountain-laurel lost height

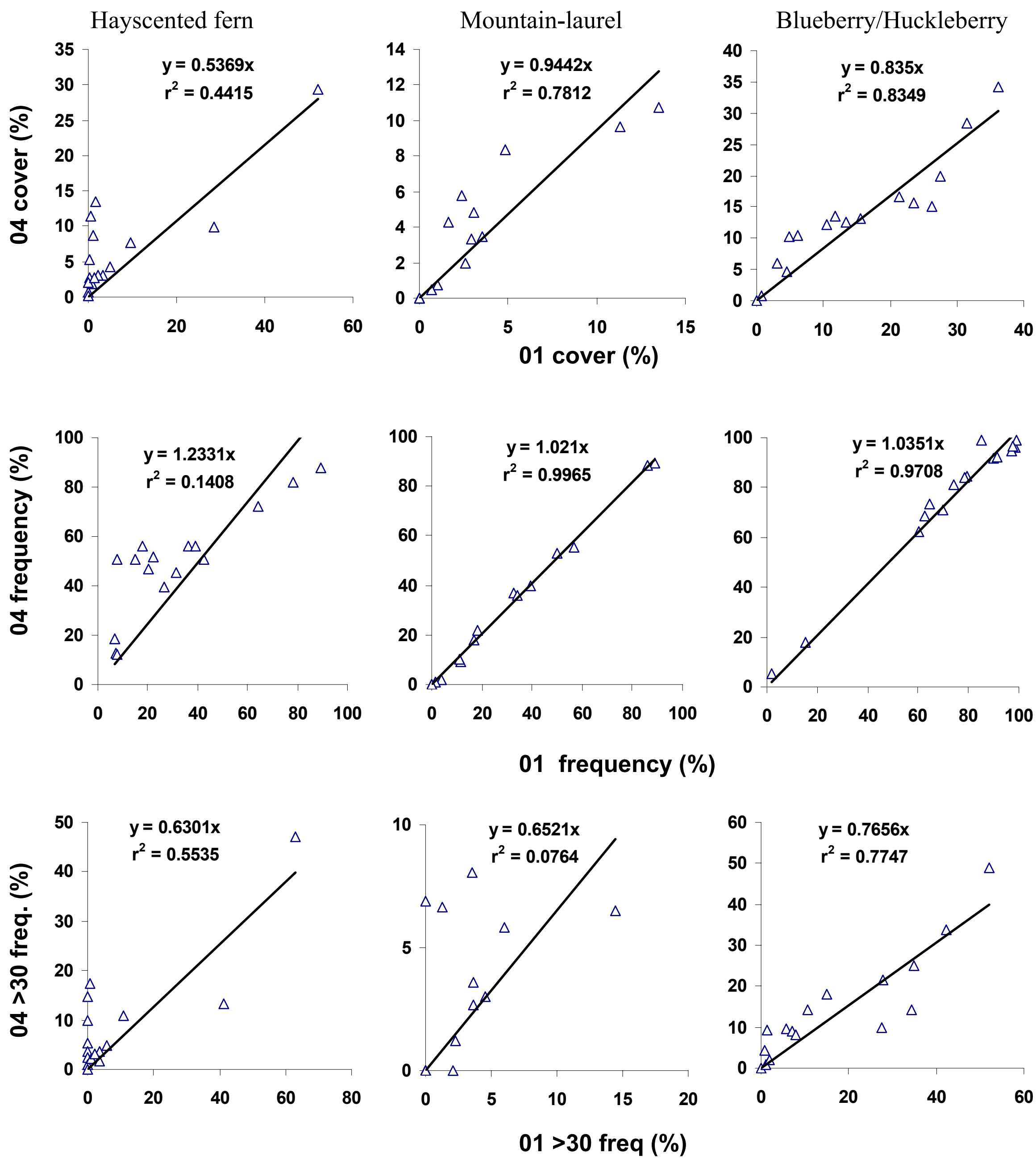



Figure 7.2. Development of average cover, occurrence frequency, and heavy cover (>30 percent) occurrence frequency of hayscented fern (left column), mountain-laurel (middle column), and low shrub including huckleberry and blueberry (right column) one (01) and four years (04) after harvest in 16 mixed-oak stands. All regression models are statistically significant ($p < 0.001$).

over time from 3.71 ft one year before harvest to 3.19 ft four years after harvest, although the change was not significant. Average height of mountain-laurel was the tallest and its variation was also the largest among the non-tree vegetation species. Low shrub species had a height similar to hayscented fern before harvest. Vegetation in this catergory gained about three inches one year after harvest, and additional one inch four years after harvest.

Table 7.1. Average height and standard deviation of hayscented fern, mountain-laurel, and low shrub species (blueberry and huckleberry) before and after overstory removal.

| Survey Time | Hayscented fern | | Mountain-laurel | | Low shrub species | |
|---|---|---|---|---|---|---|
| | Avg. Ht. (ft) | StDev | Avg. Ht. (ft) | StDev | Avg. Ht .(ft) | StDev |
| 1yr before | 1.83 [a*] | 0.38 | 3.71 [a] | 1.59 | 1.85 [a] | 0.65 |
| 1yr after | 2.00 [a] | 0.49 | 3.71 [a] | 2.04 | 2.13 [b] | 1.13 |
| 4yr after | 2.66 [b] | 0.85 | 3.19 [a] | 1.18 | 2.24 [b] | 0.89 |

*Means in the same column not sharing the same letter are significantly different at $p<0.05$.

### ***Development of seed origin regeneration***

<u>*Cumulative height*</u>

Except for black birch, cumulative height one year after harvest was correlated with advance regeneration cumulative height for all species (Figure 7.3). Red maple cumulative height one year after harvest was most predictable compared to other species ($r^2 = 0.65$). On average, its cumulative height declined by eight percent between 00 and 01 measurements. Black birch cumulative height one year after harvest was least predictable by advance regeneration. In one stand, cumulative height was only about one foot per milacre before harvest; however, it soared up to over 30 feet per milacre one year after harvest. Blackgum cumulative height had the largest increment among all the species with an increase rate of 6.03.

All three oak species had lost cumulative height by one year after harvest. On average, cumulative height for white oak, chestnut oak, and northern red oak lost 47, 39, and 22 percent, respectively, between 00 and 01 measurements. Among the three oak species, chestnut oak cumulative height was most predictable ($r^2 = 0.58$).

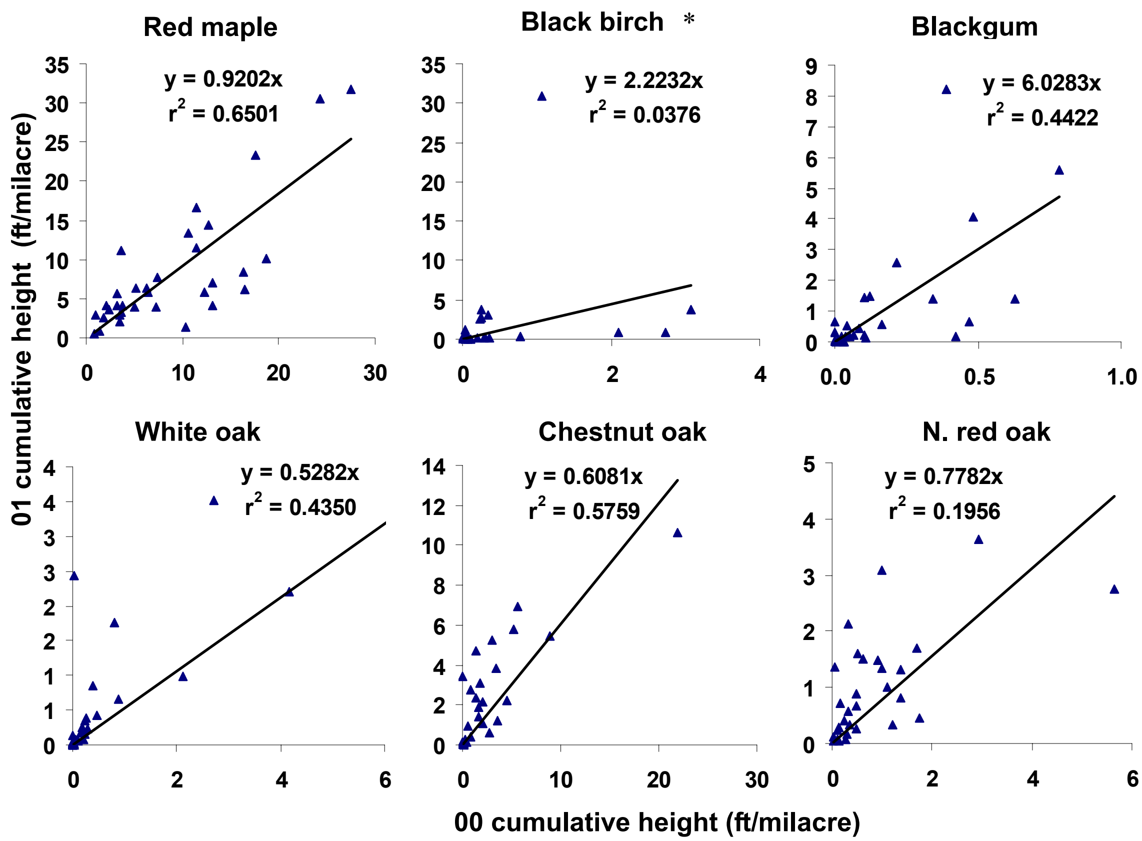



Figure 7.3. Relationship between cumulative height before (00) and one year after (01) harvest for six major regeneration species in 33 mixed-oak stands.
* Regression model is not statistically significant ($p > 0.05$)

Cumulative height four years after harvest was highly predictable based on cumulative height one year after harvest (Figure 7.4). Not surprisingly, all six species gained cumulative height during the three growing seasons. Red maple cumulative height increased 1.8 times on average, and stands with lower average red maple cumulative height one year after harvest tended to have a relatively higher rate of increment. Cumulative height for black birch increased over four-fold during this period. Its incremental rate of cumulative height was the highest among all six species during this period, but its coefficient of determination was the lowest ($r^2$ = 0.54). Blackgum cumulative height was doubled, and its coefficient of determination was the highest among the three non-oak species ($r^2$ = 0.95).

Different cumulative height incremental rates were observed for different oak species between 01 and 04 measurements (Figure 7.4). White oak had the lowest average annual increment rate during this period ($1.28^{1/3} = 1.1$), and northern red oak had the highest annual increment rate ($2.1^{1/3} = 1.28$). The average annual increment rate for chestnut oak cumulative height was about 1.24. With the coefficient of determination of 0.96, the average stand cumulative height for chestnut oak at age four could almost be perfectly predicted based on cumulative height at age one.

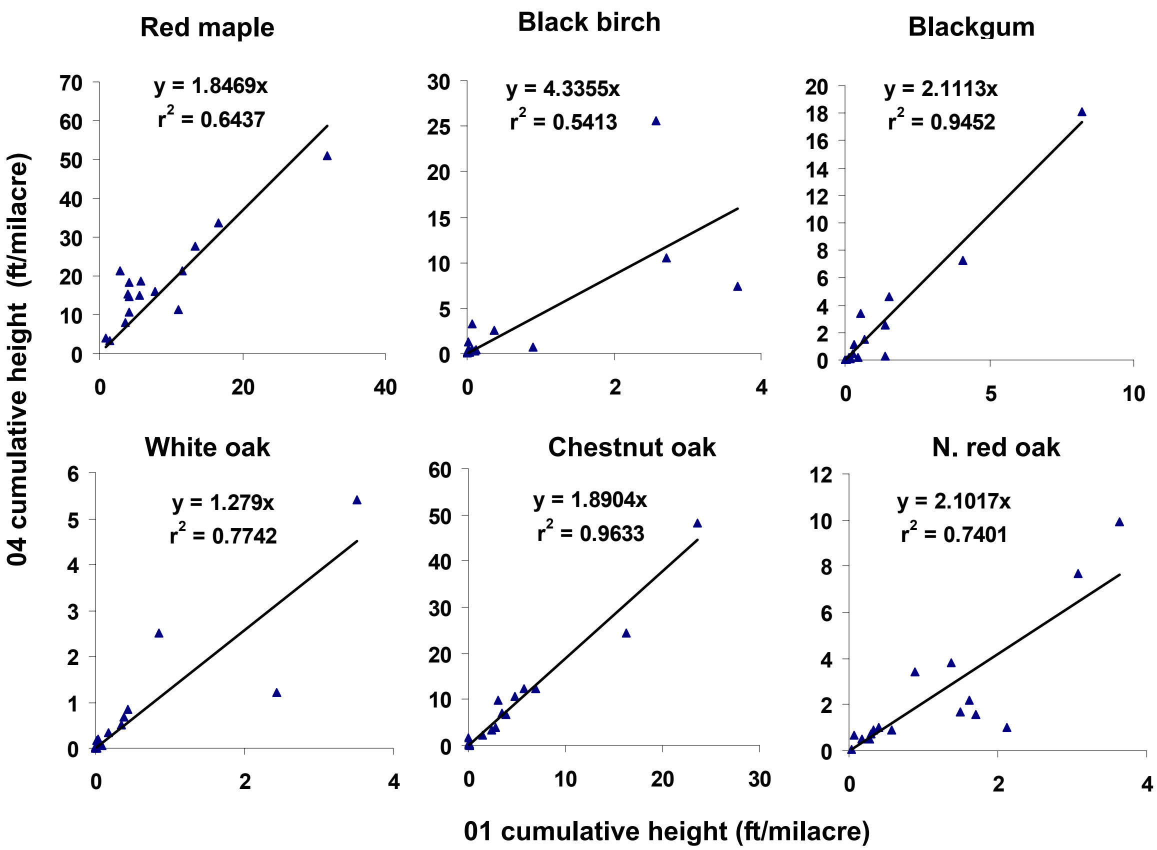



Figure 7.4. Relationship between cumulative height one (01) and four years (04) after harvest for six major regeneration species in 16 mixed-oak stands. All regression models are statistically significant ( $p < 0.001$).

*Average size and density*

Regeneration size and number of stems per acre of the three oak and non-oak species are summarized in Figure 7.5 based on 16 mixed-oak stands that had data through four years after harvest. Blackgum and black birch densities increased rapidly, reaching four-year densities five to ten times greater than before harvest densities. About 12 percent of the stems of both species had developed into the largest size class (> 5 ft) four years after harvest, despite having few large stems before harvest.

Red maple and northern red oak experienced a reduction in density in the first year after harvest, followed by a moderate recovery (Figure 7.5). The recovery is possibly due to the fact that some of these stands were shelterwoods, which provided an opportunity for new seedlings to appear. Red maple densities declined by about one-third, then recovered to about 80 percent of pre-harvest density. Northern red oak densities declined by 20 percent and recovered to a level somewhat greater than before harvest levels. Both red maple and northern red oak initially only had < 0.5 percent of their stems in the largest height class (>5 ft), but reached about four percent of seedlings in this category four years after harvest.

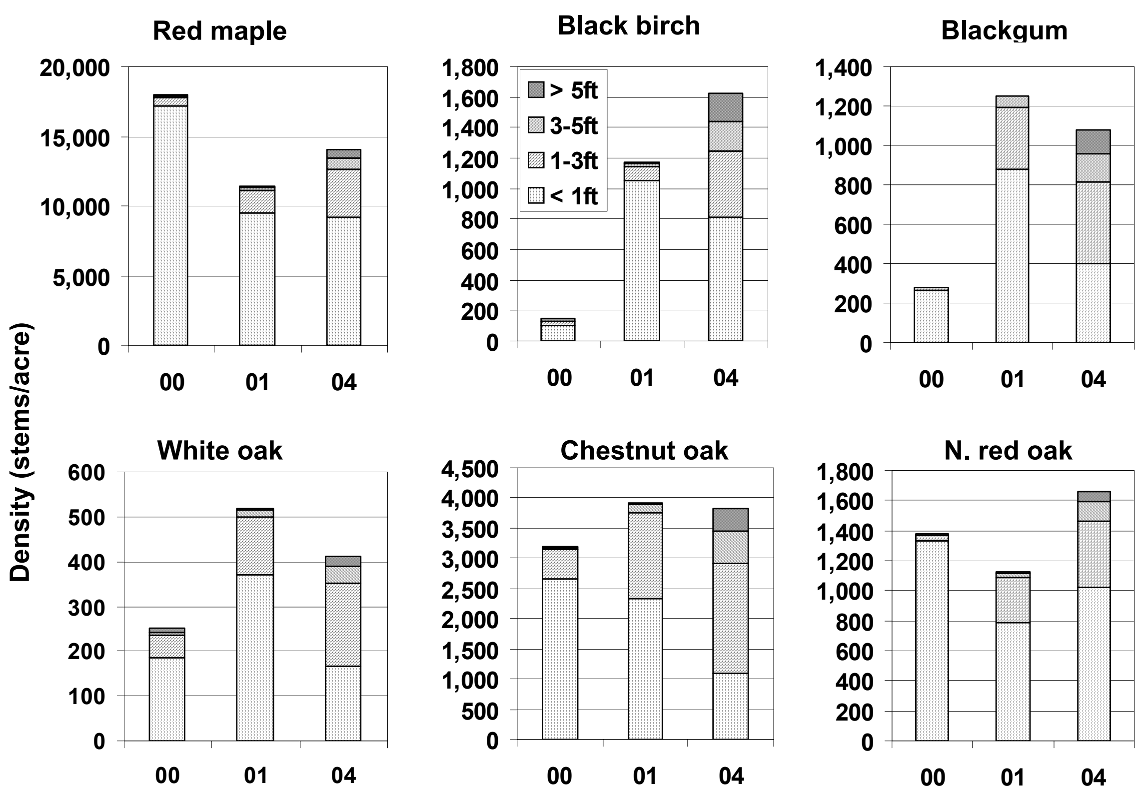



Figure 7.5. Regeneration density change from before harvest (00) to one year after harvest (01), and four years after harvest (04) by height classes for red maple, blackgum, black birch, northern red oak, white oak, and chestnut oak for 16 mixed-oak stands.

White oak and chestnut oak had gains in density one year after harvest, but densities declined four years after harvest. However, 04 densities of both species were greater than pre-harvest densities. The percentage of chestnut oaks in the largest size class increased from 0.5 percent before harvest to about 10 percent, four years after harvest. The percentage of white oaks in the largest size class remained nearly the same (around 4 percent), but the density increased.

Height development between one- and four-year after harvest for individual seedlings with dominant position indicated that seedling height growth was influenced both by its species and by its initial height. For the convenience of comparisons, both average absolute height growth and relative growth rate for the largest oak and non-oak species are presented in Figure 7.6, although they conveyed similar information. Generally, seedlings with smaller initial height one year after harvest had less absolute height growth, but had higher relative growth rate in this period. For each species, its relative growth rate somewhat converges when the initial seedling height is greater than three feet. The three non-oak species had more absolute height growth and higher relative growth rate than the three oak species. On average, black birch had the highest relative growth rate among the all the six species. Its mean annual height growth was more than doubled ($9.84^{1/3} = 2.14$) for seedlings with initial height of 2 to 6 inches. Height growth of the dominant red maple and blackgum were similar to each other. Their three year relative growth rates were between 3.9 for the smallest size class (2 to 6 in) and 2.1 for the largest size class (5 to 6 ft). On average, their height relative growth rates were smaller than black birch but larger than the oak species.

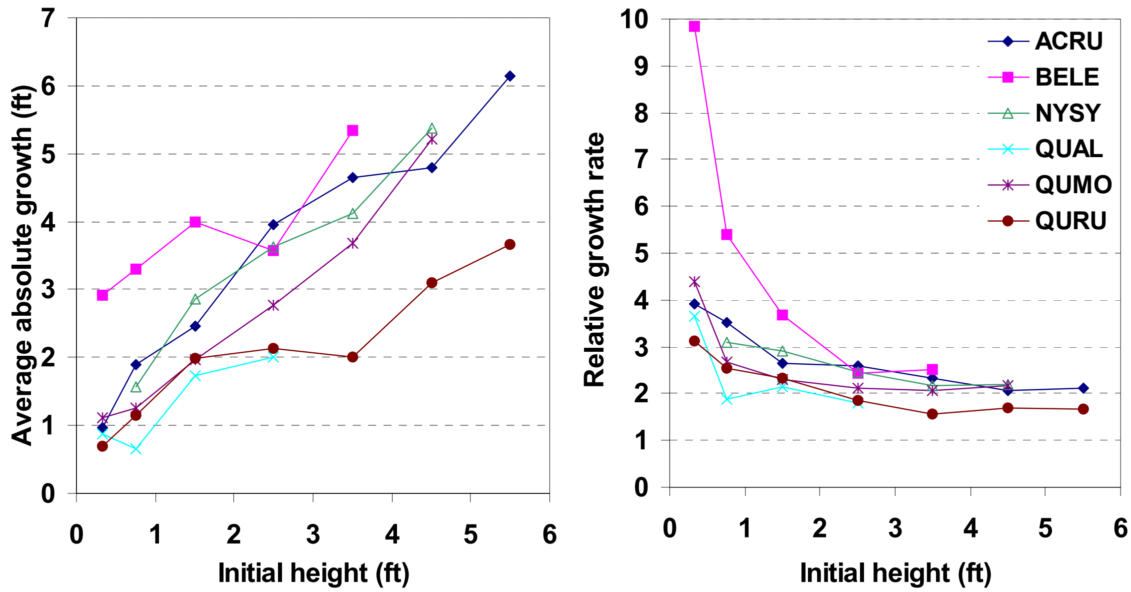



Figure 7.6. Average absolute height growth and relative growth rate of the largest oak and non-oak species on each plot between 01 and 04 measurements by their 01 height classes (ACRU: red maple, BELE: black birch, NYSY: blackgum, QUAL: white oak, QUMO: chestnut oak, QURU: northern red oak).

Chestnut oak had the highest relative growth rate among the oak species during the three-year period. Although chestnut oak had lower relative growth rate than the non-oak species on average, its seedlings with initial sizes of 2 to 6 inches and 4 to 5 feet had higher three-year relative growth rate (4.38 and 2.16, respectively) than red maple (3.93 and 2.06, respectively). On average, white oak had the smallest absolute height growth and height relative growth rate. Its height development for larger seedlings is not presented here because of a lack of larger size white oak seedlings at one year after harvest. Relative growth rates for northern red oak were similar to chestnut oak for seedlings with less than three feet initial height. However, relative growth rates for the larger northern red oak seedling were much slower than for chestnut oak. For example, northern red oak seedling with initial sizes of 4 to 5 feet gained 3.1 feet in three years on average, while chestnut oak seedlings of comparable size gained 5.2 feet.

*Frequency*

Development of occurrence frequencies for the three non-oak species in the 16 mix-oak stands was summarized in Figure 7.7. Red maple occurrence frequencies dropped seven percent between 00 and 01 measurements, but almost fully recovered to the before harvest level by four years after harvest. Black birch occurrence frequency had seven percent increment between 00 and 01 measurements and a significant 11 percent increment between 01 and 04 measurements ($p < 0.01$), and the overall increase was the largest among all the species. Blackgum gained eight percent occurrence frequency one year after harvest and had a slight reduction four years after harvest, but the changes were not significant.

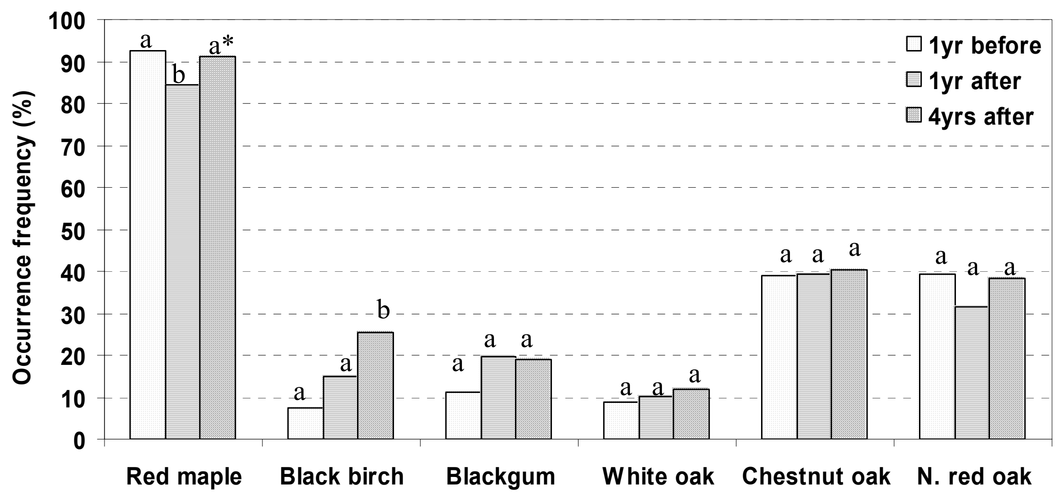



Figure 7.7. Occurrence frequency of six major regeneration species one year before, one year after, and four years after harvest in 16 mixed-oak stands.
* means for the same species not sharing the same letter are statistically different ($p < 0.01$).

