Applications of ecological modeling in managing Central Appalachian upland oak stands for old-growth characteristics.

Lawton E. Grinter

Thesis submitted to the Faculty of the
Virginia Polytechnic Institute and State University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE
in
FORESTRY

Carolyn A. Copenheaver, Co-Chair

Shepard M. Zedaker, Co-Chair

Philip J. Radtke

August 6, 2002
Blacksburg, Virginia

Keywords: old-growth, ecosystem modeling, Appalachian hardwoods, gap models, restoration ecology

Applications of ecological modeling in managing Central Appalachian upland oak stands for old-growth characteristics.

Lawton E. Grinter

Committee Chairpersons: C.A. Copenheaver, S.M. Zedaker

(ABSTRACT)

Old-growth forests provide important habitat for wildlife, support the maintenance of biodiversity and serve as control areas for scientific research. Expanding current old-growth stand area by utilizing neighboring younger, managed stands allows private landowners to meet management needs and enables government agencies and private conservation organizations to meet old-growth forest objectives. Seven old-growth upland oak stands and seven adjacent younger, managed stands of the same site and stand type were measured in the Ridge and Valley, Blue Ridge, and Piedmont provinces of Virginia and Pennsylvania in an effort to characterize species composition, diameter distribution and canopy structure. A computer-based ecosystem/gap model (JABOWA-3) was modified and used to simulate silvicultural manipulations in the younger stands that would reproduce older forest characteristics. Various silvicultural techniques were used to convert the primarily even-aged younger stands into uneven-aged stands and then into old-growth. These manipulations included single-tree selection, herbicide application, culling larger diameter stems and planting seedlings where required. Individual trees within each of the younger, managed stands were removed at various time intervals and these simulated stands were then projected to a point in time in which the stand approximated the diameter distribution and composition

of its paired old-growth stand. Several projections were made in each of the younger stands to meet this objective. Once a satisfactory projection was made for conversion of a younger stand to old-growth, a success rate was determined to gauge how close the simulated stand approximated the diameter distribution and composition of its old-growth counterpart. From this information, biologically feasible and environmentally sound management plans were created to carry out the silvicultural manipulations required by the model for each of the sites.

ACKNOWLEDGEMENTS

I would like to express my sincere gratitude to both my committee co-chairpersons, Dr. Shepard Zedaker and Dr. Carolyn Copenheaver, and to committee member, Dr. Philip Radtke. This project would not have been possible without Dr. Zedaker's guidance and financial support during the first year and for that I am truly grateful. The ecological expertise provided by Dr. Copenheaver and her accessibility for the many questions I had during the thesis writing process were immensely helpful and made my life much easier. The computer modeling and programming expertise provided by Dr. Radtke were essential in allowing me to complete the ecological modeling portion of this project.

I would also like to thank Dr. Paul Mou, Dr. Harold Burkhart, Dr. Zedaker and Dr. David Smith for opening the door to me here at Virginia Tech. I am very grateful to have been afforded the opportunity to complete my Master's degree in one of the nation's top Forestry Departments. Further, I would like to thank Dr. Copenheaver, Bob Longe, Jean Lorber, Andy Scott, David Mitchem and everyone else that helped me with various segments of this research project.

I would also like to express thanks to the various state agencies, federal agencies, and private organizations that granted permission to allow sampling on their land for this project. These agencies and organizations include: the US Forest Service, the Virginia Department of Forestry, the National Park Service, the Pennsylvania Bureau of Forestry, and the National Trust for Historic Preservation.

Finally, I would like to show gratitude to my parents, family and friends for their continued support and encouragement throughout these past two years.

TABLE OF CONTENTS

List of Figures

List of Tables

I. INTRODUCTION

Old-growth forests are woodland areas that have physical structures and ecological processes as they might have had in the absence of contemporary human activity (USFS 1998). These forests provide various non-commodity values and serve as important habitat for wildlife and plants (Hunter 1989, Rooney 1995). There are numerous communities of wildlife species that rely on old-growth forests for their survival. National attention recently has focused on endangered species such as the red-cockaded woodpecker (*Picoides borealis*) in the southeastern United States and the northern spotted owl (*Strix occidentalis*) in the Pacific Northwest because of user conflicts associated with these old-growth dependant species (Gutierrez and Carey 1985, Carey 1989). In Virginia, the red-cockaded woodpecker, pileated woodpecker (*Dryocopus pileatus*), black-throated blue warbler (*Dendroica caerulescens*), cerulean warbler (*Dendroica cerulea*), wild turkey (*Meleagris gallopavo*), black bear (*Ursus americanus*), and barred owl (*Strix varia*) all prefer mature and/or old-growth forests for habitat (Hardt and Newman 1995, Haney 1997, Jesse Overcash, personal communication, 2001).