Occurrence frequency for all three oak species did not have a significant change among the three measurements. Both white oak and chestnut oak experienced a slight increment in occurrence frequency over time with an overall increment of less than three percent. Northern red oak occurrence frequency decreased eight percent one year after harvest and nearly recovered to before-harvest levels four years after harvest. This pattern of change was different to the other two oak species, but was similar to red maple.

*Oak dominance*

The percentage of plots dominated by oak species is shown in Figure 7.8 for each measurement period based on cumulative height and maximum height. Oak dominance as measured by maximum height was much stronger than dominance based on cumulative height in each measurement period. Percentage of plots with oak cumulative height greater than or equal to non-oak cumulative height had a slight increase one year after overstory removal, and then fell to its previous level three years later. The percentage of plots with oak maximum height greater than or equal to non-oak species decreased monotonically with time from 54 percent to 39 percent.

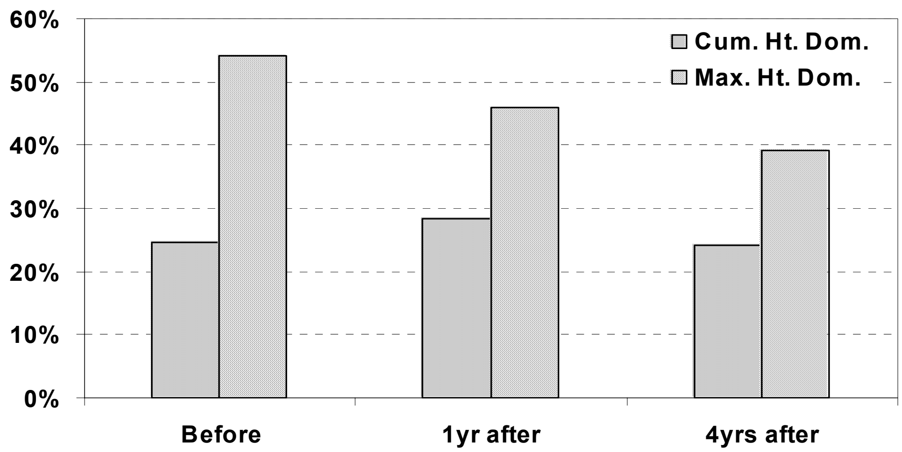



Figure 7.8. Percentage of plots dominated by oak species before, one year after and four years after harvest based on cumulative height and maximum seedling height. (Cum. Ht. Dom.: cumulative height of oak species is greater or equal to non-oak species on a given plot; Max. Ht. Dom.: largest oak seedling is taller or equal to non-oak species on a given plot).

### *Factors affecting post-harvest regeneration abundance*

Except in the case of black birch, advance regeneration was the most influential factor affecting regeneration abundance one year after overstory removal for all species. Regeneration cumulative height one year after harvest was positively correlated with cumulative height of advance regeneration for the two non-oak and three oak species, and the correlations were all very significant ($p < 0.0001$). What's more, except chestnut oak, advance regeneration abundance was the only influential factor affecting post-harvest regeneration abundance for all five species.

Non-tree vegetation abundance of hayscented fern, mountain-laurel, and low shrub species did not enter into the final model, nor did the fencing and herbicide treatments. Among all the variables related to overstory trees, total remaining overstory basal area was the only variable that had significant effect on 01 chestnut oak abundance but not other species (Figure 7.9). Post-harvest chestnut oak cumulative height was negatively associated with total remaining overstory basal area.

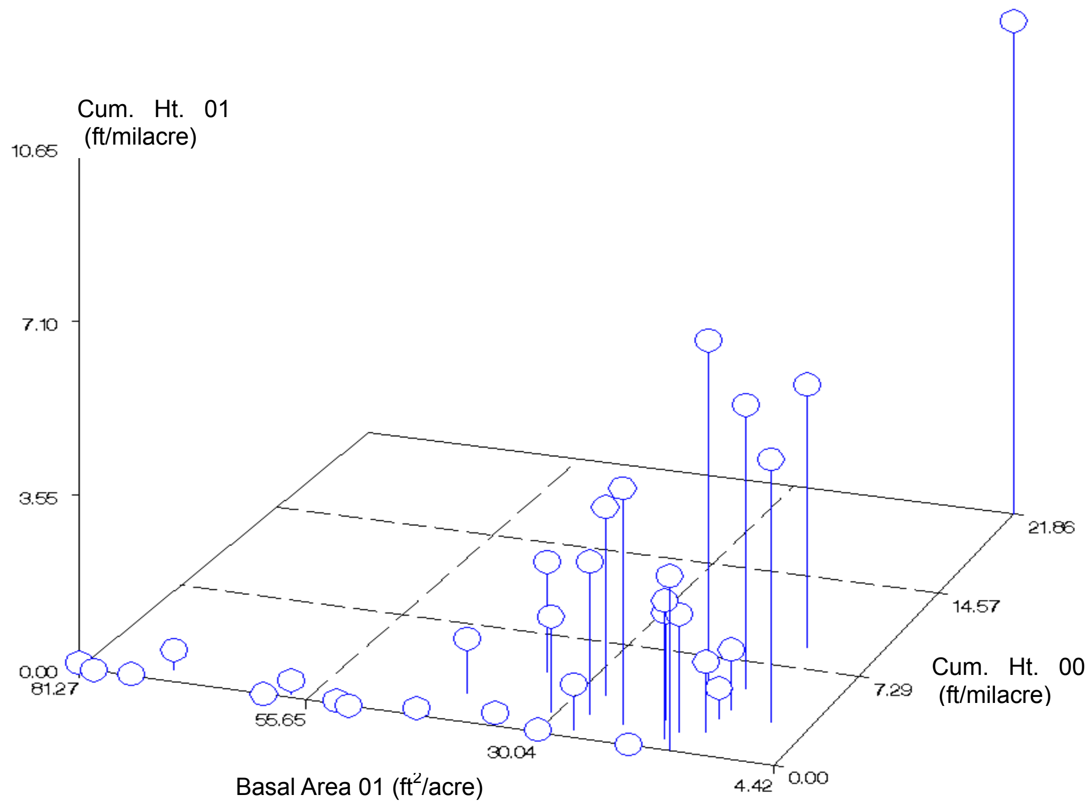



Figure 7.9. Relationship between 01 chestnut oak regeneration abundance (Cum. Ht. 01) and advance chestnut oak regeneration (Cum. Ht. 00) and remaining basal area (BA 01).

## Discussion

The analyses suggest that, except for black birch, advance regeneration is one of the most important factors influencing regeneration abundance after harvest. This has been widely observed and documented for regeneration of oak and other species in oak dominated stands (Sander et al. 1984, Crow 1988, Johnson et al. 2002). No different regeneration development patterns were found between the herbicided and un-herbicided stands, and between fenced and unfenced stands. As mentioned earlier, stands that were herbicided and/or fenced were known to have non-tree vegetation competition and/or deer browsing problems, and these stands might have experienced different development patterns than other stands if no treatments had been applied, thus the effect of the treatments was to make the stands more similar rather than more different. No different regeneration development patterns were found between the problem stands and normal stands after the treatments were applied, which indicates that the herbicide or fencing treatment effectively reduced the vegetation competition or deer browsing.

Herbicide treatment noticeably reduced hayscented fern and mountain-laurel cover percentage. The effect was more pronounced for hayscented fern than for mountain-laurel. Since there are only two herbicided stands that have been followed through four years after harvest, it is not clear if hayscented fern on those herbicided stands will recover and to what degree.

Hayscented fern took advantage of the major overstory disturbance event to expand its occurrence frequency, especially in stands with low occurrence frequencies before harvest. On average, hayscented fern occurrence frequency increased 1.6 times, and its average height increased 1.5 times four years after harvest compared to before harvest. Fortunately, heavy cover frequency of hayscented fern was decreasing after harvest at least through age four. Hayscented fern has been classified as a competitor species because of its ability to respond aggressively to sudden resource availability by way of vegetation expansion via rhizomes and sexual reproduction through spore dispersal (Groninger and McCormick 1991, Hughes and Fahey 1991).

Mountain-laurel had the most reduction during the harvest because of logging damage. But it began recovering in occurrence frequency after harvest. However, its heavy cover occurrence frequency and average height were decreasing after harvest. It is possible that mountain-laurel can withstand the shade of a high canopy better than competition from vigorous regeneration. The sudden exposure to full sunlight might be responsible for the reduction of mountain-laurel heavy cover occurrence frequency and average height. Overstory removal reduced occurrence frequency of low shrub species slightly, and reduced one-third of their heavy cover occurrence frequency. Their occurrence frequency was recovered quickly after harvest.

The reduction of non-tree vegetation cover following harvest and herbicide (when necessary) provides a "window of opportunity" for tree regeneration to establish and eventually to grow above the non-tree vegetation layer. Although the non-tree vegetation studied here may have a strong influence on advance regeneration, it appears not to directly cast a significant influence on regeneration development after harvest because of the relative low level of remaining cover. However, the "window of opportunity" is relatively narrow. For some stands, the heavy cover occurrence frequency for all three species or species group had already recovered to before-harvest levels by age four.

Although future stand composition is strongly a function of seedling size in the current stage (Sander et al. 1984), seedling density cannot be ignored and even small seedlings may contribute to future composition. Our results indicate that small oak seedlings (< 1 ft) can grow into larger size classes (> 5 ft) four years after overstory removal, since most of the large oak seedlings four years after overstory removal had developed from the small, advance-regeneration seedlings. In similar stands, Ward and Stephens (1999) found advance regeneration oaks ranging from < 1 to 5 ft in height can reach a dominant crown position 12 years after harvest.

Cumulative height, a composite measure of seedling size and density, provided the basis for reasonably deterministic models describing the early stand development, especially for regeneration development after overstory removal. The three non-oak species have a faster response to overstory removal than the oak species in terms of cumulative height. Cumulative height increment rate for black birch and blackgum are much higher than the other species. Interestingly, the top two most abundant oak species (northern red oak and chestnut oak) had higher increment rate in cumulative height than red maple in the 01 and 04 measurements. The percentage of plots dominated by oak based on cumulative height criterion has changed only slightly over time. It indicates that oak regeneration has neither lost nor gained in overall dominance, although the largest oak seedlings are not growing as fast as the largest non-oaks. Of course, we do not yet know what will happen in the future.

The results suggest that oak regeneration experiences two kinds of forest tree competitors. The first is typified by red maple. Red maple regeneration on average is not large in size, but has significantly higher density than oak species both before and after overstory removal. It occupies space which could otherwise be used by oaks. Height development of individual seedlings indicates that red maple on average has a higher relative growth rate than the oaks, at least for the dominant seedlings. The principal advantage of red maple regeneration to compete with oak is its ability to accumulate in large numbers prior to harvest and to carry it through the overstory removal process. The second type of competitor is fast growing “invader” species such as blackgum and black birch. Although both species have low density and size before harvest, they can increase dramatically after harvest both in terms of density and cumulative height.

# Chapter 8

# Measuring Regeneration Stocking

*Always bear in mind that your own resolution to succeed is more important than any other thing.*

Abraham Lincoln

***Abstract:*** Regeneration stocking charts and equations for mixed-oak stands were developed based on data collected from nearly 14,000 plots in Pennsylvania. Biological maximum stand density was identified by plotting cumulative height against number of seedlings per plot, and was used as the reference level of the average maximum stand density (100 percent stocking or A-level stocking). Minimum stand density (B-level stocking) was estimated using the crown area and seedling height relationship of open-grown seedlings. A developmental shifting point was observed for both open-grown seedlings and seedlings growing under high competition. Stocking charts were built separately for plots having average seedling height below and above the shifting point by plotting cumulative height on the y-axis and number of seedlings on the x-axis on a log-log scale. Two stocking equations were also developed for plots with short seedlings and for plots with tall seedlings. Development of regeneration stocking was then studied using the resulting regeneration stocking charts and equations. Future oak regeneration stocking was highly predictable soon after harvest. The resulting stocking charts and equations provide an objective basis for evaluating stocking of young regeneration in the upland mixed-oak forest.

## Introduction

Appropriate stocking equations or stocking charts, which serve as yardsticks to measure stand density, have long been sought by foresters. Stocking is a subjective term used to describe the adequacy of any observed level of stand density with respect to a silvicultural goal (Bickford et al. 1957, Gingrich 1964). Reineke (1933) proposed the first stocking diagram based on relative density. Since then, many stocking charts, diagrams, and monographs have been developed (Chisman and Schumacher 1940, Gevorkiantz 1944, Wilson 1946, Briegleb 1952, Krajicek 1961, Gingrich 1967, Leak et al. 1969, Roach 1977, MacLean 1979, Curtis 1982, Sampson 1983, Stout et al. 1987, McGill et al. 1999, Gilmore 2003, and Willams 2003). Stocking can be measured using numbers of trees, quadratic mean diameter, mean volume, dominant height, or other stand properties. Generally, the two major approaches to measure stocking are typified by: Reineke's (1933) stand density index (SDI) and Gingrich's (1967) stocking diagram.

All of these stocking guides share one common concept – relative density. Relative density is the ratio of absolute density to a reference level. Measures of relative density assess crowding in forest stands by comparing the growing space available per tree with the growing space available to trees of the same size at some reference level (Stout and Larson 1988). The reference level is the absolute density that normally is expected in a stand of given characteristics under some standard condition. Two reference levels with biological meanings have been widely used to measure stand density: the level of average maximum competition and the level of no competition (Curtis 1971). The average maximum competition level, which is based on the absolute density observed in undisturbed stands, is the more common and useful reference level. The maximum density lines of Reineke's (1933) SDI and the A-level in Gingrich's (1967) stocking guide are the reference levels that represent the average maximum competition level.

Most of the stocking charts, diagrams, and monographs mentioned above are suitable to bigger trees (> 12 ft in height or > 1 in in DBH), and older stands (> 20 yrs). No stocking guide for seedlings or young stands for the upland mixed-oak forest exists. The seedling stage is very important because it determines the future stand structure. Failure to obtain adequate stocking of desired species can leave a stand unproductive for many years. Hence, developing a stocking guide for the regeneration stage is necessary and pressing, and that was the objective of this study.

## Source of data

Three sets of data were used in this study. The first data set was collected in 52 mixed-oak stands in Pennsylvania. All stands were measured approximately one year before harvest (00 measurements), 33 stands were re-measured one year after harvest (01 measurements), 16 stands were re-measured four years after harvest (04 measurements), eight stands were re-measured five years after harvest (05 measurements), and four stands were re-measured six years after harvest (06 measurements). Depending on stand size, 15 to 30 permanent center points were systematically installed in a square grid throughout the stand. Four permanent sample plots with a radius of 3.72 ft (0.001-acre) were established around the center points at each cardinal direction at a distance of 16.5 ft. On each plot, all tree seedlings regardless of origin were recorded by species and height class and seedling cover percentage (i.e. percentage of plot area covered by seedling canopy) was estimated.

Data from 15 mixed-oak stands with stand ages of 6 – 12 years were also included in this study (triangle points in Figure 2.1). The overstory of each of the 15 stands was removed 6 – 12 years ago, and the stand regenerated successfully after harvest. These stands were intentionally chosen to represent crown-closure or near crown-closure conditions. Depending on the size of the stand, 15 to 40 plots with a radius of 7.44 ft (0.004 acre plots) were sampled throughout the stands. In total, 504 plots were included in this data set. On each plot, all seedlings or saplings regardless of their origin were recorded by species and height, and percentage of crown cover was estimated.

The final data set provided information for open-grown trees. Based upon abundance and availability, 567 open-grown trees that included the six major regeneration species in this region were measured in this data set: 81 red maples (*Acer rubrum* L.), 97 black birches (*Betula lenta* L.), 38 blackgums (*Nyssa sylvatica* Marsh), 92 white oaks (*Quercus alba* L.), 125 chestnut oaks (*Q. montana* Willd.), and

134 northern red oaks (*Q. rubra* L.). These trees were measured in forest stands with stand ages of 4 – 10 years old. For each tree, species, height, stem DBH, and crown diameter were recorded. In order to have best crown size estimation, crown diameters were measured in four directions: longest dimension of the crown, and 45, 90, and 135 degrees off the longest dimension through the center.

## Development of stocking guides

### *Average maximum density*

Plots from the first two data sets that had at least one seedling were compared to identify plots that were experiencing the maximum level of competition. A summary of the stand characteristics of the sampled plots is provided in Table 8.1. Since data from the first data set were not intentionally collected to identify the maximum biological boundaries, a special procedure that served to identify plots that exhibited the maximum level of competition was needed.

Table 8.1. Characteristics of surveyed plots by stand age.

| Stand age | No. of plots | Seedlings per milacre | | Seedling average height (ft) | |
|---|---|---|---|---|---|
| | | Mean | Range | Mean | Range |
| 0* | 7942 | 63 | 1-3334 | 0.6 | 0.1-21.3 |
| 1 | 4148 | 42 | 1-1217 | 0.8 | 0.1-20.4 |
| 4 | 2402 | 40 | 1-755 | 2.4 | 0.1-25.5 |
| 5 | 309 | 22 | 1-105 | 4.2 | 0.5-20.4 |
| 6 | 153 | 17 | 1-63 | 4.4 | 0.1-13.6 |
| 6-12 | 504 | 10 | 1-31 | 16.2 | 7.7-31.8 |

* plots surveyed one year before overstory removal.

Cumulative height on each plot for all the seedlings was first calculated and then plotted against seedling density on a log-log scale (Figure 8.1). Two clear boundaries are apparent. The highlighted lower boundary is the minimum plot cumulative height for a given number of seedlings. It represents plots covered only with seedlings of the smallest height (one inch in this study). Since there is a simple linear relationship between minimum cumulative height and seedling density ($CumHt = n \cdot h_{min}$), the lower boundary is also close to linear in the log-log plot. The upper boundary corresponds to the observed maximum cumulative heights over the range of observed seedling densities. To ensure that the observed maximum cumulative height represents the biological average maximum level of competition or the ecological maximum carrying capacity, plots around the upper boundary were further examined. Figure 8.1 was divided into 0.05 unit width slices along the x-axis, and the top two plots near the upper boundary in each slice were then selected. For all selected plots, percentage of seedling cover was further checked, and plots with less than 90 percent seedling cover (by measurement) were eliminated. The remaining selected plots, which are highlighted on Figure 8.1, were the ones chosen to represent the biological frontier. Maximum cumulative height increases as seedling density increases. But the increase is progressively smaller as the number of seedlings per milacre increases. The upper and lower boundaries converge as seedling density approaches the maximum.

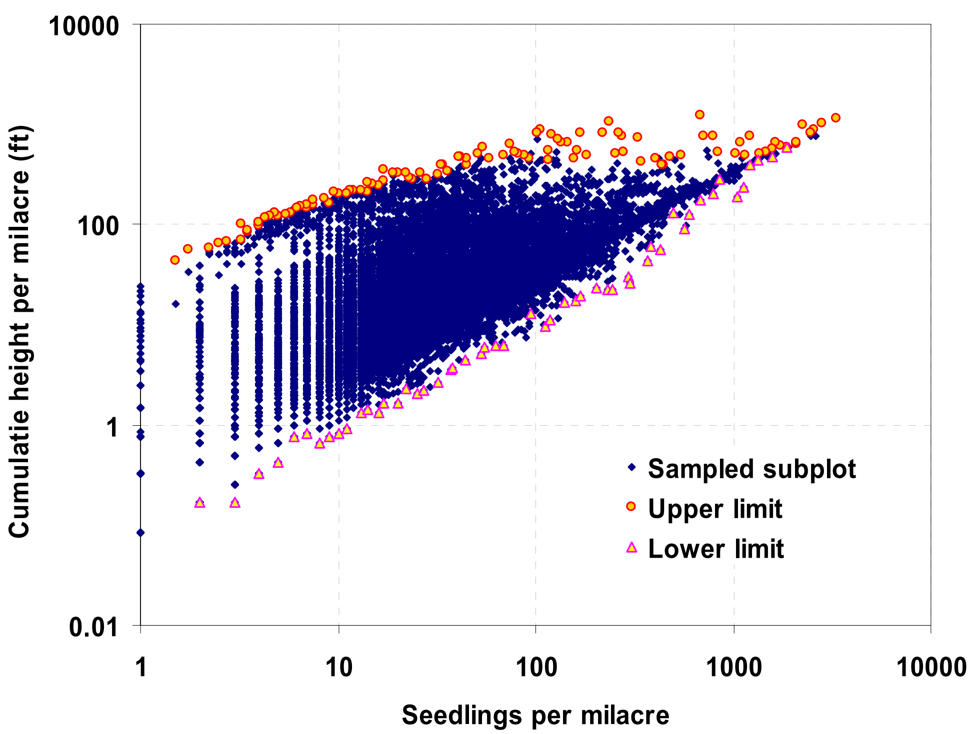



Figure 8.1. Relationships between cumulative height and density on 13,853 surveyed plots. Plots with maximum or minimum cumulative height at a given density are highlighted.

The highlighted plots around the upper boundary in Figure 8.1 were then used to study the size-density relationship at the average maximum level of competition. The relationship between average seedling height and density is shown in Figure 8.2 on a log-log scale for these upper-limit plots. Since there is an obvious shifting point around an average height of nine feet, two different regression lines were fitted to represent the two markedly different size-density relationships. It would be nicer to locate the shifting point with some mathematical or statistical software. However, for the purpose of this study, an observational judgment is sufficient. The regression line in the upper-left portion has a slope of -0.4. The regression line in the lower portion has a much steeper slope close to negative one. In other words, average height and density have an almost reciprocal relationship in that portion of the graph.

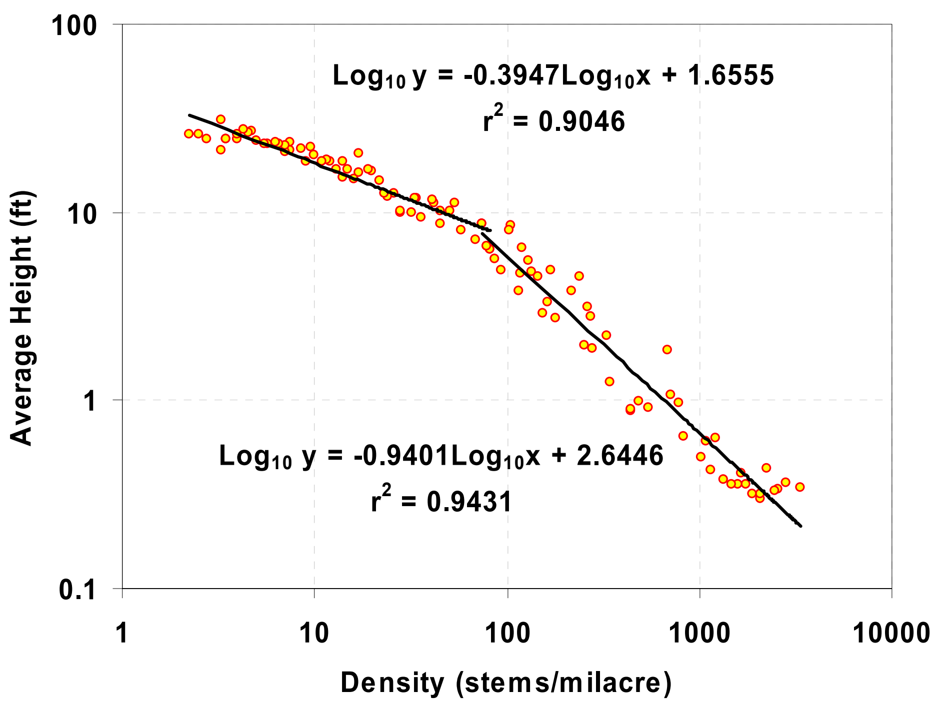



Figure 8.2. Relationships between average seedling height and density for plots experiencing maximum level of competition.

Average seedling crown area (CA) was calculated for seedlings in the upper-limit plots. CA was determined simply by dividing plot size by the total number of seedlings in these upper-limit plots. CA and average seedling height (AvgHt) have different relationships before and after the nine feet shifting point, and the average seedling crown area equations are given by:

$CA$ (ft$^2$) = 0.0682•$AvgHt$ $^{1.0032}$ = 0.0682• $(\Sigma h_i / N)^{1.0032}$ ($AvgHt < 9$ ft) [8.1]

$CA$ (ft$^2$) = 0.0044•$AvgHt$ $^{2.3667}$ = 0.0044• $(\Sigma h_i / N)^{2.3667}$ ($AvgHt \geq 9$ ft) [8.2]

Where $N$ is the total number of seedlings per plot, and $h_i$ is height of seedlings in the upper-limit plot ($i$ = 1, ……, $N$). Crown area has an almost linear relationship with seedling height for seedlings shorter than nine feet. Crown area of larger seedlings and saplings (≥ 9 ft) has a commonly seen curvilinear relationship with seedling height.

To have a clearer view of this shift in the alternative relationship between seedling height and crown size, width-height ratio (crown width / seedling height) is plotted against average seedling height in Figure 8.3. Average crown width was calculated from the CA for seedlings in the upper-limit plots. Two distinct relationships between the ratio and seedling height are again apparent, with a shifting

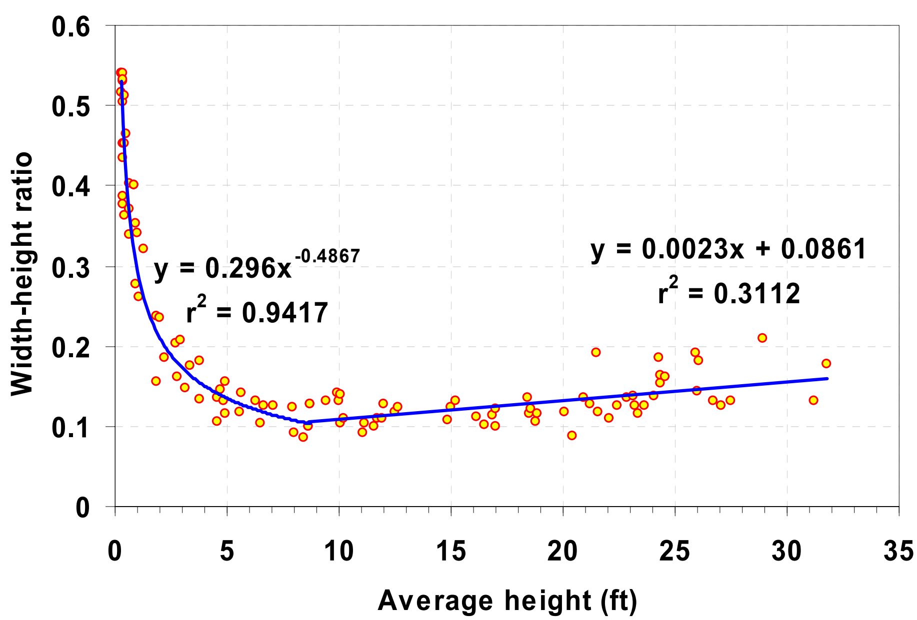



Figure 8.3. Variation of width-height ratio (crown width / seedling height) as a function of seedling height for seedlings in plots experiencing maximum levels of competition.

point around eight to nine feet. The width-height ratio initially decreases rapidly as seedling height increases, and reaching a minimum when average seedling height reaches approximately nine feet. The width-height ratio subsequently increases slowly as the tree grows further in height.

As with Gingrich's (1967) stocking chart and Reineke's (1933) SDI, average maximum competition was selected to serve as the reference level. By using the reference level of average maximum competition for regeneration stocking as shown in Figures 8.1 and 8.2, regeneration stocking charts can be built based on the reference level by using cumulative height as the y-axis and number of seedlings as the x-axis. Since there appears to be a significant developmental change appears to occur at about the time seedlings become nine feet tall (Figures 8.2 and 8.3), two sub-charts were built for plots with average height of less than nine feet and greater than nine feet. Number of seedlings were generated for various average seedling heights using equal average height; then cumulative height was computed for the corresponding average height and number of seedlings, and then plotted in a stocking chart format (Figure 8.4). Therefore, a count of 100 seedlings per milacre and a cumulative height of 300 feet per milacre represent a stocking of 50 percent in a stand where the average seedling height is three feet, and a count of four seedlings per milacre and a cumulative height of 80 feet per milacre also represents a stocking of 50 percent in a stand where the average seedling height is 20 feet. Following Gingrich's (1967) convention, the line of 100 percent stocking that represents a normal condition of maximum stocking was defined as A-level stocking.

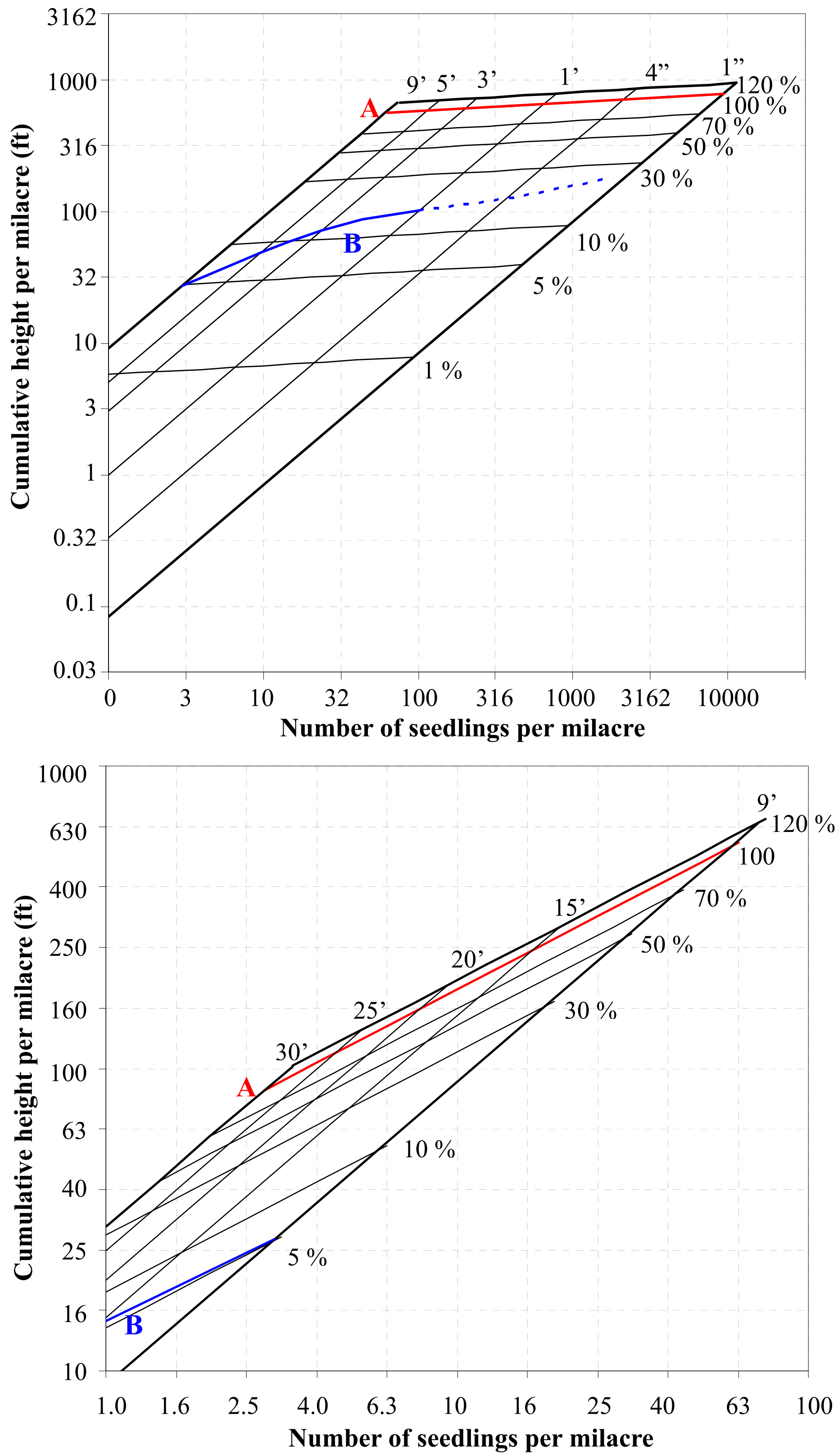



Figure 8.4. Relation of cumulative height, seedling density, and average height to stocking percentage (for average seedling height from 1 in to 9 ft (upper) and 9 to 30 ft (lower)).

### *Minimum stand density*

Minimum stand density at full canopy closure, or Gingrich's (1967) B-level stocking, represents an ideal condition in which a stand is fully covered with seedlings with maximum crown area and no inter-seedling competition. Crown areas of open-grown seedlings were used to define the maximum crown area. To compute the minimum density at a given average seedling height, the relationship between crown width and seedling height of open-grown seedlings was used.

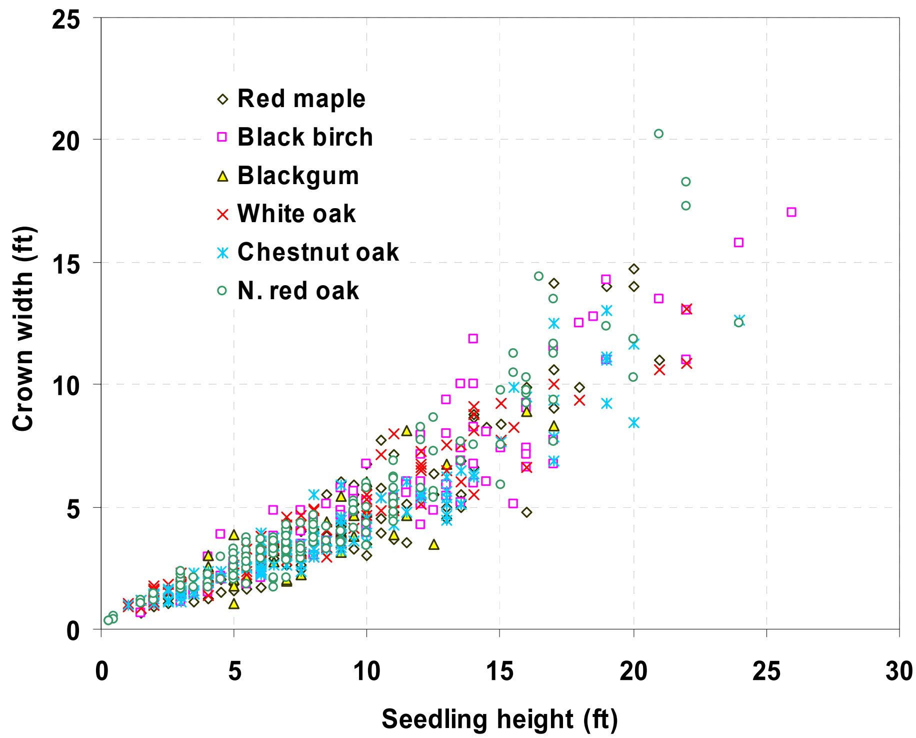



Figure 8.5. Relationship of crown width and seedling height by species for open-grown seedlings and small saplings.

Crown width is plotted against seedling height by species in Figure 8.5. Regression analysis of crown width against seedling height indicated that the overall relationship between crown width and seedling height is not significantly different among species, although crown width of oak species was slightly greater than non-oak species when seedling heights are small. Consequently, the same crown width-seedling height relationship was used for the six major regeneration species. The relationship between crown width and seedling height is non-linear. To determine if a developmental shifting point exists for open-grown seedlings, average width-height ratio for all the species is plotted against seedling height in Figure 8.6. Interestingly, a developmental shifting point around six to eight feet was observed. The width-height ratio decreases rapidly as the seedling approaching the shifting point, and then slowly regains as the seedling grows into larger seedling or small sapling.

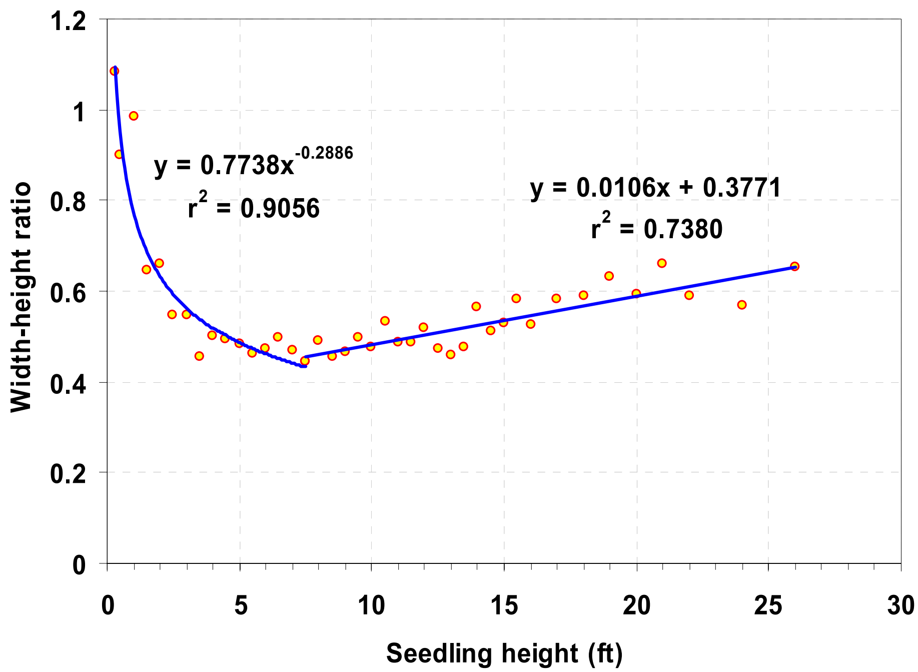



Figure 8.6. Relationship between width-height ratio (crown width / seedling height) and seedling height for open-grown seedlings.

Crown area was then calculated and regressed on seedling height (Ht) for open-grown seedlings. Two different equations were fitted for seedlings less than seven feet tall and for seedlings greater than seven feet tall. The open-grown seedling crown area equations are given by:

$$CA\ (\mathrm{ft}^2) = 0.4051 \cdot Ht^{\,1.50} \qquad (Ht < 7\ \mathrm{ft}) \qquad [8.3]$$

$$CA\ (\mathrm{ft}^2) = 0.0479 \cdot Ht^{\,2.55} \qquad (Ht \geq 7\ \mathrm{ft}) \qquad [8.4]$$

Based on the above two equations, minimum stand density with seedlings of maximum crown area was then calculated for various seedling heights, then cumulative heights were computed for the corresponding seedling heights and number of seedlings, and plotted on Figure 8.4 shown as the B-level. Because less than 10 open-grown seedlings with height smaller than one foot were measured, the crown width-seedling height relationship in this region of the graph is not as robust as for larger seedlings. Hence, a dashed line, instead of a solid line, was used in the right end of the B-level in the upper portion of Figure 8.4.

## Application

One primary application of stocking equations or stocking charts is to quantify stand development against a common standard. The primary advantage of stocking charts is their convenience in field use, and they also can be used "dynamically" to quickly access the direction and amount of change in a stand (Leary and Stansfield 1986, McGill et al. 1999). Examples of stand stocking development are provided in Figure 8.7 for four stands measured from one year before harvest through five years after harvest. Although the development pattern for average number of seedlings per acre differed from stand to stand, stocking for all four stands increased over time. None of the stands had yet approached the upper-limit ("A" level) by age five, but one stand with stocking over the B-level at age four trended to converge to the upper limit five years after harvest.

Stocking equations, instead of stocking charts, can be used to calculate stand stocking when precision is needed. Based on crown area equations 8.1 and 8.2, the stocking level on a plot with the size of $m$ acres can be calculated as follows if seedling height is measured in feet:

$$S = [(N \bullet 0.0682 \bullet AvgHt^{1.0032}) / (m \bullet 43560)] \bullet 100 = (0.00016/m) \bullet N \bullet AvgHt^{1.0032}$$

$$= (0.00016/m) \bullet N \bullet (\Sigma h_i / N)^{1.0032} \qquad (AvgHt < 9 \text{ ft}) \qquad [8.5]$$

$$S = [(N \bullet 0.0044 \bullet AvgHt^{2.3667}) / (m \bullet 43560)] \bullet 100 = (0.00001 / m) \bullet N \bullet AvgHt^{2.3667}$$

$$= (0.00001/m) \bullet N \bullet (\Sigma h_i / N)^{2.3667} \qquad (AvgHt \geq 9 \text{ ft}) \qquad [8.6]$$

Where $S$ is percentage of regeneration stocking, $N$ is the total number of seedlings per plot, $AvgHt$ is the average height of all seedlings, and $h_i$ is height of seedlings on the sampled plot ($i$ = 1, ……, $N$).

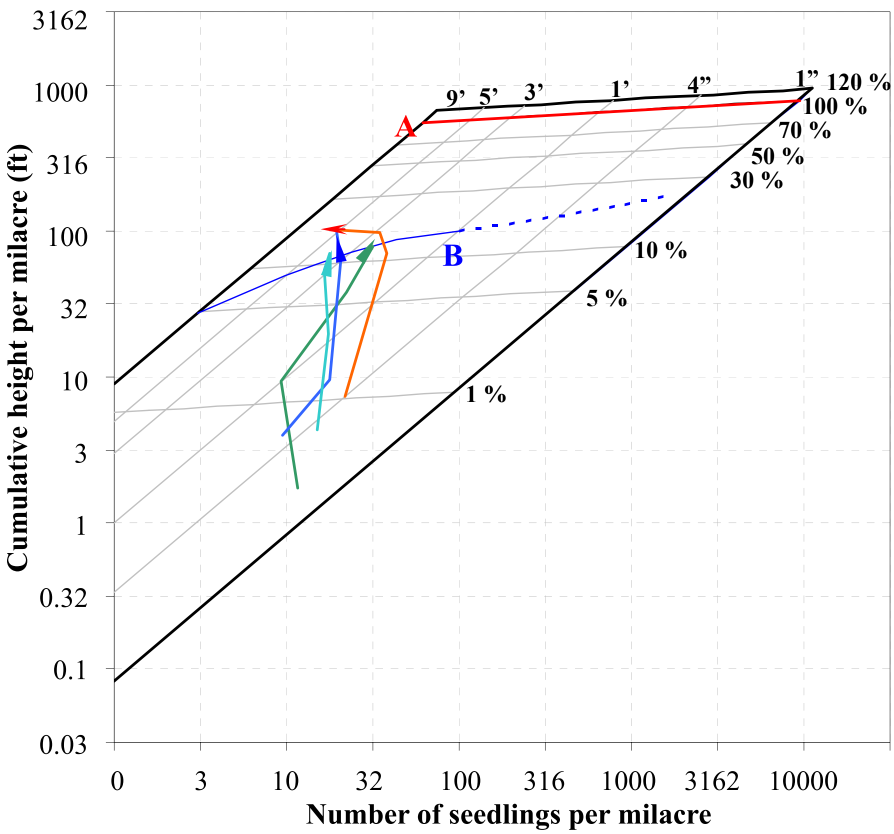



Figure 8.7. Examples of stand level regeneration stocking trajectory from one-year before harvest to five years after harvest, each arrowed line represents the developmental path of a stand.

Using the above stocking equations, average percentage of regeneration stocking for oaks, red maple, and all species was calculated and presented in Table 8.2. Since the average stocking was based on different survey periods, and a different number of stands, direct comparison among the means many not be appropriate. However, there is a general trend that regeneration stocking increases over time following harvest. On average, around 30 percent of the regeneration stocking was contributed by oak species, while about 50 percent of the stocking was contributed by red maple throughout the entire survey period.

Regression analyses between regeneration stocking at different survey times show that future stocking is more highly predictable after harvest than before (Figure 8.8). Regression of oak stocking one year after harvest against oak stocking

Table 8.2. Mean stocking levels for regeneration of oaks, red maple, and all species one year before harvest through five years after harvest.

| Time | | Oaks | | Red maple | | All species | |
|---|---|---|---|---|---|---|---|
| | | Avg. | Range | Avg. | Range | Avg. | Range |
| 1yr pre- | (n*=52) | 0.74 | 0.01-2.06 | 1.54 | 0.13-6.41 | 2.60 | 0.17-8.26 |
| 1yr post- | (n=33) | 1.06 | 0.06-4.32 | 1.42 | 0.21-6.96 | 3.00 | 0.46-10.11 |
| 4yrs post- | (n=16) | 2.64 | 0.33-9.51 | 3.50 | 0.66-9.84 | 7.71 | 1.70-16.11 |
| 5yrs post- | (n=8) | 2.89 | 0.47-7.85 | 5.69 | 1.06-9.62 | 11.94 | 6.87-18.10 |

* number of stands

one year before harvest was performed on 32 stands. One stand in this data set was an obvious outlier and was removed from the analysis. On average, oak regeneration stocking increased one year after harvest, and advance oak stocking explained 48 percent of the variance of oak stocking one year after harvest. Oak regeneration stocking at four years after harvest was highly predictable based on stocking levels one year after harvest. One-year-after-harvest stocking explained about 94 percent of variation in oak stocking four years after overstory removal. Oak regeneration stocking at five years after harvest was even more predictable based on stocking levels four years after harvest. Four-year-after harvest stocking explained over 98 percent of variation in oak stocking five years after overstory removal.

Stand level red maple regeneration stocking development was slightly different from oak regeneration. On average, red maple regeneration stocking decreased one year after harvest, and advance red maple stocking explained 72 percent of the variance of red maple stocking one year after harvest. Red maple stocking four years after harvest increased 1.76 times compared to one year after harvest. However, its four-year stocking was less predictable than oaks. Red maple regeneration stocking at five years after harvest was also very predictable based on stocking levels four years after harvest. Four years after harvest, red maple stocking explained about 98 percent of variation in red maple stocking five years after harvest.

Stocking development for all regeneration species was less predictable than for oaks or red maple regeneration. Advance regeneration stocking of all species only explained about 40 percent of the variance of one-year-after-harvest stocking. Stocking became more predictable after harvest. The coefficient of determination (r2) was 0.71 between stocking levels one and four years after harvest, and 0.76 between four and five years after harvest. The total stocking levels for all species increased over time.

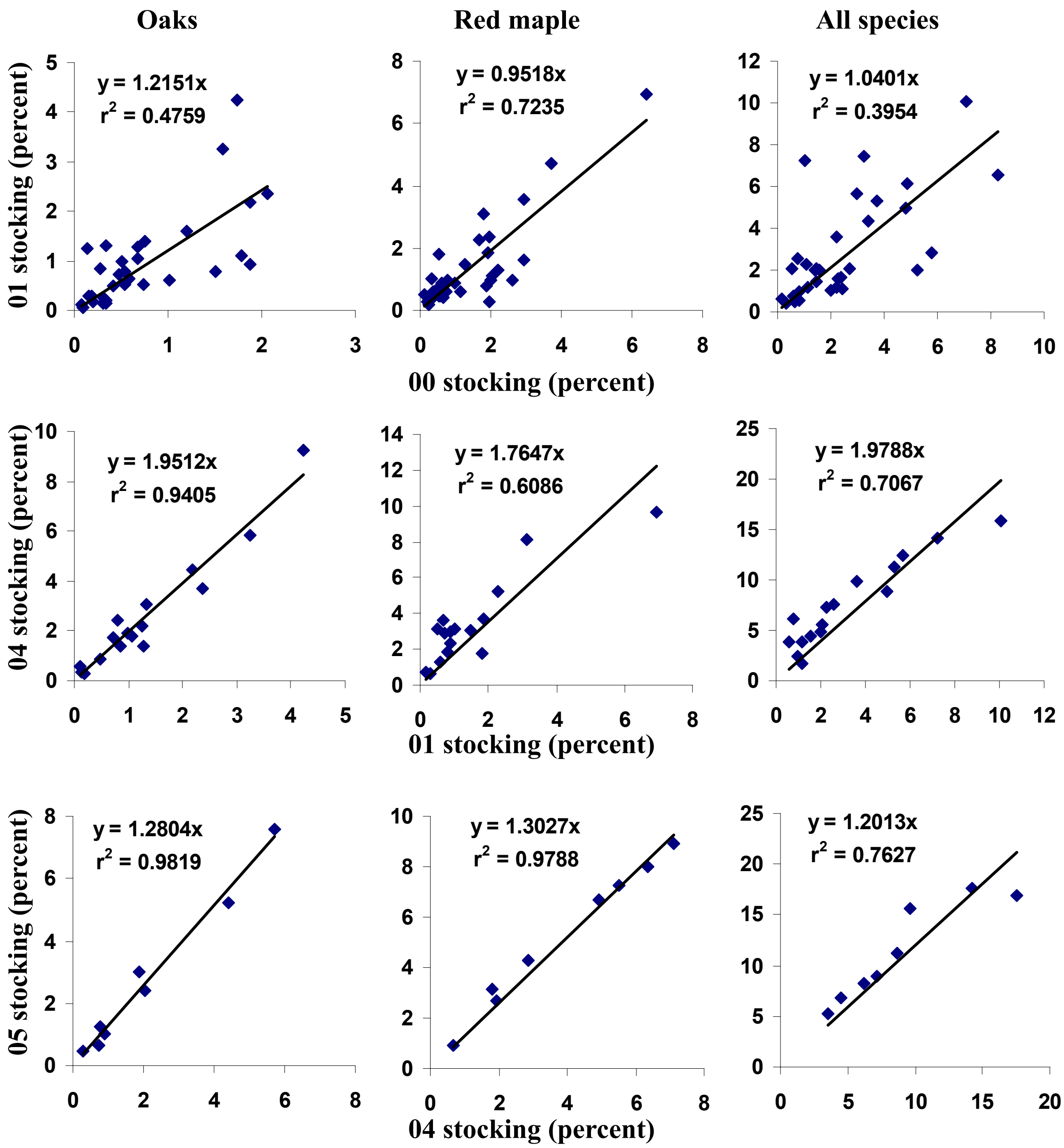



Figure 8.8. Stand level regeneration stocking development of oaks (left), red maple (middle), and all species (right) one year before (00) and after (01) harvest, one and four years (04) after harvest, and four and five years (05) after harvest.