Old-growth forests are also important in maintaining biodiversity (Noss 1991, Hansen et al. 1991, Franklin 1993, Slocombe 1993, Rooney 1995, White and Lloyd 1998) and they continually serve as control areas and benchmarks for ecological research (Vora 1994, McCarthy 1995, Goebel and Hix 1996, Nelson et al. 1997). Hunter and White (1997) noted that old-growth forest stands are rare compared to their abundance in pre-industrial times and it is this rarity that increases their value. Private landowners along with federal and state agencies are currently using selection cuts and other silvicultural methods to mimic old-growth forest structure within managed stands (Lorimer and Frelich 1994, Vora 1994, Rooney 1995, Goebel and Hix 1996). Forest managers can make more informed silvicultural recommendations for restoring old-growth stand structure in younger, managed stands by utilizing computer-based ecosystem/growth models. These computer models provide forecasts and predictions of how a stand will respond to various silvicultural manipulations. Thus, models allow land managers to predict future forest yields, explore management options, and investigate silvicultural alternatives before investing time and money on actual implementation (Vanclay 1994).

Goals and Objectives

-Goal

The goal of this study was to examine various silvicultural methods for restoring second and third growth hardwood forests in the Ridge and Valley, Blue Ridge, and Piedmont of Virginia and Pennsylvania to conditions found in nearby and adjoining upland oak old-growth forests. The species composition and structure of the old-growth stands were measured as a reference of old-growth characteristics for that site. This local old-growth structure was then used as a goal for modeling the growth response to silvicultural treatments in adjacent younger, managed stands. Using old-growth stands, paired second-growth stands, and computer-based growth models allows forest managers to make silvicultural recommendations that accelerate the development of older forest characteristics in the younger stands.

-Objectives

The objectives of this study were to (1) characterize old-growth upland oak forest stands and their adjacent younger, managed stands in Virginia and Pennsylvania, and (2) use computer growth/ecosystem modeling to examine methods of silviculturally modifying the younger, managed stands to a stand structure comparable to its neighboring old-growth stand.

II. LITERATURE REVIEW

Defining Old-Growth

There is no universally accepted definition of an old-growth forest (Hunter 1989, Hardt and Newman 1995). Typically researchers have used forest age thresholds and/or the presence of certain stand characteristics to define old-growth (Hunter and White 1997). Age thresholds are particularly problematic because different tree species have different longevities (Table 1, Loehle 1988, Burns and Honkala 1990, Oliver and Larson 1996). Old-growth structural characteristics, such as uneven-age structure, having many mature trees, high vertical diversity, an abundance of snags, an abundance of coarse woody debris (CWD) on the forest floor and in streams, pit and mound topography, steady-state nutrient and energy cycling, and steady-state volume growth (Franklin et al. 1981, Oliver and Larson 1996) may be more effective in determining whether a stand is in an old-growth state. The variability of maximum tree ages for different species accompanied with multi-species stands makes using age thresholds as the only definition for determining old-growth classification a less accurate method. For example, the typical lifespan for undisturbed, overstory white oak (*Quercus alba*) is 300 years, while the typical lifespan for black oak (*Q. velutina*) is 100 years. White oak has been documented to live as long as 600 years, while black oak may reach a maximum lifespan of only 200 years (Table 1, Loehle 1988, Virginia Big Tree Program 2001). In essence, a 120-year old black oak stand would qualify as old-growth, while a 120-year old stand of white oak would not.

Table 1. Typical lifespans and maximum lifespans for various upland oak species that have reached maturity (Loehle 1988, Stransky 1990, Virginia Big Tree Program 2001).

Latin Name	Common Name	Average Life	Maximum Life
Quercus alba	white oak	300	600
Quercus coccinea	scarlet oak	50	200
Quercus falcata	southern red oak	200	275
Quercus prinus	chestnut oak	300	400
Quercus rubra	northern red oak	200	400
Quercus stellata	post oak	250	400
Quercus velutina	black oak	100	200

Not all characteristics must be present for a stand to qualify as old-growth. For example, on drier, upland old-growth sites, it is possible that old-growth characteristics, such as snags, coarse woody debris, and pit and mound topography may not be present in southern Appalachian forests (White and Lloyd 1998). Uneven-age stand structure is another common characteristic of eastern old-growth forests (Lorimer and Frelich 1994, Abrams and Orwig 1996, Tyrell et al. 1998); however, even-aged old-growth stands do exist. The Hermitage, which is owned by The Nature Conservancy in Central Maine, is comprised of an even-aged old-growth stand of 200-year-old white pine located within an uneven-aged forest (Kyle Stockwell, personal communication, 2001). Natural disturbances, including windthrow and fire, have created even-aged patches of old-growth forest in other areas as well (Tyrell et al. 1998).