Since advance regeneration stocking only explained 48 and 40 percent of the variances of one-year-after-harvest stocking for oak and all species, respectively, potential factors that might influence the development of regeneration stocking were further investigated. As mentioned in the former chapters, fencing and herbicide were applied to some stands if there was known a deer browsing problem or high non-tree vegetation competition, and different overstory removal treatments such as clearcut and shelterwood harvest was applied on different stands. Therefore, analysis of variance was applied using relative stocking rate of change (one-year-after stocking / one-year-before stocking) as the response variable, and fencing, herbicide, overstory treatment, and physiographical province as the independent variables. Although there were some trends, such as relative stocking rate of change for oak decreased as the residual overstory basal area increased, no statistically significant treatment effects were observed.

## Discussion

The above stocking charts and equations provide an acceptable and objective basis for evaluating stocking of tree regeneration in the upland mixed-oak forest. The stocking charts have a similar format as the widely accepted Gingrich's (1967) stocking chart for saplings and mature trees. In comparing the regeneration stocking chart and Gingrich's stocking chart, cumulative height is analogous to basal area and average seedling height is analogous to average tree diameter. The only difference is that Gingrich's stocking charts are plotted on a normal scale, while the regeneration stocking charts are plotted on a log-log scale. The regeneration stocking charts can be viewed as the extension of Gingrich's stocking charts for seedlings and saplings less than three inches in diameter.

The lines that represent different levels of stocking are parallel to each other. However, because the regeneration stocking charts are plotted on a log-log scale, these stocking lines are not evenly spaced out as in the Gingrich's chart. Nevertheless, the mathematical relationship between different stocking levels still holds. For example, with a fixed average seedling height of 20 feet, if number of stems per milacre decreased 50 percent from eight to four, then cumulative height per milacre also decreased 50 percent from 160 feet to 80 feet, and the percentage of stocking decreased from 100 to 50.

In the regeneration stocking charts, the B-level stocking lines are not parallel to the A-level stocking lines. The B-level stocking lines are not parallel to the A-level stocking lines either in the stocking charts for older stands such as Gingrich's (1967) charts and McGill's (1999) charts. The reason for B-level stocking line is not parallel to A-level stocking line is that trees under no competition and trees under maximum competition have different relationships between crown-area and tree height. However, Gingrich's B-level stocking (55 to 60 percent) and McGill's B-level stocking (40 to 55 percent) for older stands are higher than the B-level stocking for regeneration (5 to 30 percent). The difference might due to the different relationships between crown-area and tree height for young seedlings and mature trees.

The set of lines that represent different average tree heights are also parallel to each other and not evenly spaced out. This is slightly different to the stocking charts for older stands. The average tree diameter lines in Gingrich's (1967) charts are not parallel to each other. This is simply because the relationship between basal area and average diameter in Gingrich's charts is not linear, but the relationship between cumulative height and average height in the regeneration stocking charts is linear.

The resulting stocking charts and equations not only have a similar format, but also have reasonable quantitative connections with the former stocking charts. Based on the regeneration stocking equation, if there is only one tree with minimum crown area (A level) on a milacre plot and the plot is fully stocked, then the height of the tree must be ≥ 49 feet. Using the highly deterministic height-diameter relationship of trees in the upper-limit plots ($Height = 8.79DBH + 6.69$, $r^2 = 0.83$), the correspondence tree must have a DBH ≥ 4.8 inches. With the same scenario, Gingrich's (1967) equation predicts a minimum DBH of 4.0 inches for oak and hickory species; McGill's (1999) equation predicts a minimum DBH of 4.7 inches for northern red oak; while Stout's (1986) equations predict a minimum DBH of 4.5 inches for red maple. In an alternative scenario, if there is only one tree with maximum crown area (B level) on a milacre plot and the plot is fully stocked, then the height of the tree must be ≥ 15 feet based on the resulting regeneration stocking, and the correspondence tree must have a DBH $\geq 1.7$ inches by the height-diameter relationship of open-grown trees ($Height = -0.90DBH^2 + 7.82DBH + 4.18$, $r^2 = 0.87$). Based on Gingrich's and McGill's equations, the minimum DBHs in the second scenario are 2.3, 1.6 inches, respectively. Therefore, the predicted tree sizes in the left portion (largest average height) of the regeneration stocking charts are similar to those in the right portion (smallest average diameter) of Gingrich's and McGill's stocking charts, which indicates a good connection between the regeneration stocking and other stocking charts for mature stands.

An interesting developmental shifting point of crown width-seedling height ratio was observed for both seedlings experiencing maximum crowding and seedlings in open-grown conditions. The shifting point, in height, for seedlings with maximum competition is slightly greater than for open-grown seedlings in terms of seedling height. The width-height ratio initially decreases rapidly as seedling height increases toward the shifting point, and then increases slowly after the shifting point as the tree grows further in height. The mechanism for this developmental shift is not clear. One possible speculation of the developmental pattern can be described as follows. After germination, the first priority of a seedling is to produce leaf for photosynthesis, which results a large crown width-seedling height ratio. After establishment, the seedling then allocates proportionally more energy to height growth to avoid becoming overtopped by other vegetation. Because seedlings can photosynthesize with multiple layers of leaves when seedlings grow taller, a given unit area can support increasingly more cumulative height or living biomass. Therefore, the crown width-seedling height ratio decrease as the seedling grows. However, at some point the lower branches will become so shaded as to become a metabolic drain on this plant, and the ratio reaches its minimum. After the shifting point, the lower branches begin to die from shading, the tree gradually expands its crown size to support further development. Niklas (1994, pp 181-182) demonstrated a similar pronounced geometric shifting or breaking point based on the relationship between stem diameter and plant height of 670 different species. A shifting point was observed at plant height of around three meters (10 feet) between "non-woody" species and "woody" species. Although there are no direct connections between the ontogenetic scaling shift observed at different stage of tree development in this chapter and Niklas's (1994) geometric shifting point among different species, there might exist some connections between these two shifting points.  The morphological and physiological mechanism for the developmental shift needs to be further explored.

Assessments of regeneration stocking using the above stocking equations indicate that oak regeneration retains its proportion of stocking (about 30 percent) at least through age five.  Regeneration stocking level is highly predictable after overstory removal, especially for oaks.  High levels of predictability for oak regeneration not only suggest that the oak regeneration process is relatively deterministic, but also that the stocking charts provide an accurate and useful quantitative basis for quantifying seedling stage regeneration.

# Chapter 9

# Conclusion

Early stage stand development is critical to renew an ecologically and economically sustainable forest, especially in the mixed-oak forest region where natural regeneration of oaks is often difficult to obtain.  Based on a very large dataset from mixed-oak stands in the central Appalachians, this research explored forest composition and regeneration potentials and limitations, studied post-harvest regeneration development, and developed a regeneration stocking guide, which provides detailed quantitative and descriptive information of early stand development.

The mixed-oak forests in the central Appalachian region are composed principally of three non-oak species (red maple [*Acer rubrum* L.], black birch [*Betula lenta* L.], and blackgum [*Nyssa sylvatica* Marsh]) and three oak species (white oak [*Quercus alba* L.], chestnut oak [*Q. montana* Willd.], and northern red oak [*Q. rubra* L.]), with four groups of non-tree vegetation (hayscented fern [*Dennstaedtia punctilobula* (Michaux) Moore], mountain-laurel [*Kalmia latifolia* L.], blueberry [*Vaccinium* spp.], and huckleberry [*Gaylussacia baccata* (Wangh.) Koch]) covering the forest floor.  Generally, there were two subtypes of forest:  red maple-northern red oak-hayscented fern subtype, found mainly on the Allegheny Plateau, and red maple-chestnut oak-blueberry subtype, found mainly in the Ridge and Valley physiographical province.

Red maple was the most abundant species in the overstory (before harvest), in advance regeneration, and in regeneration after overstory removal across the study area. The size structure of the overstory red maple had a reverse "J" distribution.   Although high red maple abundance was commonly associated with moist, north-facing slopes with no or low cover of mountain-laurel and hayscented fern, it was abundant on most of the sites.  Seed-origin red maple regeneration on average was not large in size, but had significantly higher density than oak species both before and after overstory removal. What's more, red maple stump sprouting was a significant source of regeneration.  On average, red maple produced the tallest dominant sprouts, the largest number of sprouts per stump, and the largest sprout crown diameter among all the species.  Five years after harvest, red maple stump sprouts can re-occupy about 90 percent of the space that had been used by their parent trees. The principal advantages of red maple regeneration in competition with oak are its ability to accumulate in large numbers prior to harvest and carry seedlings through the overstory removal process, and its super ability to produce abundant, fast-growing stump sprouts.

Both black birch and blackgum were more abundant in the Ridge and Valley physiographic province. Their overstory tree size structures also had a reverse "J" distribution. Although both species had low density and size before harvest, they increased dramatically after harvest in terms of density, occurrence frequency, and cumulative height, and their seedlings in a dominant position had a higher relative growth rate than other species. Both black birch and blackgum can be viewed as the fast growing "invader" species that can exert strong competition pressure on oak regeneration.

Northern red oak was the most abundant oak species on the Allegheny Plateau physiographic province, while chestnut oak was the most abundant oak species in the Ridge and Valley province. Northern red oak, chestnut oak, and white oak all had a uni-modal, normal distribution of size structure in the overstory. Advance regeneration of the three oak species was greatly favored by the abundance of overstory trees of their own kind. White oak regeneration was most abundant on south-facing, gentle, lower slopes with soils in the Buchanan series. Chestnut oak was more common on south-facing, steep upper slopes with stony soils. There was also a positive association between chestnut oak and the density of huckleberry. Northern red oak was more abundant on north-facing, moist sites with Hazleton soil, and was commonly associated with low levels of mountain-laurel and hayscented fern. With few exceptions, advance regeneration of all oak species was low both in size and density. Combining the size structures of advance regeneration (reverse "J" distribution) and overstory trees (uni-modal normal distribution), it is obvious that there was a severe "bottleneck" in density between the oak seedling and sapling stages.

Regardless of the low density and small size of advance oak regeneration, advance regeneration was one of the significant factors influencing oak regeneration abundance after harvest. Generally, seed-origin oaks had a slower response to overstory removal than the non-oak species in terms of cumulative height, and their seedlings in the dominant position also had a lower relative height growth rate. However, oak kept its occurrence frequency and level of dominance in cumulative height at least through four years after harvest. Stump sprouts were the other important source of regeneration for oak species. Sprouting probabilities for all oak species were significantly influenced by stump age and/or stump diameter. Among the oak species, chestnut oak had the most number of stems per stump, the tallest dominant sprouts, and the largest crown size, while these means were lowest for white oak. Generally, oak stump sprouts were not as competitive as red maple in the first several years after harvest, but they kept expanding their crown size at least through age twenty.

No different regeneration development patterns were found between the herbicided and non-herbicided stands, and between fenced and unfenced stands. Since these treatments were only applied to the problematic stands, the effect of the treatments was to make the stands more similar rather than more different. Similar development patterns between the normal stands and problem stands after the treatments were applied indicates that the herbicide and fencing treatment effectively reduced the vegetation competition and/or deer browsing.

Finally, regeneration stocking charts and equations were developed for the mixed-oak forest in the central Appalachian region. Stocking charts were built separately for plots having average seedling height below and above nine feet by plotting cumulative height on the y-axis and number of seedlings on the x-axis on a log-log scale. Two stocking equations were also developed for plots with short seedlings and for plots with tall seedlings. The stocking charts and equations provide an objective basis for evaluating stocking of young regeneration in the upland mixed-oak forest.

## Literature Cited


Abrams, M.D. 1992. Fire and the development of oak forests. BioScience: 42:346-353.

Abrams, M.D. 1998. The red maple paradox. BioScience. 45: 355-363.

Abrams, M.D. 2003. Where has all the white oak gone? BioScience. 53: 927-939.

Adams, A.S. and L.K. Rieske. 2003. Prescribed fire affects white oak seedling phytochemistry: Implications for insect herbivory. For. Ecol. Manage. 176: 37-47.

Allen, D. and Bowersox, T.W. 1989. Regeneration in oak stands following gypsy moth defoliations. In Proceedings, Seventh Central Hardwood Forest Conference, Southern Illinois University, Carbondale. (G. Rink and C.A. Budelsky, eds.). USDA North Central Research Station, St. Paul, MN. Gen. Tech. Rpt. NC-132: 67-73.

Avery, T.E. and H. E. Burkhart 1994. Forest Measurements. McGraw-Hill. New York. 408p.

Bailes, W.W. and J.R. Brooks. 2004. a comparison of two double sampling auxiliary variables with inventories of varying sample size. USDA For. Serv. Gen. Tech. Rep. NE-316: 101-105.

Bailey, R.G., P. E. Avers, T. King, and W. H. McNab. eds. 1994. Ecoregions and subregions of the United States (map). USG.S. Wahington, D.C.

Barnes, B.V., D.R. Zak, S.R. Denton and S.H. Spurr 1998. Forest Ecology. John Wiley and Sons. New York. 774p.

Barnett, R.J. 1977. The effect of burial by squirrels on germination and survival of oak and hickory nuts. Amer. Mid. Nat 98: 319-330.

Beck, D.E. 1970. Effects of competition on survival and height growth of red oak seedlings. USDA For. Serv. Res. Pap. SE-56. 7 p.

Beck, D.E. and R.M. Hooper. 1986. Development of a southern Appalachian hardwood stand after clearcutting. South. J. of Appl. For. 10: 168-172.

Beekhuis, J. 1965. Crown depth of radiata pine in relation to stand density and height. NZ. J. For. 10: 43-61.

Belcher, D.W., M.R. Holdway and G.J. Brand. 1982. A description of STEMS the stand and tree evaluation and modeling system. USDA. For. Serv. Gen. Tech. Rep. NC-79. 18p.

Bickford, D.A., F.S. Bake, and F.G. Wilson. 1957. Stocking, normality, and measurement of stand density. J. For. 55: 99-104.

Bowersox, T.W. and L.H. McCormick. 1987. Herbaceous communities reduce the juvenile growth of northern red oak, white ash, yellow-poplar, but not white pine. In: Proceedings of 6th central hardwoods forest conference. Koxville, TN. P.39-43.

Bowersox, T.W. and W.W. Ward. 1972. Prediction of Advance Regeneration in Mixed-oak stands of Pennsylvania. For. Sci. 18: 278-282.

Bragg. D.C. 2001. A local basal area adjustment for crown width prediction. North. J. Appl. For. 18(1): 22-28.

Briegleb, P.A. 1952. An approach to density measurement in Douglas-fir. J. For. 50: 529-536.

Brose, P., D. VanLear, and R. Cooper. 1999. Using shelterwood harvests and prescribed fire to regenerate oak stands on productive upland sites. For. Ecol. Manag. 113(2-3): 125-141.

Carvell, K.L. and E.H. Tryon. 1961. The effect of environmental factors on the abundance of oak regeneration beneath mature oak stands. For. Sci. 7(2): 98-105.

Chapman G.L. 1950. The influence of mountain-laurel undergrowth on environmental conditions and oak reproduction. Ph.D. dissertation, Yale University. 157 p.

Chrisman, H.H. and F.X. Schumacher. 1940. On the tree-area ratio and certain of its applications. J. For. 38: 311-317.

Church, T.W. 1960. Factors afftecting the development and survival of surgar male sprouts. Soc. Amer. Foresters Proc. 1960: 32-35.

Collins, R.J. and W.P. Carson. 2004. The effects of environment and life stage on *Quercus* abundance in the eastern deciduous forest, USA: are sapling densities most responsive to environmental gradients? For. Ecol. Manage. 201:241-258.

Cottam, W. and J.T. Curtis. 1956. The use of distance measures in phytosociological sampling. Ecology 37: 451-460.

Crow, T. R. 1988. Reproductive mode and mechanisms for self-replacement of northern red oak – a review. For. Sci. 34: 19-40.

Cuff, D.J., W. J. Young, E.K. Muller, W. Zelinsky, and R.F. Abler eds. 1989. The Atlas of Pennsylvania. Temple University Press. Philadelphia, PA. 288p.

Curtis, R.O. 1982. A simple index of stand density for Douglas-fir. For. Sci. 28: 92-94.

Daniel, T.W., J.A. Helms, and F.S. Baker. 1979. Principles of silviculture edition 2. McGraw-Hill Press. New York.

Davis, T.A.W. and P.W. Richards. 1933. The vegetation of Moraballi Creek, British Guiana, an ecological study limited area of Tropical Rain Forest, Part I. J. Ecol. 21: 350-384.

Davis, T.A.W. and P.W. Richards. 1934. The vegetation of Moraballi Creek, British Guiana, an ecological study limited area of Tropical Rain Forest, Part II. J. Ecol. 22: 106-155.

Dey, D.C. 1991. A comprehensive Ozark regenerator. Ph.D. Dissertation. Columbia, MO. University of Missouri. 283p.

Dey, D.C., P.S. Johnson and H.E. Garrett. 1998. Improving estimates of acceptable growing stock in young upland oak forests in the Missouri Ozarks. North. J. Appl. For. 15(1): 28-32.

Galford, J., L.R. Auchmoody, H. C. Smith, and R.S. Walters. 1991. Insects affecting establishment of northern red oak seedlings in central Pennsylvania. In: Proceedings of the 8th central hardwood forest conference. USDA For. Serv. Gen. Tech. Rep. NE-148: 271-280.

George, D.W., T.W. Bowersox and L.H. McCormick. 1991. Effectiveness of electric deer fences to protect planted seedlings in Pennsylvania. In: Proceedings of the 8th central hardwood forest conference. USDA For. Serv. Gen. Tech. Rep. NE-148: 395-401.

George, L.O., and F.A. Bazzaz. 1999. The fern understory as an ecological filter: growth and survival of canopy-tree seedlings. Ecol. 80: 846-856.

Gevorkiantz, S.R. and H.F. Scholz. 1948. Timber yields and possible returns from the mixed-oak farmwoods of southwestern Wisconsin. USDA For. Serv. Lake States Forest Experiment Station Publication 521.

Gilmore, D.W. 2003. A stocking guide for European Larch in eastern North America. North. J. Appl. For. 20: 34-38.

Gingrich, S.F. 1964. Criteria for measuring stocking in forest stands. Proceedings of 1964 Society American Foresters and National Convention: 198-201.

Gingrich, S.F. 1967. Measuring and evaluating stocking and stand density in upland hardwood forests in the Central States. For. Sci. 13: 38-53.

Goebel, P. C. and D. M. Hix. 1996. Development of mixed-oak forests in south-eastern Ohio: A comparison of second-growth and old-growth forests. For. Ecol. Manage. 84:1-21.

Gribko, L.S., T.M. Schuler, and W.M. Ford. 2002. Biotic and abiotic mechanisms in the establishment of northern red oak seedlings: a review. USDA Forest Service. Northeastern Research Station. GTR NE-295. 18 p.

Groninger, J.W. and L.H. McCormick. 1991. Invasion of a partially cut oak stand by hayscented fern. In Proceedings of the Eighth Central Hardwood Forest Conference, The Pennsylvania State University, University Park. (L.H. McCormick and K.W. Gottschalk, eds.). USDA Northeastern Forest Experiment Station, Randor, PA.Gen. Tech. Rpt. NE-148: 585-586

Hanson, P.J. and R.K. Dixon. 1987. Allelopathic effects of interrupted fern on northern red oak seedlings: Amelioration by Suillus luteus. Plant and Soil 98: 43-52.

Hicks, R.R. 1997. A resource at the crossroads: a history of the central hardwoods. USDA Forest Service Gen. Tech. Rpt. NC-188: 1-22.

Hill, J.P. and D.I. Dickmann. 1988. A comparison of three methods for naturally reproducing oak in southern Michigan. North. J. Appl. For. 5:113-117.

Hilt, D.C. 1985. User's guide to OAKSIM an individual-tree growth and simulator for managed, even-aged, upland oak stands. USDA. For. Serv. Gen. Tech. Rep. NE-104. 22p.

Honeycutt, C.W., R. L. Blevins, and R. F. Wittwer. 1982. Growth of white oak (Quercus alba L.) in relation to soil and site properties in eastern Kentucky. In Proceedings, 4th Central Hardwood Forest Conference, University of Kentucky Press. 193-206.

Horsley, S.B. 1982. Development of reproduction in Allegheny hardwood stands after herbicide-clearcuts and herbicide-shelterwood cuts. USDA For. Serv. Res. Note NE-308.

Horsley, S.B., 1993. Mechanisms of interference between hay-scented fern and black cherry. Can. J. For. Res. 23: 2059-2069.

Horsley, S.B., L.H. McCormick, and J.W. Groninger. 1992. Effects of timing of oust application on survival of hardwood seedlings. North. J. Appl. For. 9: 22-27.

Host, G.E., K.S. Pregitzer, C.W. Ramm, J.B. Hart, and D.T. Cleland. 1987. Landform-mediated differences in Successional pathways among upland forest ecosystems in northwestern lower Michigan. For. Sci. 33: 445-457.

Hughes, J.F. and T.J. Fahey. 1991. Colonization dynamics of herbs and shrubs in disturbed northern hardwood forest. J. Ecol. 79:605-616.

Jack, S.B. and J.N. Long. 1996. Linkages between silviculture and ecology: an analysis of density management diagrams. For. Ecol. Manage. 83: 205-220.

Johnson, P.S. 1975. Growth and structural development of red oak sprout clumps. For. Sci. 21(4):413-418.

Johnson, P.S. 1977. Predicting oak stump sprouting and sprout development in the Missouri Ozarks. USDA For. Serv. Res. Pap. NC-149. 11p

Johnson, P.S. and I.L. Sander. 1988. Qualifying regeneration potentials of Quercus forests in the Missouri Ozarks. USDA For. Serv. Gen. Tech. Rep. NC-120: 377-385.

Johnson, P.S. and R. Rogers. 1984. Predicting 25th-year diameters of thinned stump sprouts of northern red oak planting stock. For. Sci. 30: 1017-1026.

Johnson, P.S., R.D. Jacobs, A.J. Martin, and E.D. Godell. 1989. Regeneration northern red oak: three successful case histories. North. J. Appl. For. 6: 174-178.

Johnson, P.S., S.R. Shifley, and R. Rogers. 2002. The ecology and silviculture of oaks. CABI publishing, New York. 503 p.

Johnson, W.C. and C.S. Adkisson. 1986. Airlifting the oaks. Nat. Hist. 10: 41-49.

Kershaw, K.A. and J.H.H. Looney. 1985. Quantitative and Dynamic Plant Ecology. 3rd Edition. Edward Arnold Press, Victoria. 282p.

Kimmins, J. P. 1987. *Forest Ecology*. Macmillan Publishing Company, New York. 531 pp.

Koop, H. 1989. Forest dynamics. Springer-Verlag. Belta Offetdrunk printing. 229p.

Krajicek, J.E. and Mikihiro. 1977. Studies on the morphology and dimensions of tree crowns in evenaged stand of Sugi. J. Jap. For. Soc. 59: 233-240.

Krajicek, J.E., K.A. Brinkman, and S.F. Gingrich. 1961. Crown competition – a measure of density. For. Sci. 7: 35-42.

Leak, W.B., D.S. Solomon, and S.M. Filip. 1969. A silvicultural guide for northern hardwoods in the northeast. USDA For. Serv. Res. Pap. NE-143.

Loftis, D.L. 1990a. A shelterwood method for regenerating red oak in the Southern Appalachians. For. Sci. 36(4): 908-916.

Loftis, D.L. 1990b. Predicting post-harvest performance of advance red oak reproduction in the southern Appalachians. For. Sci. 36: 908-916.

Long, J.N. 1985. A practical approach to density management. For. Chron. 61: 23-27.

Lorimer, C., J. Chapman and W. Lambert. 1994. Tall understorey vegetation as a factor in the poor development of oak seedlings beneath mature stands. J. Ecol. 82: 227-237.

Lorimer, C.G. 1984. Development of the red maple understory in northeastern oak forests. For. Sci. 33: 445-457.

Lorimer, C.G. 1992. Causes of the oak regeneration problem. In: Oak Regeneration: Serious problems practical recommendation. USDA For. Serv. Gen. Tech. Rep. SE-84: 14-39.

Lorimer, C.G., J.W. Chapman and W.D. Lambert. 1994. Tall understorey as a factor in the poor development of oak seedlings beneath mature stands. J. Ecol. 82: 227-237.

Lowell, K.E., R.J. Mitchell, P.S. Johnson, H.E. Garrett, and G.S. Cox. 1987. Predicting growth and "success" of coppice-regeneration oak stems. For. Sci. 36(4): 740-749.

Lyon, J. and W.E. Sharpe. 1996. Hay-scented fern interference with growth of northern red oak seedlings. Tree-Phys. 16(11-12): 923-932.

MacLean, C. 1979. Relative density: The key to stocking assessment in regional analysis. USDA For. Serv. Gen. Tech. Rep. PNW-78.

Marquis, D.A. and M. J. Twery. 1992. Decision-Making for natural regeneration in the northern forest ecosystem. In: Oak Regeneration: Serious Problems. USDA For. Serv. Gen. Tech. Rep. SE-84: 156-171.

Marquis, D.A. 1994. Quantitative silviculture for hardwood forests of the Alleghenies. Gen. Tech. Rpt. NE-183. USDA NE Exp. Station, Randor, PA. 376 p.

Marquis, D.A. and R. Brennman. 1981. The impact of deer on forest vegetation in Pennsylvania. USDA For. Serv. Gen, Tech. Rep. NE-65. 7p.