Current Status of Old-Growth Restoration/Reconstruction

Restoration Treatments

Diverse silvicultural treatments have been used in old-growth management to hasten the transformation of younger, managed stands into uneven-aged stands and then into old-growth stands (Erdman 1986, Runkle 1991, Marquis et al. 1994, Lorimer and Frelich 1994, Vora 1994, Rooney 1995, Goebel and Hix 1996, Coates and Burton 1997). The primary objective of old-growth restoration projects is to accelerate old-growth stand structure formation more quickly than what natural processes will permit.

-Single-tree Selection

Single-tree selection is the removal of individual trees within a stand (Nyland 2002) and is one of the most appropriate prescriptions to convert even-aged forests into uneven-aged forests (Lorimer and Frelich 1994, Rooney 1995, Goebel and Hix 1996, Coates and Burton 1997) while maintaining a natural, undisturbed appearance (Marquis et al. 1994). Depending upon which trees are removed, this type of cut can leave an intact forest canopy, which gives the appearance of a relatively undisturbed forest (Marquis et al. 1994). The main drawbacks with this silvicultural method are that it can be damaging to nearby trees during removal, produce inadequate oak regeneration if the gap created is too small, and provide no monetary return if cut trees are left on site for coarse woody debris, which may limit its appeal as a viable option for landowners and agencies on limited budgets.

-Group Selection

Group selection is the removal of trees in small groups or clusters (Nyland 2002). Various group selection cuts may also be considered as prescriptions for converting younger, managed stands into old-growth forests (Rooney 1995). Artificial gap formation has been suggested as one treatment for shortening the time span in conversion of second growth to old-growth stand structure (Lamson et al. 1990, Lorimer and Frelich 1994, Smith et al. 1994, Singer and Lorimer 1997).

Silvicultural manipulations can be used to mimic natural disturbance regimes (Rooney 1995, Vora 1994). One common technique is the creation of canopy gaps in young forests to restore gap dynamics found commonly in eastern old-growth forests (Erdman 1986, Lorimer and Frelich 1994, Goebel and Hix 1996, Coates and Burton 1997). The establishment of canopy gaps has been employed in both the Nicolet National Forest in Wisconsin and Ottawa National Forest in Michigan in an effort to produce old-growth characteristics in younger hardwood stands (Vora 1994).

The dynamics within canopy gaps offers insight into the competitive interactions among tree species of differing shade tolerances, even though it may take hundreds of years for an individual gap to cycle (Shugart 2000). Forcier (1975) found that yellow birch (*Betula alleghaniensis*) showed a more opportunistic reproductive strategy in a New Hampshire climax forest of American beech (*Fagus grandifolia*), sugar maple (*Acer saccharum*) and yellow birch. These three species covered approximately equal portions of the dominant trees in that stand, but yellow birch seedlings were consistently found in higher densities on newly created canopy gaps. Forcier concluded that because yellow birch is less shade tolerant than both American beech and sugar maple, it takes advantage of canopy gaps as soon as they are formed. Foresters and land managers can use this knowledge of reproductive strategies and competition to hasten the attainment of an old-growth stand structure.

-Other Thinning and Conversion Operations

Crown release treatments accelerate growth of selected trees while reducing adjacent competitors. In younger stands, freeing competition on all sides of the release tree is typical, however; in mature northern hardwood stands, a 50-75% release around the perimeter of the crown is common and the reduced cutover area averts the creation of unnecessarily large canopy gaps (Singer and Lorimer 1997). Crown release in older trees also has been found to be effective for some oak species. In 75 to 80-year-old hardwood stands in West Virginia, 44% mean diameter growth-rate responses to full crown release were documented for northern red oak (*Q. rubra*) five years after the release (Smith and Miller 1991).

Thinning also aids in producing the multilayered canopies typical of old-growth stands. Reducing the basal area of a stand to five m^2/ha less than "full stocking" has been recommended for producing larger trees (Sander 1977, Erdman 1986). Another method to increase the number of large trees is to thin oak stump sprouts around age 10 while leaving the single best quality stem (Erdman 1986).