Marquis, D.A. and R.L. Ernst. 1988. User's guide to SILVAH a stand analysis, prescription and management simulator program for hardwood stands of the Alleghenis. PA: USDA For. Serv. NE Exp. Station. 161p.

Marquis, D.A., P.L. Eckert and B.A. Roach. 1976. Acorn weevils, rodents and deer all contribute to oak regeneration difficulties in Pennsylvania. USDA For. Serv. Res. Pap. NE-356.

Martin, C.W. and L.M. Tritton. 1991. Role of sprouts in regeneration of a whole-tree clearcut in central hardwoods of Connecticut. In: 8th Central Hardwood Forest Conference. USDA. For. Serv. Gen. Tech. Rep. NE-148: 305-320.

Maslen, P. (1988) Response of immature oaks to prescribed fore in the North Carolina piedmont. In: Fifth biennial southern silvicultrual research conference. USDA. For. Serv. Gen. Tech. Rep. SO-74: 259-266.

McCune, B. and G. Cottam. 1985. The successional status of a southern Wisconsin oak woods. Ecol. 66: 1270-1278.

McCune, B. and J.B. Grace. 2002. Analysis of Ecological Communities. MjM software design press. Gleneden Beach, Oregon. 300p.

McGill, D.W., R. Rogers, A.J. Martin, and P.S. Johnson. 1999. Measuring stocking in Northern red oak stand in Wisconsin. North. J. Appl. For. 16(3): 144-150.

McIntyre, A.C. 1936. Sprout groups and their relation to the oak forests of Pennsylvania. J. For. 32: 1054-1058.

McQuilkin, R.A. 1975. Growth of four types of white oak reproduction after clearcutting in the Missouri Ozarks. USDA For. Serv. Res. Pap. NC-116.

McQuilkin. R.A. 1990. In: Silvics in North America. USDA Forest Service. Agriculture handbook 654: 605-613.

McWilliams, W.H., C.A. Alerich, D.A. Devlin, A.J. Lister, T.W. Lister, S.L. Sterner, and J.A. Westfall. 2004. Annual inventory report for Pennsylvania's forests: results from the first three years. USDA Forest Service. NE-159 95 p.

McWilliams, W.H., S.L. Stout, T.W. Bowersox, and L.H. McCormick. 1995. Adequacy of advance tree-seedling regeneration in Pennsylvania's forests. Northern J. Appl. For. 12: 187-191.

Miller, A.S., and D.R. Phillips. 1984. Chainsaw and shear cutting of upland hardwoods: Impact on regeneration. Georgia For. Comm. For. Res. Pap. 53: 4-11.

Miner, C.L., N.R. Walters and M.L. Belli. 1988. A guide to the TWIGS program for the North Central United States. USDA. For. Serv. Gen. Tech. Rep. NC-125. 105p.

Moser, K.W., M.J. Ducey, and P.M.S. Ashton. 1996. Effects of fire intensity on competitive dynamics between red and black oaks and mountain-laurel. Nor. J. App. For. 13 (3): 199-123.

Mueller-Dombois, D. and H. Ellenberg. 1974. Aims and Methods of Vegetation Ecology. John Willey & Sons Press, New York. 547p.

Myers, J.R. 1985. A comparison of two-stage sampling designs with an Appalachian hardwood population. M.S. Thesis. West Virginia University, Morgantown, WV. 75pp.

Neter, J., Kutner, M.H., Nachtshein, C.J. and Wasserman, W. 1996. Applied Linear Statistical Models. McGraw-Hill. USA. 1408 p.

Niklas, K.J. 1994. Plant allometry. The University of Chicago Press, Chicago. 395pp.

Northrup, M.J. 2003. Classifying patterns of vegetation and regeneration in mixed-oak forests of Pennsylvania. Master thesis, The Pennsylvania State University. 145 p.

Nowacki, G.J., M.D. Abrams, and C.G. Lorimer. 1990. Composition, structure, and historical development of northern red oak stands along an edaphic gradient in north-central Wisconsin. For. Sci. 36: 276-292.

Oliver, C.D. and B.C. Larson. 1996. Forest stand dynamics. John Wiley & Sons, Inc. New York. 520p.

Palik, B.J. and K.S. Pregitzer. 1992. The age and height structure of red maple (*Acer rubrum*) populations in northern Michigan bigtooth aspen (*Populus grandidentata*) forests. Can. J. For. Res. 22: 1449-1462.

Pennsylvania Bureau of Forestry. 1975. A chronology of events in Pennsylvania forestry. Published by Pennsylvania Bureau of Forestry.

Pubanz, D.M. and C.G. Lorimer. Oak regeneration experiments in southwestern Wisconsin: two-year results. Res. Pap. R3552. Madison, WI: School of Natural Resources, College of Agricultural and Life Sciences, University of Wisconsin-Madison. 16p.

Pyne, S.J. 1982. Fire in America. Princeton University Press. Princeton, New Jersey.

Reineke, L.H. 1933. Perfecting a stand-density index for even-aged forests. J. Ag. Res. 46: 627-638.

Roach, B.A. 1977. A stocking guide for Allegheny hardwoods and its use in controlling intermediate cuttings. USDA For. Serv. Gen. Tech. Pap. NE-373. 30p.

Robles, C., J. B. Fehrenbacher, and A. R. Gilmore. 1976. Site productivity of oaks in relation to soil taxonomic units in northern Illinois. In Proceedings, First Central Hardwood Forest Conference. 299-307.

Rogers, R. 1974. Blueberries [forest ranges]. USDA Forest Service. GTR NE-9:12-15.

Rogers, R. and P.S. Johnson. 1993. Describing population dynamics of northern red oak. In: Symposium on environmental constraints and oaks: ecological and physiological aspects. Nancy, France, p.95.

Rogers, R. and P.S. Johnson. 1998. Approaches to modeling natural regeneration in oak-dominated forests. For. Ecol. Manag. 106: 45-54.

Ross, M.S., T.L. Sharik, and D.W. Smith. 1986. Oak regeneration after clear felling in southwest Virginia. For. Sci. 32: 157-169.

Roth, E.R. and G.H. Hepting. 1943. Origin and development of oak srump sprouts as affecting their likelihood to decay. J. For. 41: 27-36.

Sakai, A.K., M.R. Roberts, and C.L. Jolls. 1985. Successional changes in a mature aspen forest in northern lower Michigan: 1974-1981 Amer. Mid. Nat. 113: 271-282.

Sampson, T.L. 1983. A stocking guide for northern red oak in New England. University of New Hampshire, Durham. 98p. Thesis.

Sander, I.L. 1972. Size of oak advance reproduction: Key to growth following harvest cutting. USDA For. Serv. Res. Pap. NC-79.

Sander, I.L. and F.B. Clark. 1971. Reproduction of upland hardwood forests in the Central States. Ag. Handb. No. 405. USDA For. Serv. 25p.

Sander, I.L., P.S. Johnson and R. Rogers. 1984. Evaluating oak advance reproduction in the Missouri Ozarks. USDA For. Serv. Res. Pap. NC-251. 16p.

Schuler, T.M. and G.W. Miller. 1995. Shelterwood treatments fail to establish oak regeneration on mesic forest sites in West Virginia. USDA. For. Serv. Gen. Tech. Rep. NE-197: 375-387.

Seymour, R.S. and D.M. Smith. 1987. A new stocking guide frmulation applied to eastern white pine. For. Sci. 33: 469-484.

Smith, D.M. 1986. The practice of silviculture. 8th ed. John Wiley & Sons, New York. 527 p.

Smith, D.M., B.C. Larson, M.J. Kelty, P.M.S. Ashton. 1997. The practice of silviculture. John Wiley & Sons Inc. New York. 537p.

Smith, L.L. and J. L. Vankat. 1991. Communities and tree seedling distribution in *Quercus rubra*- and *Prunus serotina*-dominated forest in southern Pennsylvania. Am. Midl. Nat. 126: 294-307.

Solomon, D.S., and B.M. Blum. 1967. Stump sprouting of four northern hardwoods. USDA. For. Serv. Gen. Tech. Rep. NE-59. 13 p.

Steiner, K.C. 1995. Autumn predation of northern red oak seed crops. In: Procedings of 10th central hardwood forest conference. USDA For. Serv. Gen. Tech. Rep. NE-197: 489-494.

Steiner, K.C. and B.J. Joyce. 1999. Survival and growth of a *Quercus rubra* regeneration cohort during five years following masting. In: Proceedings of the 12th central hardwood forest conference. USDA For. Serv. Gen. Tech. Rep. SRS-24: 255-257.

Stout, S.L. 1991. Stand density, stand structure, and species composition in transition oak stands of northwestern Pennsylvania. USDA Forest Service Gen. Tech. Rpt. NE-148: 194-206.

Stout, S.L., B.C. Larson, 1988. Relative stand density: Why do we need to know? In: Schmidt, Wyman C., Comp. Proc. stand culture symp.: Future forests of the mountain west. 1986 September 29 - October 3. Missoula, MT. Ogden, UT: USDA For. Serv. Gen. Tech. Rep. INT-243: p. 73-79. 402p.

Stout, S.L., D.A. Marquis and R.L. Ernst. 1987. A relative density measure for mixed-species stands. J. For. 85(7): 45-47.

Ter-Mikaelian, M.T. and M.D. Korzukhin 1997. Biomass equations for sixty-five North American tree species. For. Ecol. Manage. 97: 1-24.

Triplehorn, R. 1955. The Asiatic oak weevil in Delaware. J. Econ. Ent. 48: 289-293.

Tritton, L.M. and J.W. Hornbeck 1982. Biomass equations for major tree species of the northeast. USDA For. Serv. Gen. Tech. Rep. NE-69.

Trumbull, V.L., E.J. Zielinski, and E.C. Aharrah. 1989. The impact of deer browsing on the Allegheny forest type. North. J. Appl. For. (6): 162-165.

USDA Soil Conservation Service. 1981. Soil survey of Centre County, Pennsylvania. 162 p.

USDA Soil Conservation Service. 1993. Soil survey of Cameron and Elk counties, Pennsylvania. 132 p.

USDA-NRCS Soil Survey Division. 2003. http://nasis.usda.gov/reportest

USGS. 2003. http://ned.usgs.gov

Vandermast, D.B., D.H. Van Lear, and B.D. Clinton. 2002. American chestnut as an allelopath in the southern Appalachians. For. Ecol. Manage. 165:173-181.

Waldrop, T.A., E.R. Buckner, H.H. Shugart and C.E. McGee. 1986. FORCAT: a single tree model and stand development following clearcutting on the Cumberland Plateau. For. Sci. 32:297-317.

Walters, R.S. and H.W. Yawney. 1990. In: Silvics of North America. USDA For. Serv. Agriculture handbook 654: 60-69.

Ward J. S. and E. Gluck. 1999. Using prescribed burning to release oak seedlings from shrub competition in southern Connecticut USDA Forest Service GTR SRS-188: 283.

Ward, J.H. 1963. Hierachical grouping to optimize an objective function. J. Amer. Stat. Assoc. 58: 236-244.

Ward, J.S. and G.R. Stephens. 1994. Crown class transition rates of maturing northern red oak. For. Sci. 40: 221-237.

Waterman, J.R., A.R. Gillespie, J.M. Vose, and W.T. Swank. 1995. The influence of mountain-laurel on regeneration of pitch pine canopy gaps of the Coweeta Basin, North Carolina, USA. Can. J. For. Res. 25: 1756-1762.

Weigel, D.R. and P.S. Johnson. 1988. Planting northern red oak in the Ozark Highlands: A shelterwood prescription. USDA For. Ser. TB-NC-6.

Wendel, G.W. 1975. Stump sprout growth and quality of several Appalachian hardwood species after clearcutting. USDA For. Serv. Res. Pap. NE-375.

White, L.L., D.R. Zak and B.V. Barnes 2004. Biomass accumulation and soil nitrogen availability in an 87-year-old *Populus grandidentata* chronosequence. For. Ecol. Manage. 191: 121-127.

Wiant, H.V. and B. Zeide. 1979. A note on double sampling – point sampling. BLM Inventory Resources Notes 24:13-14.

Williams, R.A. 2003. Use of stand density index as an alternative to stocking percent in Upland hardwoods. North. J. Appl. For. 20: 137-142.

Wilson, F.G. 1946. Numerical stocking in terms of height. J. For. 44: 758-761.

Zaczek, J.J. 2002. Composition, diversity, and height of tree regeneration, 3 years after soil scarification in a mixed-oak shelterwood. For. Ecol. Manage. 163: 205-215.

Zeide, B. and P. Pfeifer. 1991. A method for estimation of fractal dimension of tree crowns. For. Sci. 37: 1253-1265.

Appendix A1. Average densities of major overstory oak and non-oak species by stand.

| Stand ID | Density (stems/acre) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Red Maple | Black Birch | Black-gum | White Oak | Chestnut Oak | N. Red Oak | All Oaks | All Trees |
| 000100 | 76 | 9 | 57 | 43 | 7 | 1 | 58 | 239 |
| 000200 | 110 | 0 | 6 | 2 | 3 | 39 | 45 | 165 |
| 000300 | 55 | 5 | 64 | 0 | 57 | 4 | 62 | 195 |
| 000400 | 11 | 3 | 11 | 59 | 1 | 3 | 63 | 179 |
| 020100 | 147 | 39 | 7 | 0 | 34 | 46 | 88 | 286 |
| 020200 | 127 | 0 | 0 | 5 | 1 | 84 | 93 | 229 |
| 020300 | 89 | 3 | 12 | 9 | 1 | 38 | 51 | 173 |
| 020400 | 126 | 0 | 0 | 9 | 2 | 59 | 70 | 203 |
| 020500 | 132 | 1 | 0 | 3 | 5 | 25 | 34 | 192 |
| 020600 | 97 | 1 | 84 | 15 | 27 | 5 | 48 | 256 |
| 020700 | 135 | 17 | 0 | 0 | 3 | 20 | 23 | 197 |
| 030100 | 54 | 57 | 98 | 8 | 43 | 17 | 72 | 288 |
| 030200 | 94 | 1 | 4 | 10 | 21 | 5 | 51 | 178 |
| 030300 | 185 | 3 | 2 | 20 | 15 | 6 | 45 | 303 |
| 030400 | 90 | 0 | 0 | 3 | 2 | 24 | 31 | 182 |
| 030500 | 176 | 0 | 0 | 6 | 1 | 33 | 42 | 245 |
| 030600 | 82 | 9 | 8 | 37 | 26 | 55 | 124 | 273 |
| 960100 | 36 | 0 | 1 | 2 | 70 | 16 | 102 | 150 |
| 960200 | 160 | 0 | 6 | 26 | 34 | 30 | 99 | 282 |
| 960300 | 66 | 20 | 10 | 3 | 33 | 38 | 76 | 205 |
| 960400 | 43 | 28 | 88 | 1 | 52 | 9 | 63 | 270 |
| 960600 | 127 | 4 | 7 | 6 | 3 | 39 | 49 | 214 |
| 960700 | 29 | 5 | 100 | 37 | 47 | 3 | 109 | 277 |
| 961100 | 159 | 1 | 0 | 19 | 25 | 28 | 83 | 273 |
| 961200 | 72 | 0 | 15 | 46 | 58 | 5 | 132 | 280 |
| 970100 | 37 | 1 | 3 | 11 | 44 | 31 | 104 | 174 |
| 970200 | 102 | 6 | 2 | 11 | 57 | 12 | 82 | 238 |
| 970600 | 65 | 1 | 0 | 13 | 11 | 39 | 81 | 156 |
| 971100 | 195 | 21 | 13 | 10 | 38 | 8 | 83 | 339 |
| 971400 | 51 | 52 | 14 | 7 | 35 | 7 | 60 | 232 |
| 971500 | 121 | 61 | 35 | 1 | 16 | 17 | 38 | 363 |
| 971600 | 128 | 0 | 26 | 18 | 23 | 10 | 54 | 213 |
| 971700 | 89 | 0 | 22 | 9 | 46 | 3 | 75 | 223 |
| 971800 | 66 | 10 | 49 | 5 | 99 | 28 | 150 | 481 |
| 980100 | 47 | 0 | 13 | 19 | 13 | 9 | 61 | 129 |
| 980200 | 111 | 1 | 2 | 9 | 69 | 38 | 130 | 271 |
| 980300 | 54 | 10 | 10 | 42 | 14 | 4 | 73 | 252 |
| 980400 | 90 | 3 | 136 | 0 | 101 | 10 | 113 | 349 |
| 980500 | 57 | 53 | 11 | 10 | 38 | 8 | 66 | 244 |
| 980600 | 73 | 0 | 0 | 11 | 133 | 5 | 169 | 259 |
| 980700 | 59 | 9 | 21 | 8 | 14 | 8 | 33 | 194 |
| 980800 | 79 | 0 | 25 | 9 | 18 | 9 | 39 | 149 |
| 990100 | 81 | 47 | 25 | 5 | 19 | 13 | 37 | 213 |
| 990200 | 102 | 0 | 0 | 9 | 10 | 23 | 56 | 205 |
| 990300 | 120 | 0 | 6 | 31 | 8 | 9 | 56 | 214 |
| 990400 | 108 | 7 | 23 | 6 | 41 | 26 | 79 | 219 |
| 990500 | 43 | 12 | 0 | 5 | 28 | 10 | 48 | 135 |
| 990600 | 93 | 0 | 0 | 7 | 19 | 26 | 61 | 177 |
| 990700 | 98 | 0 | 0 | 10 | 6 | 35 | 60 | 163 |
| 990800 | 67 | 0 | 1 | 8 | 1 | 32 | 45 | 129 |
| 990900 | 90 | 1 | 43 | 4 | 30 | 19 | 61 | 207 |
| 991000 | 100 | 0 | 8 | 35 | 25 | 11 | 82 | 214 |

Appendix A2. Average basal areas of major overstory oak and non-oak species by stand.

| Stand ID | Basal Area (ft$^2$/acre) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Red Maple | Black Birch | Black-gum | White Oak | Chestnut Oak | N. Red Oak | All Oaks | All Trees |
| 000100 | 13 | 1 | 9 | 45 | 9 | 1 | 64 | 95 |
| 000200 | 42 | 0 | 1 | 1 | 3 | 69 | 74 | 121 |
| 000300 | 14 | 1 | 20 | 0 | 72 | 2 | 77 | 113 |
| 000400 | 2 | 0 | 2 | 57 | 1 | 4 | 61 | 87 |
| 020100 | 25 | 13 | 1 | 0 | 28 | 54 | 90 | 130 |
| 020200 | 36 | 0 | 0 | 3 | 0 | 92 | 99 | 137 |
| 020300 | 39 | 1 | 5 | 7 | 1 | 47 | 59 | 109 |
| 020400 | 27 | 0 | 0 | 7 | 2 | 85 | 94 | 124 |
| 020500 | 55 | 0 | 0 | 2 | 4 | 38 | 45 | 103 |
| 020600 | 21 | 0 | 14 | 20 | 26 | 9 | 57 | 100 |
| 020700 | 32 | 3 | 0 | 0 | 5 | 51 | 56 | 96 |
| 030100 | 13 | 6 | 18 | 7 | 36 | 20 | 68 | 106 |
| 030200 | 31 | 0 | 0 | 14 | 17 | 7 | 66 | 113 |
| 030300 | 50 | 2 | 0 | 21 | 13 | 6 | 43 | 106 |
| 030400 | 41 | 0 | 0 | 4 | 2 | 59 | 74 | 128 |
| 030500 | 46 | 0 | 0 | 5 | 1 | 49 | 57 | 105 |
| 030600 | 13 | 3 | 1 | 24 | 14 | 65 | 110 | 137 |
| 960100 | 7 | 0 | 0 | 1 | 55 | 14 | 83 | 93 |
| 960200 | 26 | 0 | 1 | 19 | 25 | 38 | 95 | 124 |
| 960300 | 12 | 8 | 2 | 3 | 23 | 54 | 84 | 108 |
| 960400 | 13 | 15 | 11 | 0 | 52 | 13 | 66 | 110 |
| 960600 | 31 | 1 | 0 | 6 | 2 | 60 | 68 | 108 |
| 960700 | 4 | 0 | 11 | 25 | 29 | 2 | 73 | 93 |
| 961100 | 36 | 0 | 0 | 14 | 18 | 33 | 77 | 116 |
| 961200 | 12 | 0 | 2 | 22 | 34 | 4 | 85 | 106 |
| 970100 | 8 | 0 | 0 | 7 | 23 | 32 | 78 | 90 |
| 970200 | 20 | 1 | 0 | 8 | 43 | 14 | 67 | 99 |
| 970600 | 18 | 0 | 0 | 8 | 8 | 57 | 92 | 112 |
| 971100 | 27 | 2 | 2 | 3 | 22 | 5 | 42 | 77 |
| 971400 | 11 | 9 | 2 | 11 | 49 | 6 | 84 | 130 |
| 971500 | 29 | 4 | 6 | 0 | 24 | 26 | 56 | 105 |
| 971600 | 19 | 0 | 4 | 15 | 23 | 14 | 55 | 79 |
| 971700 | 13 | 0 | 4 | 6 | 30 | 2 | 60 | 82 |
| 971800 | 5 | 2 | 3 | 2 | 50 | 18 | 82 | 117 |
| 980100 | 10 | 0 | 2 | 19 | 10 | 20 | 91 | 106 |
| 980200 | 10 | 0 | 0 | 6 | 45 | 38 | 99 | 118 |
| 980300 | 12 | 1 | 2 | 49 | 13 | 7 | 87 | 124 |
| 980400 | 9 | 1 | 16 | 0 | 67 | 11 | 79 | 108 |
| 980500 | 9 | 7 | 1 | 9 | 41 | 11 | 78 | 120 |
| 980600 | 8 | 0 | 0 | 6 | 71 | 6 | 97 | 106 |
| 980700 | 13 | 5 | 5 | 9 | 13 | 8 | 34 | 111 |
| 980800 | 10 | 0 | 5 | 15 | 15 | 18 | 55 | 74 |
| 990100 | 27 | 18 | 6 | 9 | 25 | 18 | 55 | 113 |
| 990200 | 30 | 0 | 0 | 7 | 6 | 30 | 59 | 91 |
| 990300 | 27 | 0 | 1 | 17 | 4 | 9 | 41 | 72 |
| 990400 | 19 | 4 | 3 | 5 | 33 | 35 | 78 | 104 |
| 990500 | 8 | 1 | 0 | 5 | 31 | 18 | 58 | 72 |
| 990600 | 25 | 0 | 0 | 9 | 19 | 34 | 73 | 105 |
| 990700 | 27 | 0 | 0 | 10 | 4 | 62 | 92 | 121 |
| 990800 | 24 | 0 | 0 | 6 | 1 | 53 | 66 | 97 |
| 990900 | 16 | 1 | 7 | 4 | 25 | 39 | 77 | 105 |
| 991000 | 22 | 0 | 1 | 23 | 20 | 12 | 71 | 98 |

Appendix A3. Occurrence frequencies of major overstory oak and non-oak species by stand.

| Stand ID | Frequency (percent) | | | | | | |
|---|---|---|---|---|---|---|---|
| | Red Maple | Black Birch | Black-gum | White Oak | Chestnut Oak | N. Red Oak | All Oaks |
| 000100 | 77 | 17 | 67 | 83 | 27 | 3 | 93 |
| 000200 | 100 | 0 | 13 | 7 | 10 | 80 | 80 |
| 000300 | 84 | 12 | 64 | 0 | 84 | 20 | 88 |
| 000400 | 27 | 13 | 20 | 93 | 7 | 7 | 93 |
| 020100 | 100 | 80 | 4 | 0 | 64 | 100 | 100 |
| 020200 | 100 | 0 | 0 | 17 | 3 | 90 | 97 |
| 020300 | 87 | 10 | 10 | 20 | 7 | 67 | 73 |
| 020400 | 97 | 0 | 0 | 37 | 10 | 100 | 100 |
| 020500 | 100 | 3 | 0 | 13 | 27 | 70 | 77 |
| 020600 | 93 | 7 | 87 | 50 | 67 | 17 | 90 |
| 020700 | 100 | 40 | 0 | 0 | 13 | 60 | 70 |
| 030100 | 88 | 73 | 78 | 28 | 85 | 43 | 93 |
| 030200 | 97 | 5 | 18 | 31 | 54 | 23 | 77 |
| 030300 | 95 | 11 | 5 | 50 | 39 | 18 | 84 |
| 030400 | 92 | 0 | 0 | 8 | 5 | 62 | 74 |
| 030500 | 100 | 0 | 0 | 23 | 3 | 77 | 87 |
| 030600 | 93 | 23 | 10 | 48 | 70 | 83 | 98 |
| 960100 | 62 | 0 | 3 | 5 | 92 | 46 | 100 |
| 960200 | 100 | 0 | 18 | 68 | 68 | 73 | 100 |
| 960300 | 100 | 44 | 19 | 13 | 81 | 81 | 94 |
| 960400 | 82 | 50 | 68 | 5 | 91 | 36 | 95 |
| 960600 | 100 | 10 | 13 | 20 | 10 | 77 | 83 |
| 960700 | 57 | 10 | 70 | 77 | 80 | 10 | 100 |
| 961100 | 97 | 6 | 0 | 45 | 65 | 65 | 97 |
| 961200 | 93 | 0 | 37 | 80 | 73 | 20 | 100 |
| 970100 | 90 | 5 | 10 | 43 | 76 | 71 | 100 |
| 970200 | 92 | 16 | 4 | 32 | 72 | 40 | 92 |
| 970600 | 90 | 3 | 0 | 37 | 23 | 93 | 100 |
| 971100 | 100 | 43 | 13 | 26 | 83 | 17 | 100 |
| 971400 | 87 | 77 | 27 | 23 | 77 | 33 | 83 |
| 971500 | 100 | 77 | 54 | 4 | 50 | 54 | 81 |
| 971600 | 96 | 0 | 50 | 46 | 57 | 36 | 89 |
| 971700 | 93 | 0 | 33 | 30 | 73 | 17 | 90 |
| 971800 | 76 | 10 | 48 | 7 | 97 | 76 | 100 |
| 980100 | 100 | 0 | 43 | 64 | 50 | 43 | 107 |
| 980200 | 93 | 7 | 7 | 17 | 83 | 63 | 97 |
| 980300 | 76 | 28 | 16 | 80 | 52 | 20 | 96 |
| 980400 | 97 | 13 | 87 | 0 | 97 | 33 | 100 |
| 980500 | 91 | 64 | 27 | 36 | 68 | 27 | 86 |
| 980600 | 87 | 0 | 0 | 23 | 97 | 20 | 100 |
| 980700 | 83 | 24 | 48 | 21 | 41 | 28 | 69 |
| 980800 | 75 | 0 | 44 | 44 | 56 | 31 | 75 |
| 990100 | 96 | 74 | 52 | 15 | 52 | 44 | 89 |
| 990200 | 93 | 0 | 0 | 33 | 30 | 50 | 83 |
| 990300 | 100 | 0 | 6 | 63 | 19 | 19 | 81 |
| 990400 | 100 | 27 | 57 | 20 | 70 | 67 | 97 |
| 990500 | 67 | 17 | 0 | 17 | 75 | 42 | 92 |
| 990600 | 100 | 0 | 0 | 28 | 44 | 78 | 100 |
| 990700 | 92 | 0 | 0 | 36 | 16 | 72 | 96 |
| 990800 | 90 | 0 | 3 | 37 | 3 | 80 | 93 |
| 990900 | 89 | 7 | 59 | 15 | 59 | 63 | 93 |
| 991000 | 93 | 0 | 10 | 90 | 50 | 27 | 100 |

Appendix A4. Importance values of major overstory oak and non-oak species by stand.

| Stand ID | Importance Value (percent) | | | | | | |
|---|---|---|---|---|---|---|---|
| | Red Maple | Black Birch | Black-gum | White Oak | Chestnut Oak | N. Red Oak | All Oaks |
| 000100 | 64 | 8 | 49 | 85 | 19 | 3 | 124 |
| 000200 | 145 | 0 | 10 | 5 | 9 | 116 | 130 |
| 000300 | 68 | 7 | 71 | 0 | 120 | 11 | 135 |
| 000400 | 15 | 5 | 13 | 121 | 4 | 7 | 132 |
| 020100 | 95 | 43 | 4 | 0 | 49 | 82 | 149 |
| 020200 | 122 | 0 | 0 | 11 | 2 | 140 | 162 |
| 020300 | 120 | 6 | 16 | 19 | 4 | 91 | 124 |
| 020400 | 118 | 0 | 0 | 24 | 6 | 133 | 163 |
| 020500 | 157 | 2 | 0 | 9 | 16 | 75 | 100 |
| 020600 | 82 | 2 | 68 | 39 | 53 | 15 | 109 |
| 020700 | 141 | 27 | 0 | 0 | 12 | 87 | 99 |
| 030100 | 50 | 42 | 68 | 16 | 68 | 34 | 128 |
| 030200 | 106 | 2 | 7 | 26 | 41 | 15 | 129 |
| 030300 | 137 | 6 | 2 | 41 | 29 | 14 | 92 |
| 030400 | 114 | 0 | 0 | 7 | 4 | 81 | 105 |
| 030500 | 155 | 0 | 0 | 17 | 3 | 91 | 115 |
| 030600 | 60 | 10 | 6 | 42 | 35 | 86 | 175 |
| 960100 | 53 | 0 | 2 | 3 | 139 | 42 | 223 |
| 960200 | 101 | 0 | 7 | 41 | 48 | 59 | 168 |
| 960300 | 66 | 27 | 11 | 7 | 55 | 86 | 157 |
| 960400 | 46 | 35 | 58 | 2 | 87 | 23 | 115 |
| 960600 | 121 | 6 | 8 | 15 | 7 | 99 | 121 |
| 960700 | 27 | 4 | 62 | 56 | 65 | 6 | 167 |
| 961100 | 113 | 2 | 0 | 31 | 41 | 55 | 151 |
| 961200 | 55 | 0 | 14 | 52 | 67 | 9 | 171 |
| 970100 | 50 | 2 | 4 | 24 | 68 | 69 | 201 |
| 970200 | 88 | 8 | 2 | 21 | 87 | 30 | 142 |
| 970600 | 84 | 2 | 0 | 26 | 21 | 102 | 195 |
| 971100 | 115 | 18 | 10 | 12 | 59 | 12 | 127 |
| 971400 | 46 | 43 | 12 | 16 | 66 | 13 | 120 |
| 971500 | 81 | 36 | 26 | 1 | 37 | 40 | 88 |
| 971600 | 114 | 0 | 33 | 42 | 58 | 34 | 143 |
| 971700 | 80 | 0 | 23 | 20 | 76 | 8 | 152 |
| 971800 | 35 | 6 | 23 | 4 | 84 | 38 | 152 |
| 980100 | 72 | 0 | 23 | 49 | 32 | 36 | 189 |
| 980200 | 74 | 2 | 3 | 13 | 85 | 62 | 183 |
| 980300 | 46 | 10 | 9 | 72 | 27 | 11 | 140 |
| 980400 | 61 | 5 | 78 | 0 | 117 | 22 | 143 |
| 980500 | 49 | 40 | 11 | 18 | 63 | 18 | 124 |
| 980600 | 60 | 0 | 0 | 16 | 146 | 13 | 212 |
| 980700 | 60 | 14 | 26 | 16 | 28 | 17 | 70 |
| 980800 | 93 | 0 | 39 | 41 | 52 | 41 | 152 |
| 990100 | 87 | 58 | 31 | 14 | 45 | 34 | 96 |
| 990200 | 114 | 0 | 0 | 23 | 21 | 61 | 144 |
| 990300 | 124 | 0 | 6 | 57 | 15 | 22 | 119 |
| 990400 | 94 | 14 | 28 | 13 | 69 | 63 | 159 |
| 990500 | 62 | 15 | 0 | 15 | 85 | 44 | 160 |
| 990600 | 102 | 0 | 0 | 20 | 40 | 67 | 157 |
| 990700 | 117 | 0 | 0 | 28 | 13 | 100 | 171 |
| 990800 | 108 | 0 | 2 | 25 | 2 | 108 | 151 |
| 990900 | 82 | 3 | 43 | 10 | 55 | 63 | 147 |
| 991000 | 93 | 0 | 7 | 64 | 46 | 25 | 162 |

Appendix B1. Average cover and occurrence frequency of major understory vegetation by stand.

| Stand ID | Hayscented fern | | Mountain-laurel | | Huckleberry | | Blueberry | |
|---|---|---|---|---|---|---|---|---|
| | Cover (%) | Freq. (%) | Cover (%) | Freq. (%) | Cover (%) | Freq. (%) | Cover (%) | Freq. (%) |
| 000100 | 0 | 1 | 5 | 30 | 10 | 67 | 14 | 91 |
| 000200 | 19 | 58 | 13 | 61 | 1 | 5 | 8 | 73 |
| 000300 | 3 | 13 | 17 | 82 | 3 | 14 | 14 | 87 |
| 000400 | 0 | 2 | 0 | 0 | 1 | 2 | 3 | 50 |
| 020100 | 5 | 21 | 3 | 15 | 6 | 39 | 12 | 88 |
| 020200 | 1 | 10 | 3 | 21 | 4 | 38 | 12 | 99 |
| 020300 | 6 | 28 | 0 | 2 | 1 | 3 | 4 | 73 |
| 020400 | 5 | 47 | 0 | 0 | 0 | 0 | 7 | 73 |
| 020500 | 50 | 93 | 2 | 16 | 0 | 1 | 2 | 35 |
| 020600 | 0 | 3 | 13 | 48 | 10 | 59 | 13 | 97 |
| 020700 | 22 | 83 | 24 | 55 | 0 | 2 | 1 | 35 |
| 030100 | 0 | 4 | 3 | 29 | 7 | 56 | 7 | 94 |
| 030200 | 3 | 19 | 0 | 1 | 1 | 6 | 7 | 68 |
| 030300 | 2 | 9 | 18 | 64 | 5 | 40 | 8 | 95 |
| 030400 | 22 | 67 | 0 | 0 | 0 | 1 | 0 | 3 |
| 030500 | 6 | 25 | 8 | 33 | 5 | 40 | 9 | 96 |
| 030600 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 15 |
| 960100 | 0 | 0 | 5 | 22 | 8 | 23 | 35 | 95 |
| 960200 | 0 | 0 | 15 | 45 | 0 | 5 | 6 | 42 |
| 960300 | 0 | 0 | 0 | 2 | 1 | 9 | 15 | 61 |
| 960400 | 0 | 0 | 13 | 58 | 7 | 35 | 4 | 56 |
| 960600 | 32 | 75 | 13 | 26 | 0 | 0 | 0 | 12 |
| 960700 | 0 | 0 | 2 | 11 | 33 | 95 | 21 | 99 |
| 961100 | 18 | 46 | 13 | 37 | 0 | 2 | 4 | 79 |
| 961200 | 0 | 5 | 19 | 66 | 1 | 5 | 25 | 96 |
| 970100 | 1 | 10 | 0 | 5 | 6 | 27 | 20 | 82 |
| 970200 | 0 | 13 | 20 | 79 | 2 | 21 | 9 | 89 |
| 970600 | 46 | 78 | 0 | 0 | 0 | 0 | 1 | 23 |
| 971100 | 0 | 2 | 41 | 97 | 17 | 70 | 12 | 86 |
| 971400 | 0 | 5 | 0 | 0 | 0 | 0 | 3 | 38 |
| 971500 | 2 | 18 | 0 | 0 | 0 | 3 | 8 | 71 |
| 971600 | 29 | 66 | 9 | 41 | 1 | 12 | 9 | 93 |
| 971700 | 5 | 19 | 0 | 0 | 9 | 27 | 14 | 77 |
| 971800 | 0 | 0 | 2 | 9 | 9 | 34 | 9 | 86 |
| 980100 | 4 | 14 | 0 | 0 | 10 | 43 | 13 | 91 |
| 980200 | 1 | 10 | 3 | 8 | 9 | 31 | 10 | 68 |
| 980300 | 0 | 2 | 0 | 2 | 0 | 4 | 4 | 55 |
| 980400 | 0 | 0 | 24 | 94 | 8 | 31 | 11 | 86 |
| 980500 | 0 | 0 | 0 | 0 | 1 | 6 | 7 | 58 |
| 980600 | 0 | 3 | 1 | 14 | 6 | 30 | 10 | 93 |
| 980700 | 5 | 23 | 0 | 0 | 0 | 0 | 4 | 28 |
| 980800 | 0 | 9 | 0 | 2 | 23 | 69 | 10 | 86 |
| 990100 | 6 | 24 | 8 | 48 | 5 | 29 | 5 | 43 |
| 990200 | 19 | 48 | 13 | 43 | 2 | 12 | 12 | 85 |
| 990300 | 0 | 3 | 51 | 100 | 1 | 3 | 18 | 97 |
| 990400 | 0 | 0 | 9 | 48 | 16 | 52 | 12 | 74 |
| 990500 | 8 | 31 | 3 | 21 | 1 | 21 | 15 | 92 |
| 990600 | 20 | 67 | 1 | 7 | 0 | 1 | 4 | 50 |
| 990700 | 36 | 80 | 4 | 18 | 0 | 0 | 2 | 36 |
| 990800 | 48 | 84 | 0 | 0 | 0 | 0 | 6 | 51 |
| 990900 | 3 | 12 | 6 | 23 | 5 | 26 | 17 | 83 |
| 991000 | 3 | 9 | 9 | 53 | 9 | 33 | 15 | 88 |

Appendix B2. Heavy cover (>30 percent) frequency (HFreq.) and importance value (IV) of major understory vegetation by stand.

| Stand ID | Hayscented fern | | Mountain-laurel | | Huckleberry | | Blueberry | |
|---|---|---|---|---|---|---|---|---|
| | HFreq. (%) | IV (%) | HFreq. (%) | IV (%) | HFreq. (%) | IV (%) | HFreq. (%) | IV (%) |
| 000100 | 0 | 0 | 8 | 21 | 11 | 46 | 14 | 63 |
| 000200 | 28 | 48 | 18 | 44 | 0 | 3 | 6 | 45 |
| 000300 | 4 | 10 | 26 | 59 | 3 | 10 | 15 | 58 |
| 000400 | 0 | 3 | 0 | 0 | 2 | 4 | 0 | 97 |
| 020100 | 7 | 18 | 6 | 13 | 8 | 30 | 13 | 66 |
| 020200 | 0 | 7 | 4 | 15 | 3 | 27 | 10 | 71 |
| 020300 | 11 | 32 | 0 | 2 | 1 | 4 | 1 | 74 |
| 020400 | 7 | 44 | 0 | 0 | 0 | 0 | 3 | 68 |
| 020500 | 78 | 114 | 1 | 13 | 0 | 1 | 1 | 26 |
| 020600 | 0 | 2 | 21 | 36 | 13 | 38 | 14 | 60 |
| 020700 | 35 | 69 | 38 | 55 | 0 | 1 | 0 | 21 |
| 030100 | 0 | 3 | 2 | 19 | 4 | 37 | 4 | 58 |
| 030200 | 5 | 22 | 1 | 1 | 0 | 7 | 6 | 80 |
| 030300 | 3 | 6 | 30 | 49 | 6 | 24 | 5 | 53 |
| 030400 | 42 | 118 | 0 | 0 | 0 | 1 | 0 | 4 |
| 030500 | 10 | 19 | 14 | 26 | 4 | 25 | 2 | 58 |
| 030600 | 0 | 4 | 0 | 0 | 0 | 0 | 0 | 96 |
| 960100 | 0 | 0 | 8 | 21 | 12 | 25 | 53 | 103 |
| 960200 | 0 | 0 | 19 | 64 | 0 | 5 | 7 | 52 |
| 960300 | 0 | 0 | 0 | 2 | 2 | 14 | 25 | 100 |
| 960400 | 0 | 0 | 19 | 52 | 13 | 31 | 3 | 41 |
| 960600 | 48 | 99 | 18 | 36 | 0 | 0 | 0 | 11 |
| 960700 | 0 | 0 | 3 | 7 | 54 | 79 | 32 | 69 |
| 961100 | 25 | 46 | 20 | 36 | 0 | 1 | 4 | 52 |
| 961200 | 0 | 3 | 23 | 57 | 1 | 4 | 39 | 81 |
| 970100 | 1 | 9 | 0 | 4 | 11 | 28 | 26 | 86 |
| 970200 | 0 | 7 | 29 | 59 | 2 | 12 | 12 | 53 |
| 970600 | 64 | 123 | 0 | 0 | 0 | 0 | 1 | 23 |
| 971100 | 0 | 1 | 66 | 79 | 25 | 44 | 11 | 45 |
| 971400 | 0 | 12 | 0 | 0 | 0 | 0 | 3 | 91 |
| 971500 | 4 | 22 | 0 | 0 | 1 | 3 | 9 | 85 |
| 971600 | 38 | 61 | 13 | 29 | 1 | 7 | 10 | 53 |
| 971700 | 8 | 21 | 0 | 0 | 13 | 31 | 22 | 76 |
| 971800 | 0 | 0 | 2 | 8 | 14 | 35 | 10 | 76 |
| 980100 | 5 | 13 | 0 | 0 | 9 | 39 | 14 | 74 |
| 980200 | 2 | 10 | 5 | 11 | 15 | 36 | 11 | 68 |
| 980300 | 0 | 3 | 0 | 3 | 1 | 7 | 3 | 92 |
| 980400 | 0 | 0 | 38 | 69 | 13 | 23 | 13 | 52 |
| 980500 | 0 | 0 | 0 | 0 | 0 | 10 | 6 | 98 |
| 980600 | 0 | 3 | 1 | 11 | 9 | 27 | 4 | 76 |
| 980700 | 8 | 50 | 0 | 0 | 0 | 0 | 4 | 59 |
| 980800 | 0 | 6 | 0 | 1 | 34 | 64 | 8 | 62 |
| 990100 | 10 | 23 | 9 | 41 | 6 | 25 | 4 | 34 |
| 990200 | 31 | 44 | 22 | 36 | 4 | 9 | 11 | 57 |
| 990300 | 0 | 2 | 80 | 100 | 2 | 2 | 17 | 65 |
| 990400 | 0 | 0 | 13 | 37 | 24 | 45 | 16 | 55 |
| 990500 | 15 | 27 | 4 | 15 | 2 | 14 | 17 | 71 |
| 990600 | 29 | 74 | 0 | 6 | 0 | 1 | 4 | 44 |
| 990700 | 53 | 96 | 7 | 18 | 0 | 0 | 2 | 29 |
| 990800 | 69 | 110 | 0 | 0 | 0 | 0 | 8 | 43 |
| 990900 | 4 | 11 | 10 | 22 | 6 | 23 | 26 | 75 |
| 991000 | 3 | 8 | 10 | 38 | 13 | 27 | 22 | 63 |

Appendix C1. Average advance regeneration density of six oak and non-oak species by stand.

| Stand ID | Density (stems/milacre) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Red Maple | Black Birch | Black-gum | White Oak | Chestnut Oak | N. Red Oak | All Oaks | All Trees |
| 000100 | 27.0 | 0.2 | 1.0 | 7.2 | 3.6 | 0.1 | 12.9 | 48.1 |
| 000200 | 21.9 | 0.0 | 0.0 | 0.0 | 0.0 | 12.0 | 12.0 | 35.1 |
| 000300 | 18.1 | 0.2 | 1.1 | 0.0 | 12.3 | 0.2 | 12.5 | 32.4 |
| 000400 | 5.2 | 0.0 | 0.0 | 7.3 | 0.1 | 2.1 | 9.7 | 26.3 |
| 020100 | 16.2 | 0.3 | 0.0 | 0.0 | 0.1 | 8.5 | 9.2 | 26.2 |
| 020200 | 47.3 | 0.0 | 0.0 | 0.0 | 0.0 | 6.2 | 6.4 | 56.2 |
| 020300 | 31.8 | 0.4 | 0.2 | 0.1 | 0.1 | 1.9 | 2.1 | 36.1 |
| 020400 | 43.9 | 0.0 | 0.0 | 0.0 | 0.0 | 4.8 | 4.9 | 52.9 |
| 020500 | 23.8 | 0.9 | 0.0 | 0.6 | 1.4 | 20.5 | 22.5 | 50.9 |
| 020600 | 40.1 | 0.1 | 0.7 | 1.1 | 5.0 | 0.2 | 6.4 | 51.3 |
| 020700 | 34.1 | 0.9 | 0.0 | 0.0 | 0.3 | 24.0 | 24.3 | 60.0 |
| 030100 | 17.3 | 1.4 | 1.2 | 0.2 | 1.9 | 3.2 | 5.5 | 27.2 |
| 030200 | 48.9 | 0.4 | 0.1 | 2.2 | 2.9 | 0.6 | 6.5 | 62.2 |
| 030300 | 30.9 | 1.3 | 0.0 | 0.2 | 0.4 | 0.8 | 1.4 | 36.4 |
| 030400 | 54.1 | 0.2 | 0.0 | 0.2 | 0.1 | 0.6 | 0.8 | 63.3 |
| 030500 | 40.3 | 0.0 | 0.0 | 0.0 | 0.0 | 16.8 | 16.9 | 59.3 |
| 030600 | 15.2 | 0.5 | 0.1 | 0.0 | 0.0 | 0.4 | 0.4 | 19.2 |
| 960100 | 8.8 | 0.0 | 0.0 | 0.0 | 3.8 | 0.1 | 4.3 | 13.3 |
| 960200 | 6.9 | 0.0 | 0.0 | 0.0 | 0.3 | 0.1 | 0.5 | 7.9 |
| 960300 | 9.0 | 0.5 | 0.1 | 0.0 | 6.5 | 2.2 | 8.8 | 20.3 |
| 960400 | 5.3 | 0.4 | 0.1 | 0.0 | 1.0 | 2.5 | 3.4 | 10.2 |
| 960600 | 13.6 | 0.5 | 0.0 | 0.0 | 0.0 | 7.7 | 7.7 | 23.0 |
| 960700 | 17.0 | 0.1 | 1.0 | 1.5 | 5.9 | 0.6 | 10.6 | 30.6 |
| 961100 | 8.0 | 0.0 | 0.0 | 0.1 | 0.3 | 1.4 | 1.9 | 11.4 |
| 961200 | 8.9 | 0.0 | 0.3 | 0.4 | 3.8 | 0.7 | 6.1 | 16.2 |
| 970100 | 22.7 | 0.0 | 0.0 | 1.0 | 3.5 | 0.7 | 5.8 | 29.2 |
| 970200 | 29.1 | 0.1 | 0.0 | 0.0 | 0.5 | 1.1 | 1.8 | 32.4 |
| 970600 | 47.8 | 0.0 | 0.0 | 0.0 | 0.0 | 2.6 | 5.7 | 55.1 |
| 971100 | 31.9 | 0.1 | 0.1 | 0.1 | 1.2 | 0.3 | 2.1 | 34.9 |
| 971400 | 29.7 | 0.2 | 0.6 | 0.2 | 4.0 | 0.3 | 5.0 | 41.2 |
| 971500 | 21.9 | 0.4 | 0.8 | 0.0 | 5.4 | 1.1 | 7.2 | 33.3 |
| 971600 | 20.9 | 0.1 | 0.1 | 0.1 | 0.1 | 0.8 | 1.1 | 23.3 |
| 971700 | 42.5 | 0.1 | 1.1 | 0.4 | 5.2 | 0.2 | 6.6 | 51.2 |
| 971800 | 2.0 | 0.0 | 0.1 | 0.0 | 1.1 | 0.3 | 1.7 | 4.1 |
| 980100 | 34.3 | 0.1 | 0.3 | 2.1 | 4.1 | 1.2 | 10.1 | 45.7 |
| 980200 | 12.8 | 0.2 | 0.0 | 0.3 | 9.3 | 2.3 | 12.5 | 27.0 |
| 980300 | 42.3 | 1.2 | 0.1 | 5.8 | 4.3 | 0.9 | 13.8 | 68.2 |
| 980400 | 9.6 | 0.1 | 0.9 | 0.0 | 1.4 | 0.3 | 1.8 | 13.2 |
| 980500 | 18.6 | 2.1 | 0.5 | 0.1 | 3.3 | 0.3 | 4.2 | 30.9 |
| 980600 | 12.7 | 0.0 | 0.0 | 0.4 | 12.9 | 0.8 | 15.2 | 29.1 |
| 980700 | 12.7 | 5.0 | 0.5 | 0.4 | 1.6 | 0.2 | 2.5 | 29.5 |
| 980800 | 13.7 | 0.1 | 1.5 | 1.0 | 2.0 | 2.5 | 6.4 | 23.3 |
| 990100 | 87.1 | 2.7 | 0.5 | 0.0 | 0.7 | 0.5 | 1.3 | 96.6 |
| 990200 | 38.3 | 0.0 | 0.0 | 0.1 | 0.1 | 2.7 | 3.3 | 42.0 |
| 990300 | 10.4 | 0.0 | 0.0 | 0.0 | 0.0 | 0.2 | 0.3 | 12.3 |
| 990400 | 21.0 | 0.5 | 0.1 | 0.2 | 1.4 | 9.7 | 11.6 | 33.8 |
| 990500 | 26.0 | 1.7 | 0.0 | 0.1 | 6.8 | 0.9 | 8.7 | 38.1 |
| 990600 | 7.7 | 1.6 | 0.0 | 0.0 | 0.2 | 2.3 | 2.6 | 15.1 |
| 990700 | 23.0 | 0.2 | 0.0 | 0.2 | 0.1 | 13.7 | 14.3 | 38.3 |
| 990800 | 6.0 | 0.0 | 0.0 | 0.1 | 0.0 | 4.5 | 4.7 | 11.5 |
| 990900 | 28.6 | 0.1 | 0.1 | 0.6 | 5.7 | 2.3 | 8.7 | 39.2 |
| 991000 | 34.5 | 0.0 | 0.0 | 1.9 | 4.5 | 0.7 | 7.4 | 42.9 |

Appendix C2. Average advance regeneration cumulative height of six oak and non-oak species by stand.