Tubbs (1977) suggested leaving 14-20 m^2/ha basal area or the best quality 130 trees/ha that are at least 12 cm DBH or larger to change an even-aged northern hardwoods stand into an uneven-aged stand. Erdman's (1986) conversion method from even-aged to uneven-aged structure involves cutting to 80% residual crown cover, except on areas where trees are subject to windthrow such as exposed ridgetops and sites with shallow or wet soils.

-Non-harvesting Alternatives

Alternatives to harvesting also may be used to mimic old-growth stand structure. Girdling trees and leaving them is one option that has been employed to create snags and provide suitable cavity trees for wildlife habitat (Runkle 1991, Singer and Lorimer 1997). Snags and CWD should be left intact after any type of thinning, prescribed burning, or silvical restoration for the same reason (Hansen et al. 1991, Rominske and Busch 1991, Welsh et al. 1992, Crow et al. 1993, Goebel and Hix 1996). As part of its old-growth management plan, the Ottawa National Forest in Michigan has created snags along with using modified conventional uneven-aged silviculture in younger, managed stands to increase the total amount of its forest containing old-growth characteristics (Vora 1994, Lorimer and Frelich 1994).

Planting oaks in canopy gaps or under thin canopies also has been suggested in areas where natural oak regeneration is being outcompeted by more shade-tolerant species such as red maple (Burns 1983). This method can be labor intensive and financially expensive and therefore should be avoided if the probability of success of natural regeneration can be assured through a preliminary regeneration survey (Sander et al. 1984). One method to improve the success of natural oak regeneration or manually planted oak seedlings is to use seedling protection tubes or fencing for protection from deer browsing (Marquis et al. 1984, Singer and Lorimer 1997).

Old-Growth Management Areas

The Allegheny National Forest (ANF) in Pennsylvania is currently managing 25% of its entire land base for old-growth characteristics (Nelson et al. 1997). The ANF is using a landscape approach in its old-growth management by connecting 16,190 ha of large, unfragmented parcels to continuous canopy corridors. The two largest of these parcels are 3,640 ha and 4,050 ha in size, and are connected by 33,185 ha in corridors. Currently the ANF contains less than 2,020 ha of remnant old-growth stands. In an effort to increase the amount of forest with old-growth characteristics, the ANF is employing an adaptive management approach. In maturing hardwood forests, managers have released subordinate conifers and have underplanted conifers in hardwood stands that are only partially cut. Coarse woody debris has been enhanced by leaving downed trees on the ground after tornado salvages and partial cuts. ANF also has taken a proactive approach to managing old-growth areas that might be affected by windstorms, tornadoes, and insect and disease outbreaks in the future. In these situations, silvicultural restoration involving planting and fencing of newly planted areas to prevent seedling mortality from deer browsing will be employed to re-establish these old-growth areas.

The Huron and Manistee National Forests in Michigan have designated 18% (70,000 ha) of their total combined forests to be managed for old-growth structure. Their agreement involves managing for old-growth over the entire range of ecosystems found within their forest boundaries. Both of these National Forests are using an island-corridor approach that involves incorporating a network of "islands" of future old-growth and connecting corridors. Proposed corridors would include wetlands and various riparian zones as important landscape features. Additionally, silvicultural thinning operations aimed at generating large diameter trees and increasing vertical and horizontal diversity are being implemented to achieve old-growth management goals in these two National Forests. 10 to 30% of the designated 70,000 ha will remain unthinned for biodiversity as stated in the Huron and Manistee's old-growth restoration guidelines (Vora 1994).

Apostle Islands National Seashore (AINS) in Wisconsin is currently investigating various restoration objectives. AINS is planning to restore second growth ecosystems within its boundaries to conditions that would represent a forest free from human disturbance for 100 years by using silvicultural techniques to manipulate forest structure in second-growth forests adjacent to the park's only sizable tract of old-growth (Lorimer and Frelich 1994, Singer and Lorimer 1997).

Ecological Modeling Management Applications

Computer-based ecosystem/growth models allow forest managers to make silvicultural recommendations for the creation of old-growth stand structure in younger stands. A large number of models are available to foresters for a variety of uses, and selecting a proper model must involve careful consideration of forest type and management objectives (Shugart 1984, Botkin 1993, Vanclay 1994, Pacala et al. 1996, Hof and Bevers 2000). Typical even-aged growth and yield models, such as PCWThin, NE Twigs, and G-HAT are not sufficient for modeling the complex dynamics of uneven-aged forests (Vanclay 1994). They were designed for even-age rotation forestry and short-term intervals, which is not suitable for old-growth restoration silviculture.