| Stand ID | Cumulative Height (ft/milacre) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Red Maple | Black Birch | Black-gum | White Oak | Chestnut Oak | N. Red Oak | All Oaks | All Trees |
| 000100 | 16.5 | 0.3 | 0.4 | 6.2 | 3.5 | 0.0 | 11.7 | 33.6 |
| 000200 | 5.0 | 0.0 | 0.0 | 0.0 | 0.0 | 4.7 | 4.7 | 10.2 |
| 000300 | 5.2 | 0.3 | 0.5 | 0.0 | 4.5 | 0.1 | 4.6 | 10.8 |
| 000400 | 2.4 | 0.0 | 0.0 | 5.6 | 0.1 | 2.2 | 8.2 | 33.3 |
| 020100 | 3.7 | 0.1 | 0.0 | 0.0 | 0.0 | 3.5 | 3.9 | 7.9 |
| 020200 | 31.5 | 0.0 | 0.0 | 0.0 | 0.0 | 2.3 | 2.4 | 35.4 |
| 020300 | 24.0 | 0.1 | 0.1 | 0.0 | 0.0 | 0.6 | 0.7 | 26.0 |
| 020400 | 28.7 | 0.0 | 0.0 | 0.0 | 0.0 | 1.6 | 1.6 | 31.9 |
| 020500 | 6.8 | 1.2 | 0.0 | 0.2 | 0.6 | 9.0 | 9.8 | 19.8 |
| 020600 | 10.8 | 0.1 | 0.4 | 0.4 | 2.0 | 0.1 | 2.6 | 15.4 |
| 020700 | 6.3 | 2.8 | 0.0 | 0.0 | 0.1 | 11.1 | 11.2 | 20.9 |
| 030100 | 7.9 | 3.1 | 0.7 | 0.1 | 0.8 | 1.4 | 2.4 | 16.1 |
| 030200 | 10.0 | 0.2 | 0.1 | 1.1 | 2.0 | 0.3 | 3.7 | 18.3 |
| 030300 | 5.1 | 0.2 | 0.0 | 0.1 | 0.1 | 0.2 | 0.4 | 8.1 |
| 030400 | 13.3 | 0.1 | 0.0 | 0.1 | 0.0 | 0.2 | 0.3 | 17.9 |
| 030500 | 6.4 | 0.0 | 0.0 | 0.0 | 0.0 | 5.8 | 5.9 | 13.1 |
| 030600 | 3.1 | 0.1 | 0.0 | 0.0 | 0.0 | 0.1 | 0.1 | 4.3 |
| 960100 | 2.0 | 0.0 | 0.0 | 0.0 | 1.4 | 0.1 | 1.6 | 3.7 |
| 960200 | 0.9 | 0.0 | 0.0 | 0.0 | 0.1 | 0.0 | 0.1 | 1.2 |
| 960300 | 2.4 | 0.3 | 0.1 | 0.0 | 3.4 | 0.9 | 4.3 | 9.9 |
| 960400 | 1.4 | 0.2 | 0.0 | 0.0 | 0.4 | 1.2 | 1.6 | 4.1 |
| 960600 | 3.7 | 0.3 | 0.0 | 0.0 | 0.0 | 2.9 | 2.9 | 7.5 |
| 960700 | 10.7 | 0.1 | 0.5 | 2.7 | 5.3 | 0.5 | 11.9 | 25.0 |
| 961100 | 3.2 | 0.0 | 0.0 | 0.0 | 0.1 | 0.5 | 0.8 | 4.7 |
| 961200 | 3.9 | 0.0 | 0.1 | 0.2 | 1.7 | 0.3 | 2.5 | 7.4 |
| 970100 | 11.4 | 0.0 | 0.0 | 0.5 | 1.8 | 0.3 | 2.8 | 14.7 |
| 970200 | 6.1 | 0.0 | 0.0 | 0.0 | 0.2 | 0.5 | 0.7 | 7.6 |
| 970600 | 13.1 | 0.0 | 0.0 | 0.0 | 0.0 | 1.0 | 2.2 | 16.1 |
| 971100 | 10.3 | 0.4 | 0.0 | 0.2 | 1.4 | 0.3 | 2.6 | 14.4 |
| 971400 | 11.3 | 0.3 | 0.3 | 0.1 | 2.2 | 0.1 | 2.7 | 17.1 |
| 971500 | 11.5 | 2.1 | 0.3 | 0.0 | 5.6 | 1.7 | 8.8 | 26.4 |
| 971600 | 6.4 | 0.0 | 0.1 | 0.0 | 0.0 | 0.3 | 0.4 | 7.3 |
| 971700 | 27.6 | 0.2 | 0.6 | 0.4 | 7.1 | 0.3 | 8.5 | 37.8 |
| 971800 | 0.8 | 0.0 | 0.1 | 0.0 | 0.5 | 0.1 | 0.7 | 2.0 |
| 980100 | 24.2 | 0.0 | 0.1 | 2.1 | 3.0 | 0.6 | 7.4 | 32.4 |
| 980200 | 3.7 | 0.3 | 0.0 | 0.3 | 9.0 | 1.4 | 11.1 | 15.9 |
| 980300 | 18.7 | 2.7 | 0.1 | 4.2 | 2.7 | 0.5 | 9.4 | 38.1 |
| 980400 | 3.2 | 0.1 | 0.4 | 0.0 | 0.8 | 0.1 | 1.0 | 5.1 |
| 980500 | 5.1 | 0.3 | 0.3 | 0.1 | 1.8 | 0.1 | 2.1 | 10.4 |
| 980600 | 7.4 | 0.0 | 0.0 | 0.2 | 9.6 | 0.5 | 11.2 | 19.5 |
| 980700 | 3.5 | 0.8 | 0.2 | 0.2 | 0.8 | 0.1 | 1.2 | 10.0 |
| 980800 | 6.3 | 0.1 | 0.8 | 0.8 | 1.6 | 1.0 | 3.9 | 12.2 |
| 990100 | 16.3 | 1.1 | 0.2 | 0.0 | 0.3 | 0.2 | 0.5 | 23.0 |
| 990200 | 12.3 | 0.0 | 0.0 | 0.0 | 0.0 | 1.1 | 1.3 | 14.6 |
| 990300 | 3.5 | 0.0 | 0.0 | 0.0 | 0.0 | 0.1 | 0.1 | 4.9 |
| 990400 | 6.3 | 0.2 | 0.0 | 0.1 | 0.5 | 3.6 | 4.4 | 11.2 |
| 990500 | 12.7 | 3.1 | 0.0 | 0.3 | 21.9 | 1.4 | 25.3 | 45.5 |
| 990600 | 3.0 | 2.2 | 0.0 | 0.0 | 0.2 | 1.9 | 2.1 | 12.1 |
| 990700 | 7.3 | 0.1 | 0.0 | 0.1 | 0.0 | 5.6 | 5.9 | 13.6 |
| 990800 | 1.8 | 0.0 | 0.0 | 0.0 | 0.0 | 1.8 | 1.8 | 4.0 |
| 990900 | 13.1 | 0.0 | 0.1 | 0.2 | 2.1 | 0.9 | 3.3 | 18.0 |
| 991000 | 17.6 | 0.0 | 0.0 | 0.9 | 2.1 | 0.3 | 3.4 | 21.7 |

Appendix C3. Advance regeneration occurrence frequency of six oak and non-oak species by stand.

| Stand ID | Frequency (percent) | | | | | | |
|---|---|---|---|---|---|---|---|
| | Red Maple | Black Birch | Black-gum | White Oak | Chestnut Oak | N. Red Oak | All Oaks |
| 000100 | 99.2 | 5.8 | 32.5 | 80.8 | 32.5 | 4.2 | 96.7 |
| 000200 | 91.7 | 0.8 | 1.7 | 0.0 | 1.7 | 90.0 | 90.0 |
| 000300 | 96.0 | 14.0 | 35.0 | 2.0 | 82.0 | 18.0 | 90.0 |
| 000400 | 73.3 | 1.7 | 1.7 | 78.3 | 1.7 | 53.3 | 90.0 |
| 020100 | 94.0 | 14.0 | 0.0 | 0.0 | 6.0 | 85.0 | 89.0 |
| 020200 | 100.0 | 0.0 | 0.0 | 0.0 | 0.8 | 67.2 | 68.1 |
| 020300 | 97.5 | 15.8 | 6.7 | 6.7 | 5.8 | 50.8 | 58.3 |
| 020400 | 100.0 | 0.8 | 0.0 | 2.5 | 1.7 | 80.8 | 80.8 |
| 020500 | 95.0 | 9.2 | 0.0 | 10.0 | 17.5 | 85.0 | 90.8 |
| 020600 | 98.3 | 9.2 | 30.0 | 25.8 | 60.8 | 17.5 | 75.8 |
| 020700 | 87.5 | 30.0 | 0.0 | 0.0 | 7.5 | 84.2 | 85.8 |
| 030100 | 98.1 | 36.9 | 41.3 | 11.3 | 38.1 | 78.8 | 87.5 |
| 030200 | 98.7 | 19.2 | 9.6 | 32.7 | 43.6 | 32.7 | 78.8 |
| 030300 | 90.1 | 17.1 | 2.6 | 7.9 | 8.6 | 17.8 | 31.6 |
| 030400 | 100.0 | 9.9 | 3.3 | 11.8 | 3.3 | 37.5 | 47.4 |
| 030500 | 95.0 | 1.7 | 0.8 | 4.2 | 0.8 | 86.7 | 87.5 |
| 030600 | 98.1 | 18.8 | 2.5 | 1.9 | 0.6 | 27.5 | 30.0 |
| 960100 | 85.9 | 0.6 | 0.0 | 0.0 | 59.6 | 9.6 | 68.6 |
| 960200 | 96.6 | 0.0 | 0.0 | 3.4 | 11.4 | 9.1 | 29.5 |
| 960300 | 92.2 | 18.8 | 9.4 | 1.6 | 43.8 | 84.4 | 93.8 |
| 960400 | 78.4 | 22.7 | 5.7 | 0.0 | 30.7 | 61.4 | 76.1 |
| 960600 | 95.0 | 15.8 | 2.5 | 0.8 | 0.8 | 83.3 | 83.3 |
| 960700 | 93.3 | 5.8 | 30.8 | 40.8 | 67.5 | 30.0 | 96.7 |
| 961100 | 94.4 | 0.0 | 0.0 | 10.5 | 13.7 | 49.2 | 59.7 |
| 961200 | 95.8 | 0.0 | 9.2 | 20.8 | 44.2 | 38.3 | 86.7 |
| 970100 | 95.2 | 0.0 | 0.0 | 21.4 | 48.8 | 34.5 | 76.2 |
| 970200 | 89.0 | 3.0 | 0.0 | 2.0 | 22.0 | 32.0 | 55.0 |
| 970600 | 98.3 | 0.0 | 0.0 | 0.0 | 0.0 | 55.0 | 66.7 |
| 971100 | 87.0 | 12.0 | 1.1 | 4.3 | 46.7 | 20.7 | 68.5 |
| 971400 | 100.0 | 15.0 | 16.7 | 10.0 | 55.0 | 20.8 | 71.7 |
| 971500 | 97.1 | 24.0 | 27.9 | 1.0 | 51.9 | 48.1 | 81.7 |
| 971600 | 95.5 | 6.3 | 8.9 | 4.5 | 8.9 | 32.1 | 43.8 |
| 971700 | 99.2 | 8.3 | 42.5 | 18.3 | 67.5 | 14.2 | 83.3 |
| 971800 | 56.0 | 2.6 | 8.6 | 2.6 | 31.0 | 21.6 | 57.8 |
| 980100 | 98.2 | 10.7 | 10.7 | 35.7 | 41.1 | 55.4 | 92.9 |
| 980200 | 93.3 | 11.7 | 2.5 | 10.0 | 71.7 | 68.3 | 93.3 |
| 980300 | 97.0 | 32.0 | 8.0 | 70.0 | 33.0 | 32.0 | 93.0 |
| 980400 | 90.0 | 6.7 | 39.2 | 0.0 | 40.8 | 17.5 | 50.8 |
| 980500 | 98.9 | 23.9 | 18.2 | 9.1 | 42.0 | 18.2 | 61.4 |
| 980600 | 87.5 | 0.0 | 0.0 | 12.5 | 92.5 | 45.0 | 96.7 |
| 980700 | 92.2 | 49.1 | 19.8 | 12.9 | 31.0 | 18.1 | 54.3 |
| 980800 | 96.9 | 6.3 | 32.8 | 25.0 | 28.1 | 45.3 | 79.7 |
| 990100 | 100.0 | 40.2 | 25.2 | 2.8 | 30.8 | 22.4 | 43.9 |
| 990200 | 87.5 | 1.7 | 0.0 | 3.3 | 1.7 | 54.2 | 64.2 |
| 990300 | 76.6 | 0.0 | 1.6 | 1.6 | 0.0 | 14.1 | 21.9 |
| 990400 | 93.3 | 18.3 | 5.0 | 4.2 | 27.5 | 85.0 | 90.0 |
| 990500 | 95.8 | 50.0 | 4.2 | 6.3 | 75.0 | 39.6 | 89.6 |
| 990600 | 84.7 | 25.0 | 0.0 | 4.2 | 4.2 | 56.9 | 63.9 |
| 990700 | 89.0 | 6.0 | 0.0 | 2.0 | 4.0 | 82.0 | 83.0 |
| 990800 | 74.2 | 0.0 | 0.0 | 4.2 | 0.0 | 76.7 | 78.3 |
| 990900 | 98.1 | 7.4 | 7.4 | 14.8 | 53.7 | 59.3 | 88.9 |
| 991000 | 98.3 | 1.7 | 3.3 | 50.8 | 40.0 | 37.5 | 85.8 |

Appendix C4. Advance regeneration importance values of six oak and non-oak species by stand.

| Stand ID | Importance Value (percent) | | | | | | |
|---|---|---|---|---|---|---|---|
| | Red Maple | Black Birch | Black-gum | White Oak | Chestnut Oak | N. Red Oak | All Oaks |
| 000100 | 126 | 2 | 10 | 50 | 25 | 1 | 96 |
| 000200 | 150 | 0 | 1 | 0 | 1 | 118 | 119 |
| 000300 | 137 | 9 | 20 | 1 | 108 | 8 | 117 |
| 000400 | 40 | 0 | 0 | 59 | 1 | 25 | 90 |
| 020100 | 150 | 8 | 0 | 0 | 3 | 114 | 130 |
| 020200 | 214 | 0 | 0 | 0 | 0 | 45 | 49 |
| 020300 | 218 | 8 | 3 | 3 | 3 | 27 | 35 |
| 020400 | 209 | 0 | 0 | 1 | 1 | 44 | 45 |
| 020500 | 113 | 11 | 0 | 6 | 11 | 114 | 133 |
| 020600 | 175 | 3 | 12 | 12 | 39 | 6 | 58 |
| 020700 | 123 | 27 | 0 | 0 | 4 | 127 | 131 |
| 030100 | 137 | 34 | 19 | 4 | 21 | 41 | 70 |
| 030200 | 153 | 6 | 2 | 16 | 24 | 9 | 61 |
| 030300 | 191 | 14 | 1 | 5 | 7 | 13 | 28 |
| 030400 | 190 | 4 | 1 | 4 | 1 | 13 | 19 |
| 030500 | 152 | 1 | 0 | 2 | 0 | 105 | 108 |
| 030600 | 191 | 12 | 2 | 1 | 0 | 16 | 17 |
| 960100 | 166 | 0 | 0 | 0 | 97 | 8 | 121 |
| 960200 | 229 | 0 | 0 | 4 | 18 | 9 | 37 |
| 960300 | 96 | 10 | 4 | 1 | 79 | 45 | 126 |
| 960400 | 120 | 19 | 4 | 0 | 31 | 79 | 110 |
| 960600 | 146 | 11 | 1 | 1 | 0 | 104 | 105 |
| 960700 | 119 | 2 | 12 | 24 | 55 | 10 | 134 |
| 961100 | 176 | 0 | 0 | 6 | 11 | 42 | 65 |
| 961200 | 138 | 0 | 6 | 11 | 60 | 20 | 124 |
| 970100 | 190 | 0 | 0 | 14 | 42 | 17 | 89 |
| 970200 | 211 | 2 | 0 | 1 | 14 | 24 | 43 |
| 970600 | 205 | 0 | 0 | 0 | 0 | 30 | 59 |
| 971100 | 201 | 8 | 1 | 4 | 33 | 12 | 65 |
| 971400 | 161 | 5 | 7 | 3 | 35 | 6 | 53 |
| 971500 | 133 | 15 | 10 | 0 | 50 | 21 | 88 |
| 971600 | 223 | 4 | 6 | 3 | 5 | 23 | 36 |
| 971700 | 184 | 3 | 15 | 7 | 48 | 5 | 76 |
| 971800 | 125 | 4 | 11 | 4 | 72 | 28 | 125 |
| 980100 | 177 | 3 | 4 | 21 | 30 | 19 | 99 |
| 980200 | 96 | 6 | 1 | 5 | 110 | 36 | 164 |
| 980300 | 125 | 14 | 2 | 29 | 18 | 7 | 76 |
| 980400 | 174 | 5 | 31 | 0 | 43 | 12 | 60 |
| 980500 | 133 | 15 | 8 | 3 | 38 | 6 | 57 |
| 980600 | 107 | 0 | 0 | 6 | 119 | 18 | 166 |
| 980700 | 97 | 35 | 7 | 6 | 20 | 5 | 38 |
| 980800 | 140 | 3 | 23 | 19 | 30 | 33 | 99 |
| 990100 | 191 | 19 | 9 | 1 | 11 | 8 | 20 |
| 990200 | 221 | 1 | 0 | 2 | 1 | 42 | 57 |
| 990300 | 198 | 0 | 1 | 1 | 0 | 12 | 19 |
| 990400 | 153 | 10 | 2 | 3 | 19 | 92 | 119 |
| 990500 | 122 | 24 | 1 | 3 | 86 | 16 | 115 |
| 990600 | 106 | 37 | 0 | 2 | 4 | 50 | 56 |
| 990700 | 151 | 4 | 0 | 2 | 2 | 111 | 119 |
| 990800 | 135 | 0 | 0 | 3 | 0 | 122 | 129 |
| 990900 | 177 | 3 | 3 | 7 | 43 | 30 | 84 |
| 991000 | 193 | 1 | 1 | 25 | 33 | 15 | 80 |

Appendix D. Soil properties of major soil series encountered within the study area.

| Province | Soil Series | Family | Subgroup | Formation | Deepness | Drainage | Permeability | Available Water Capacity |
|---|---|---|---|---|---|---|---|---|
| Ridge and Valley | Berks | Loamy-skeletal | Typic Dystrochrepts | shale siltstone residuum | moderate | well | moderate to rapid | very low |
| | Buchanan | Fine-loamy | Aquic Fragiudults | sandstone and siltstone colluvium | deep | moderate well | low | moderate |
| | Hazleton | Loamy-skeletal | Typic Dystrochrepts | sandstone residuum | deep | well | moderate to rapid | low to moderate |
| | Hazleton-Dekalb | Loamy-skeletal | Typic Dystrochrepts | sandstone residuum | moderate | well | moderate to rapid | low to very low |
| | Laidig | Fine-loamy | Typic Fragiudults | sandstone and siltstone alluvium | deep | well | moderate to low | moderate |
| | Meckesville | Fine-loamy | Typic Fragiudults | sandstone and siltstone colluvium | deep | well | moderate to low | moderate |
| | Ungers | Fine-loamy | Typic Hapludults | sandstone and siltstone residuum | deep | well | moderate | moderate |
| Allegheny Plateau | Clymer | Fine-loamy | Typic Hapludults | sandstone and siltstone residuum | deep | well | moderate to rapid | moderate |
| | Cookport | Fine-loamy | Aquic Fragiudults | sandstone and siltstone residuum | deep | moderate well | moderate to low | moderate |
| | Hazleton | Loamy-skeletal | Typic Dystrochrepts | sandstone residuum | deep | well | moderate to rapid | low to moderate |
| | Wharton | Fine-loamy | Typic Hapludults | shale siltstone residuum | deep | moderate well | moderate to low | high |

Appendix E: Average cover percentage, occurrence frequency (Freq.), and heavy cover (>30 percent) frequency (HFreq.) for major understory vegetation one and four years after overstory removal by assessment ID.

| Assessment ID* | Hayscented fern | | | Mountain-laurel | | | Low shrub species | | |
|---|---|---|---|---|---|---|---|---|---|
| | Cover (%) | Freq. (%) | HFreq. (%) | Cover (%) | Freq. (%) | HFreq. (%) | Cover (%) | Freq. (%) | HFreq. (%) |
| 000101 | 0.0 | 3.3 | 0.0 | 2.8 | 27.5 | 5.0 | 4.9 | 96.7 | 0.8 |
| 000201 | 11.2 | 61.7 | 15.8 | 6.7 | 60.8 | 2.5 | 7.2 | 78.3 | 2.5 |
| 000301 | 2.5 | 38.5 | 3.1 | 8.0 | 70.8 | 8.3 | 16.4 | 93.8 | 20.8 |
| 960101 | 1.8 | 36.4 | 0.8 | 2.6 | 16.7 | 4.5 | 27.5 | 98.5 | 34.8 |
| 960104 | 5.3 | 56.1 | 17.4 | 5.8 | 18.2 | 3.0 | 10.3 | 96.2 | 25.0 |
| 960201 | 0.3 | 7.9 | 0.0 | 2.4 | 39.5 | 1.3 | 4.8 | 64.5 | 1.3 |
| 960204 | 2.7 | 50.7 | 5.3 | 0.0 | 40.0 | 6.7 | 13.5 | 73.3 | 9.3 |
| 960301 | 0.3 | 15.1 | 0.0 | 0.0 | 3.8 | 0.0 | 11.7 | 69.8 | 15.1 |
| 960304 | 2.1 | 50.9 | 3.6 | 4.8 | 1.8 | 0.0 | 10.4 | 70.9 | 18.2 |
| 960401 | 0.1 | 20.5 | 0.0 | 3.1 | 50.0 | 2.3 | 6.1 | 62.5 | 5.7 |
| 960404 | 0.7 | 47.0 | 2.4 | 0.7 | 53.0 | 1.2 | 34.2 | 68.7 | 9.6 |
| 960601** | 9.7 | 64.2 | 11.0 | 2.9 | 18.3 | 3.7 | 0.0 | 1.8 | 0.0 |
| 960604 | 29.4 | 72.1 | 10.8 | 0.0 | 21.6 | 3.6 | 0.8 | 5.4 | 0.0 |
| 960701 | 0.0 | 7.3 | 0.0 | 1.0 | 11.5 | 2.1 | 36.3 | 99.0 | 52.1 |
| 960704 | 8.8 | 12.5 | 1.0 | 8.4 | 9.4 | 0.0 | 15.6 | 99.0 | 49.0 |
| 961101** | 0.4 | 18.1 | 0.0 | 1.6 | 32.8 | 0.0 | 3.1 | 74.1 | 0.9 |
| 961104 | 3.1 | 56.0 | 14.7 | 0.0 | 37.1 | 6.9 | 16.6 | 81.0 | 4.3 |
| 961201 | 1.0 | 38.9 | 0.0 | 4.8 | 56.6 | 3.5 | 23.5 | 97.3 | 27.4 |
| 961204 | 4.3 | 56.3 | 9.8 | 0.0 | 55.4 | 8.0 | 4.6 | 94.6 | 9.8 |
| 970101 | 3.4 | 26.5 | 3.6 | 0.0 | 1.2 | 0.0 | 21.4 | 79.5 | 27.7 |
| 970104 | 10.0 | 39.3 | 3.6 | 3.5 | 1.2 | 0.0 | 12.1 | 84.5 | 21.4 |
| 970601 | 52.2 | 89.3 | 63.1 | 0.0 | 0.0 | 0.0 | 0.8 | 15.5 | 1.0 |
| 970604 | 1.8 | 88.0 | 47.0 | 10.8 | 0.0 | 0.0 | 28.3 | 18.0 | 1.0 |
| 971101 | 0.9 | 7.8 | 1.1 | 13.5 | 88.9 | 14.4 | 31.5 | 97.8 | 42.2 |
| 971104 | 13.5 | 12.0 | 2.2 | 2.0 | 89.1 | 6.5 | 19.8 | 96.7 | 33.7 |
| 971501 | 4.9 | 42.6 | 5.9 | 0.0 | 0.0 | 0.0 | 4.6 | 60.4 | 2.0 |
| 971504 | 3.0 | 51.0 | 4.8 | 0.0 | 0.0 | 0.0 | 12.5 | 62.5 | 1.9 |
| 971601 | 28.5 | 78.4 | 41.4 | 3.5 | 34.2 | 3.6 | 10.5 | 90.1 | 7.2 |
| 971604 | 0.2 | 82.1 | 13.4 | 9.7 | 35.7 | 2.7 | 15.2 | 92.0 | 8.9 |
| 971701 | 2.3 | 31.3 | 3.6 | 0.0 | 0.0 | 0.0 | 13.4 | 78.6 | 10.7 |
| 971704 | 2.8 | 45.5 | 1.8 | 0.5 | 0.0 | 0.0 | 13.2 | 83.9 | 14.3 |
| 971801 | 0.5 | 27.7 | 0.0 | 0.7 | 5.4 | 1.8 | 14.1 | 91.1 | 10.7 |
| 980101 | 3.2 | 38.5 | 3.8 | 0.0 | 1.9 | 0.0 | 9.6 | 96.2 | 1.9 |
| 980201 | 0.7 | 15.0 | 0.0 | 0.9 | 10.0 | 0.8 | 7.1 | 76.7 | 3.3 |
| 980301 | 1.1 | 44.0 | 1.0 | 0.0 | 0.0 | 0.0 | 3.0 | 51.0 | 2.0 |
| 980401 | 0.0 | 6.9 | 0.0 | 11.3 | 86.2 | 6.0 | 26.3 | 91.4 | 34.5 |
| 980404 | 7.7 | 18.3 | 0.0 | 3.3 | 88.3 | 5.8 | 0.0 | 92.5 | 14.2 |
| 980601 | 1.5 | 22.0 | 2.0 | 0.7 | 11.0 | 0.0 | 15.7 | 85.0 | 8.0 |
| 980604 | 11.5 | 51.5 | 3.0 | 4.3 | 10.1 | 0.0 | 6.1 | 99.0 | 8.1 |
| 980701 | 4.6 | 32.1 | 7.1 | 0.0 | 0.0 | 0.0 | 2.4 | 26.2 | 1.2 |
| 980801 | 0.5 | 9.4 | 1.6 | 0.0 | 0.0 | 0.0 | 12.2 | 92.2 | 7.8 |
| 990101 | 6.5 | 38.0 | 10.2 | 1.7 | 38.9 | 0.0 | 5.4 | 61.1 | 2.8 |
| 990201** | 0.0 | 20.0 | 0.0 | 6.3 | 40.0 | 5.0 | 9.6 | 83.3 | 5.8 |
| 990301** | 0.0 | 0.0 | 0.0 | 11.0 | 93.3 | 5.0 | 15.4 | 98.3 | 8.3 |
| 990501 | 8.7 | 51.1 | 14.9 | 1.3 | 23.4 | 0.0 | 12.6 | 80.9 | 10.6 |
| 990701** | 0.6 | 37.0 | 0.0 | 1.3 | 17.0 | 0.0 | 1.4 | 39.0 | 0.0 |
| 990801** | 2.1 | 48.3 | 2.5 | 0.0 | 0.0 | 0.0 | 1.6 | 48.3 | 0.0 |
| 990901 | 2.7 | 13.5 | 3.8 | 1.9 | 22.1 | 0.0 | 8.5 | 87.5 | 3.8 |
| 991001 | 4.4 | 47.1 | 5.8 | 2.4 | 39.4 | 0.0 | 21.1 | 94.2 | 22.1 |

* First four digits of the assessment ID represents the location of a stand, and last two digits represents number of years after overstory removal; ** Herbicided stands.

Appendix F1. Average regeneration density of six oak and non-oak species one and four years after harvest by assessment ID.

| Assessment ID* | Regeneration Density (stems/milacre) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Red Maple | Black Birch | Black-gum | White Oak | Chestnut Oak | N. Red Oak | All Oaks | All Trees |
| 000101 | 12.6 | 0.1 | 0.5 | 2.1 | 1.3 | 0.2 | 4.6 | 20.7 |
| 000201 | 17.9 | 0.1 | 0.1 | 0.0 | 0.3 | 21.5 | 21.8 | 41.2 |
| 000301 | 14.8 | 6.0 | 1.0 | 0.0 | 3.7 | 0.4 | 4.1 | 27.2 |
| 960101 | 6.4 | 0.0 | 0.6 | 0.0 | 4.2 | 1.2 | 6.2 | 13.4 |
| 960104 | 7.3 | 0.1 | 0.3 | 0.0 | 4.4 | 1.4 | 6.2 | 14.3 |
| 960201 | 8.2 | 0.1 | 0.5 | 0.0 | 0.1 | 0.1 | 0.3 | 9.6 |
| 960204 | 21.5 | 0.9 | 0.8 | 0.4 | 2.3 | 0.1 | 2.9 | 27.1 |
| 960301 | 7.1 | 8.3 | 0.3 | 0.1 | 4.5 | 3.5 | 8.1 | 25.5 |
| 960304 | 13.7 | 8.6 | 0.2 | 0.2 | 4.1 | 2.0 | 6.5 | 30.3 |
| 960401 | 2.7 | 7.3 | 1.1 | 0.0 | 0.5 | 0.6 | 1.1 | 13.0 |
| 960404 | 6.7 | 9.5 | 1.6 | 0.0 | 0.3 | 1.0 | 1.4 | 21.0 |
| 960601 | 22.8 | 1.5 | 0.1 | 0.0 | 0.1 | 3.3 | 3.5 | 35.0 |
| 960604 | 17.8 | 1.9 | 0.0 | 0.1 | 0.0 | 11.7 | 11.8 | 37.4 |
| 960701 | 14.2 | 0.1 | 6.4 | 2.5 | 5.2 | 0.8 | 10.6 | 36.9 |
| 960704 | 11.7 | 0.2 | 4.0 | 1.8 | 4.2 | 1.1 | 8.8 | 29.7 |
| 961101 | 16.9 | 0.0 | 0.0 | 0.1 | 0.0 | 0.4 | 0.6 | 18.1 |
| 961104 | 22.0 | 0.2 | 0.0 | 0.1 | 0.1 | 0.4 | 0.6 | 23.3 |
| 961201 | 7.6 | 0.0 | 0.9 | 0.3 | 2.0 | 0.2 | 3.1 | 13.7 |
| 961204 | 7.6 | 0.1 | 0.1 | 0.3 | 1.6 | 0.5 | 2.5 | 11.1 |
| 970101 | 10.7 | 0.0 | 0.2 | 0.6 | 3.9 | 0.2 | 4.9 | 17.3 |
| 970104 | 13.3 | 0.3 | 0.1 | 0.6 | 4.7 | 0.3 | 5.9 | 21.9 |
| 970601 | 6.4 | 0.1 | 0.0 | 0.0 | 0.0 | 3.7 | 4.1 | 12.2 |
| 970604 | 9.1 | 0.4 | 0.0 | 0.1 | 0.0 | 4.9 | 5.3 | 17.1 |
| 971101 | 2.4 | 0.1 | 0.3 | 0.2 | 1.5 | 0.9 | 2.8 | 6.0 |
| 971104 | 5.8 | 0.6 | 0.2 | 0.2 | 1.6 | 0.5 | 2.5 | 9.8 |
| 971501 | 17.0 | 0.7 | 2.4 | 0.0 | 5.4 | 1.0 | 7.4 | 32.6 |
| 971504 | 23.8 | 0.6 | 0.6 | 0.0 | 5.7 | 0.6 | 6.9 | 40.9 |
| 971601 | 15.4 | 0.2 | 1.1 | 3.0 | 5.6 | 0.8 | 9.5 | 27.8 |
| 971604 | 20.5 | 1.7 | 1.3 | 1.2 | 4.9 | 0.5 | 6.9 | 33.8 |
| 971701 | 31.0 | 0.1 | 1.5 | 1.1 | 13.3 | 0.3 | 15.7 | 49.1 |
| 971704 | 28.8 | 0.1 | 2.4 | 1.5 | 9.4 | 0.4 | 11.9 | 44.3 |
| 971801 | 1.3 | 0.7 | 0.3 | 0.0 | 1.7 | 0.1 | 1.9 | 4.5 |
| 980101 | 24.1 | 0.6 | 0.1 | 0.6 | 4.3 | 1.2 | 7.4 | 32.6 |
| 980201 | 9.8 | 0.2 | 0.0 | 0.3 | 5.9 | 1.2 | 7.9 | 24.5 |
| 980301 | 14.9 | 1.8 | 0.3 | 3.1 | 1.3 | 1.0 | 6.0 | 27.8 |
| 980401 | 5.4 | 0.3 | 4.7 | 0.0 | 2.4 | 0.2 | 2.6 | 14.6 |
| 980404 | 7.3 | 0.8 | 5.6 | 0.0 | 2.0 | 0.3 | 2.3 | 18.5 |
| 980601 | 7.7 | 0.0 | 0.1 | 0.3 | 14.0 | 0.8 | 15.6 | 24.3 |
| 980604 | 8.4 | 0.1 | 0.0 | 0.3 | 15.8 | 0.6 | 17.6 | 27.1 |
| 980701 | 9.6 | 1.3 | 1.3 | 0.2 | 0.9 | 0.1 | 1.4 | 24.1 |
| 980801 | 9.7 | 0.3 | 3.1 | 1.8 | 1.7 | 1.5 | 5.3 | 19.1 |
| 990101 | 24.0 | 37.4 | 1.9 | 0.4 | 0.6 | 1.2 | 2.2 | 69.3 |
| 990201 | 17.6 | 0.0 | 0.0 | 0.0 | 0.1 | 2.3 | 2.5 | 20.4 |
| 990301 | 6.5 | 0.0 | 0.0 | 0.0 | 0.0 | 0.2 | 0.2 | 8.9 |
| 990501 | 11.9 | 2.0 | 0.1 | 0.2 | 6.4 | 1.0 | 8.7 | 28.6 |
| 990701 | 12.3 | 0.0 | 0.0 | 0.2 | 0.0 | 6.2 | 6.4 | 19.7 |
| 990801 | 8.2 | 0.0 | 0.0 | 0.0 | 0.0 | 1.2 | 1.4 | 10.3 |
| 990901 | 13.8 | 3.2 | 1.3 | 0.3 | 2.0 | 2.6 | 5.2 | 26.8 |
| 991001 | 30.7 | 0.4 | 0.0 | 1.1 | 3.4 | 0.6 | 5.2 | 38.5 |

* First four digits of the assessment ID represents the location of a stand, and last two digits represents number of years after overstory removal.

Appendix F2. Average regeneration cumulative height of six oak and non-oak species one and four years after harvest by assessment ID.

| Assessment ID* | Regeneration Cumulative Height (ft/milacre) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Red Maple | Black Birch | Black-gum | White Oak | Chestnut Oak | N. Red Oak | All Oaks | All Trees |
| 000101 | 6.2 | 0.2 | 0.2 | 2.1 | 1.2 | 0.1 | 4.6 | 12.8 |
| 000201 | 3.9 | 0.1 | 0.0 | 0.0 | 0.1 | 9.2 | 9.3 | 14.5 |
| 000301 | 6.3 | 3.1 | 0.7 | 0.0 | 2.2 | 0.2 | 2.5 | 13.6 |
| 960101 | 4.1 | 0.0 | 0.7 | 0.0 | 4.7 | 1.4 | 6.8 | 12.0 |
| 960104 | 14.6 | 0.1 | 1.5 | 0.0 | 10.5 | 3.8 | 15.3 | 32.3 |
| 960201 | 2.8 | 0.0 | 0.3 | 0.0 | 0.1 | 0.0 | 0.1 | 3.4 |
| 960204 | 21.3 | 1.3 | 1.1 | 0.2 | 1.6 | 0.1 | 2.0 | 26.5 |
| 960301 | 3.6 | 2.7 | 0.2 | 0.0 | 3.8 | 1.5 | 5.3 | 13.2 |
| 960304 | 7.9 | 10.6 | 0.1 | 0.1 | 6.8 | 1.7 | 8.9 | 29.6 |
| 960401 | 0.8 | 2.6 | 0.5 | 0.0 | 0.2 | 0.3 | 0.5 | 5.0 |
| 960404 | 4.2 | 25.6 | 3.4 | 0.0 | 0.4 | 0.9 | 1.3 | 37.8 |
| 960601 | 11.1 | 3.7 | 0.2 | 0.0 | 0.1 | 3.6 | 3.8 | 40.4 |
| 960604 | 11.2 | 7.4 | 0.2 | 0.0 | 0.0 | 10.0 | 10.0 | 52.1 |
| 960701 | 13.4 | 0.0 | 4.1 | 3.5 | 5.8 | 0.9 | 13.2 | 34.5 |
| 960704 | 27.7 | 0.3 | 7.3 | 5.4 | 12.3 | 3.4 | 26.3 | 68.1 |
| 961101 | 5.7 | 0.0 | 0.0 | 0.1 | 0.0 | 0.3 | 0.4 | 6.2 |
| 961104 | 15.0 | 0.1 | 0.0 | 0.0 | 0.2 | 0.5 | 0.7 | 16.2 |
| 961201 | 4.2 | 0.0 | 0.4 | 0.2 | 1.4 | 0.1 | 2.0 | 7.7 |
| 961204 | 18.4 | 0.0 | 0.2 | 0.3 | 2.2 | 0.7 | 3.4 | 23.1 |
| 970101 | 16.6 | 0.0 | 0.3 | 0.4 | 3.1 | 0.2 | 3.8 | 22.1 |
| 970104 | 33.6 | 0.5 | 0.5 | 0.8 | 9.7 | 0.5 | 11.7 | 49.8 |
| 970601 | 4.2 | 0.1 | 0.0 | 0.0 | 0.0 | 3.1 | 3.4 | 9.5 |
| 970604 | 10.7 | 0.4 | 0.0 | 0.2 | 0.0 | 7.7 | 8.4 | 26.0 |
| 971101 | 1.4 | 0.1 | 0.2 | 0.3 | 2.4 | 2.1 | 5.1 | 7.3 |
| 971104 | 3.4 | 0.4 | 0.2 | 0.5 | 3.3 | 1.0 | 5.4 | 10.2 |
| 971501 | 11.6 | 0.9 | 1.4 | 0.0 | 6.9 | 1.7 | 10.8 | 33.3 |
| 971504 | 21.5 | 0.7 | 0.3 | 0.0 | 12.3 | 1.6 | 15.8 | 48.9 |
| 971601 | 5.9 | 0.1 | 1.5 | 2.4 | 3.5 | 0.6 | 6.5 | 14.9 |
| 971604 | 18.6 | 3.2 | 4.7 | 1.2 | 7.1 | 0.9 | 9.5 | 44.1 |
| 971701 | 31.8 | 0.1 | 1.4 | 0.8 | 16.3 | 0.4 | 18.8 | 53.3 |
| 971704 | 51.1 | 0.2 | 2.6 | 2.5 | 24.3 | 1.0 | 29.8 | 85.7 |
| 971801 | 0.6 | 0.2 | 0.2 | 0.0 | 0.9 | 0.1 | 1.0 | 2.0 |
| 980101 | 30.6 | 0.4 | 0.2 | 1.0 | 5.3 | 1.5 | 9.2 | 40.9 |
| 980201 | 3.2 | 0.2 | 0.0 | 0.2 | 5.4 | 0.8 | 6.7 | 11.4 |
| 980301 | 10.1 | 0.9 | 0.1 | 2.2 | 0.6 | 0.7 | 4.0 | 18.9 |
| 980401 | 4.0 | 0.4 | 8.2 | 0.0 | 2.8 | 0.3 | 3.1 | 16.7 |
| 980404 | 15.4 | 2.6 | 18.1 | 0.0 | 4.0 | 0.7 | 4.8 | 44.2 |
| 980601 | 7.8 | 0.0 | 0.1 | 0.4 | 23.5 | 1.6 | 26.5 | 35.6 |
| 980604 | 15.9 | 0.1 | 0.0 | 0.7 | 48.4 | 2.2 | 54.3 | 72.4 |
| 980701 | 2.9 | 0.4 | 0.6 | 0.1 | 0.4 | 0.1 | 0.6 | 9.7 |
| 980801 | 6.3 | 0.2 | 5.6 | 1.8 | 1.9 | 1.3 | 5.3 | 18.2 |
| 990101 | 8.5 | 30.9 | 2.6 | 0.1 | 0.3 | 0.7 | 1.1 | 48.1 |
| 990201 | 5.9 | 0.0 | 0.0 | 0.0 | 0.0 | 1.0 | 1.1 | 7.4 |
| 990301 | 2.1 | 0.0 | 0.0 | 0.0 | 0.0 | 0.1 | 0.1 | 3.5 |
| 990501 | 14.4 | 3.8 | 0.1 | 0.2 | 10.6 | 1.3 | 14.0 | 42.1 |
| 990701 | 3.9 | 0.0 | 0.0 | 0.1 | 0.0 | 2.8 | 2.8 | 7.2 |
| 990801 | 2.5 | 0.0 | 0.0 | 0.0 | 0.0 | 0.5 | 0.5 | 3.2 |
| 990901 | 7.1 | 1.1 | 1.4 | 0.2 | 1.1 | 1.5 | 2.9 | 14.0 |
| 991001 | 23.4 | 0.2 | 0.0 | 0.7 | 2.2 | 0.3 | 3.2 | 28.5 |

* First four digits of the assessment ID represents the location of a stand, and last two digits represents number of years after overstory removal.

Appendix F3. Regeneration occurrence frequency of six oak and non-oak species one and four years after harvest by assessment ID.

| Assessment ID* | Frequency (%) | | | | | | |
|---|---|---|---|---|---|---|---|
| | Red Maple | Black Birch | Black-gum | White Oak | Chestnut Oak | N. Red Oak | All Oaks |
| 000101 | 95.0 | 3.3 | 21.7 | 52.5 | 22.5 | 8.3 | 78.3 |
| 000201 | 91.7 | 4.2 | 3.3 | 0.8 | 2.5 | 96.7 | 96.7 |
| 000301 | 95.8 | 63.5 | 27.1 | 2.1 | 66.7 | 17.7 | 69.8 |
| 960101 | 61.4 | 0.8 | 3.0 | 0.8 | 56.8 | 39.4 | 79.5 |
| 960104 | 76.5 | 3.0 | 6.1 | 0.0 | 59.1 | 47.7 | 82.6 |
| 960201 | 80.3 | 5.3 | 6.6 | 2.6 | 5.3 | 6.6 | 17.1 |
| 960204 | 100.0 | 41.3 | 12.0 | 14.7 | 22.7 | 13.3 | 49.3 |
| 960301 | 90.6 | 52.8 | 13.2 | 3.8 | 30.2 | 58.5 | 75.5 |
| 960304 | 90.9 | 63.6 | 5.5 | 10.9 | 27.3 | 54.5 | 76.4 |
| 960401 | 70.5 | 73.9 | 25.0 | 0.0 | 22.7 | 38.6 | 52.3 |
| 960404 | 84.3 | 90.4 | 37.3 | 0.0 | 14.5 | 51.8 | 57.8 |
| 960601 | 92.7 | 38.5 | 2.8 | 1.8 | 3.7 | 56.9 | 59.6 |
| 960604 | 94.6 | 43.2 | 4.5 | 2.7 | 0.9 | 87.4 | 87.4 |
| 960701 | 89.6 | 2.1 | 52.1 | 47.9 | 59.4 | 35.4 | 93.8 |
| 960704 | 89.6 | 7.3 | 51.0 | 54.2 | 59.4 | 45.8 | 96.9 |
| 961101 | 92.2 | 0.0 | 0.0 | 3.4 | 4.3 | 23.3 | 32.8 |
| 961104 | 100.0 | 12.1 | 0.9 | 8.6 | 11.2 | 26.7 | 39.7 |
| 961201 | 91.2 | 0.9 | 22.1 | 13.3 | 32.7 | 10.6 | 61.9 |
| 961204 | 92.0 | 5.4 | 6.3 | 16.1 | 33.9 | 28.6 | 63.4 |
| 970101 | 83.1 | 2.4 | 3.6 | 21.7 | 53.0 | 16.9 | 73.5 |
| 970104 | 89.3 | 17.9 | 3.6 | 21.4 | 58.3 | 21.4 | 77.4 |
| 970601 | 77.7 | 3.9 | 1.9 | 2.9 | 1.0 | 68.0 | 69.9 |
| 970604 | 89.0 | 5.0 | 0.0 | 3.0 | 1.0 | 74.0 | 77.0 |
| 971101 | 70.0 | 5.6 | 4.4 | 5.6 | 38.9 | 33.3 | 61.1 |
| 971104 | 77.2 | 15.2 | 4.3 | 5.4 | 40.2 | 31.5 | 62.0 |
| 971501 | 93.1 | 27.7 | 42.6 | 1.0 | 55.4 | 23.8 | 70.3 |
| 971504 | 97.1 | 20.2 | 13.5 | 0.0 | 60.6 | 23.1 | 77.9 |
| 971601 | 94.6 | 8.1 | 24.3 | 36.9 | 43.2 | 30.6 | 77.5 |
| 971604 | 96.4 | 36.6 | 34.8 | 22.3 | 38.4 | 26.8 | 67.9 |
| 971701 | 99.1 | 6.3 | 33.0 | 16.1 | 79.5 | 12.5 | 89.3 |
| 971704 | 99.1 | 9.8 | 40.2 | 20.5 | 76.8 | 19.6 | 90.2 |
| 971801 | 47.3 | 30.4 | 16.1 | 0.9 | 45.5 | 10.7 | 53.6 |
| 980101 | 96.2 | 25.0 | 5.8 | 21.2 | 46.2 | 51.9 | 90.4 |
| 980201 | 96.7 | 6.7 | 0.8 | 17.5 | 63.3 | 53.3 | 91.7 |
| 980301 | 94.0 | 38.0 | 12.0 | 50.0 | 22.0 | 33.0 | 74.0 |
| 980401 | 85.3 | 9.5 | 78.4 | 0.0 | 50.0 | 17.2 | 56.0 |
| 980404 | 89.2 | 30.8 | 82.5 | 0.0 | 47.5 | 20.8 | 57.5 |
| 980601 | 81.0 | 3.0 | 2.0 | 7.0 | 95.0 | 35.0 | 98.0 |
| 980604 | 91.9 | 6.1 | 0.0 | 10.1 | 92.9 | 39.4 | 100.0 |
| 980701 | 86.9 | 39.3 | 39.3 | 10.7 | 20.2 | 13.1 | 46.4 |
| 980801 | 93.8 | 18.8 | 39.1 | 28.1 | 29.7 | 40.6 | 68.8 |
| 990101 | 93.5 | 78.7 | 31.5 | 6.5 | 16.7 | 46.3 | 56.5 |
| 990201 | 86.7 | 0.8 | 0.0 | 4.2 | 3.3 | 50.0 | 58.3 |
| 990301 | 73.3 | 1.7 | 0.0 | 1.7 | 1.7 | 15.0 | 21.7 |
| 990501 | 95.7 | 48.9 | 4.3 | 8.5 | 63.8 | 42.6 | 80.9 |
| 990701 | 94.0 | 1.0 | 2.0 | 3.0 | 0.0 | 61.0 | 67.0 |
| 990801 | 95.8 | 0.8 | 0.8 | 0.0 | 0.0 | 45.0 | 50.0 |
| 990901 | 96.2 | 39.4 | 32.7 | 13.5 | 44.2 | 62.5 | 83.7 |
| 991001 | 99.0 | 13.5 | 3.8 | 41.3 | 33.7 | 30.8 | 75.0 |

* First four digits of the assessment ID represents the location of a stand, and last two digits represents number of years after overstory removal.

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## PUBLICATIONS

**Fei**, **S.**, P.J. Gould, K.C. Steiner, J.C. Finley, and M.E. McDill. Cumulative height -- a composite variable to predict early-stage mixed-oak stand development. Forest Ecology and Management. (Submitted).

**Fei**, **S.**, P.J. Gould, K.C. Steiner, J.C. Finley, and M.E. McDill. Forest regeneration composition and development in upland, mixed-oak forests. Tree Physiology. (Submitted).

Rathbun, S. and **S. Fei**. 2005. A spatial zero-inflated Poisson model for oak regeneration. Environmental and Ecological Statistics, 12 (2) (In press, EES-MS-2004-0705).

**Fei**, **S.**, K.C. Steiner, J.C. Finley, M.E. McDill, and P.J. Gould. 2004. Composition and development of non-tree vegetation and its relationship with tree regeneration in mixed-oak forest stands. USDA, Forest Service, Gen. Tech. Rep. NE-316: 297-303.

P.J. Gould, K.C. Steiner, J.C. Finley, M.E. McDill, and **S. Fei**. 2004. The post-harvest competitive environment in 13 mixed-oak stands in Pennsylvania. USDA, Forest Service, Gen. Tech. Rep. NE-316: 427-433.

**Fei**, **S.**, K.C. Steiner, J.C. Finley, and M. E. McDill. 2003. Relationships between biotic and abiotic factors and regeneration of chestnut oak, white oak, and northern red oak. USDA, Forest Service, Gen. Tech. Rep. NC-234: 223-227.

Fang, J., **S. Fei**, K. Zhao, Y. Fan, D. Zhuang, and M. Wu. 2000. Anatomical characteristics of beech (*Fagus*) species in Zhejiang and their taxonomic significance. Acta Scientiarum Naturalium Universitatis Pekinensis 36 (4): 509-516.

Fang, J., **S. Fei**, Y. Fan, and K. Cui. 2000. Ecological patterns in anatomic characters of leaves and woods of *Fagus lucida* and their climatic control in Mountain Fanjingshan, Guizhou, China. Acta Botanica Sinica 42 (6): 636-642.

**Fei, S.**, J. Fang, Y. Fan, K. Zhao, X, Liu, and K. Cui. 1999. Anatomical characteristic of leaves and woods of *Fagus lucida* and their relationship to ecological factors in Mountain Fanjingshan, Guizhou, China. Acta Botanica Sinica 41 (9): 1002-1009.