Gap Models

Gap models were designed to answer questions about successional trends. These models have been in existence since the early 1970's (Botkin 1993) and examples include JABOWA, FORET, ZELIG, and SORTIE**.** All of these models explain varying developmental stages of succession in relation to the point at which an overstory tree in a stand falls and creates a canopy opening or gap. Understanding the abilities and limitations of these various models is essential in choosing the correct one for specific research objectives.

ZELIG is a spatially explicit, individual-based gap model, developed by Urban that provides a variety of stand structure insights into a simulation and was designed to be more versatile than JABOWA-FORET style gap models (Urban 1990, Dan Druckenbrod, personal communication, 2001). This model simulates forest dynamics by quantifying the germination, annual diameter growth, and death of each individual tree in a forest. It also takes into account the following abiotic factors: available sunlight, soil moisture, soil fertility, and temperature. ZELIG uses a "landscape" level approach as opposed to the "stand" level approach that the other gap models use. Thus ZELIG is not as site specific as the JABOWA-FORET type gap models.

SORTIE is a spatial gap model developed by Pacala that focuses on long-term dynamics (modeling hundreds to thousands of years) of transition oak-northern hardwood forests in the northeastern United States (Pacala et al. 1996). This individual tree-growth model forecasts the dynamics of populations by predicting the birth, dispersal, growth, survivorship, and reproduction of single trees in a forest community (9 ha plot size minimum) by utilizing submodels defined from collected field data. This field data is then used to simulate species-specific growth interactions between individual trees by taking into account horizontal and vertical distribution of these trees within a plot.

FORET is a gap model originally developed by Shugart and West (1977). This model was created by modifying another gap model, JABOWA, to specifically mimic forests in eastern Tennessee. This model simulates the growth of 33 tree species on 1/12 ha plots in a typical southern Appalachian deciduous forest. Species include most of the upland oaks, hickories, shade-tolerants such as maples, and shade-intolerants such as yellow-poplar (*Liriodendron tulipifera*).

Botkin, Janak, and Wallis developed the JABOWA gap model in 1970 through an agreement between the IBM Research Division and Yale University in an effort to model the growth of uneven-aged, mixed-species stands of trees in the Hubbard Brook Ecosystem in northern New Hampshire (Botkin et al. 1972a, Botkin et al. 1972b, Botkin 1992, Botkin 1993). This model simulates individual tree growth on 1/100 ha forest plots by using the following parameters: tree height, diameter at breast height (DBH), air temperature, rainfall, soil moisture and nitrogen content, elevation, latitude, and competition among trees for light. It was originally developed for use in northern hardwood forests, but can be modified for use in the Appalachians and other areas of the US by adding different tree species, adding weather data files, and by changing the plot size to adjust for the species diversity and the average size of trees that comprise the forest. Larger plots are required in forests of the southern Appalachians because they contain relatively "large" overstory trees compared to northeastern forests (Shugart and West 1979).

In the past, JABOWA has been used for a varying array of ecological studies. The model has been applied to research on Holocene vegetation records (Davis and Botkin 1985), succession in semiarid grasslands (Coffin and Lauenroth 1990), tree dynamics in the boreal forests of Alaska's interior (Bonan and Korzuhin 1989), and to investigate global warming and climate change effects on Pacific Northwest forests (Dale and Franklin 1989). In a previous study conducted at Hartwick Pines State Park, Michigan, JABOWA was used to predict succession dynamics in an old-growth forest reserve (Botkin 1993), but no literature exists on uses of this model for old-growth restoration in younger, managed stands.

Using gap models to examine old-growth restoration is feasible, and both JABOWA and FORET are capable of handling the manipulations needed to accomplish the restoration objective of this study with one major exception (Dan Botkin, pers. comm., 2001, Dan Druckenbrod, pers. comm., 2001). FORET does not have a soil analysis input component, which limits the use of this model to bottomland areas of the southern Appalachians (Shugart 1974). Most of the sites being used in this project are ridgetop or sideslope sites so using the FORET model was not a viable option. JABOWA also had some drawbacks because of its high spatial resolution; 1/100 ha plots are used, which have been found to be too small for use in modeling southern Appalachian forests (Shugart and West 1979). However, JABOWA incorporates a soil analysis component, the plot size can be increased to a greater size, and the user support community was larger since this model is more widely used, and not specific to forests of a small area. After considering these factors, I chose the JABOWA gap model for the simulations needed in this project.

JABOWA Review and Analysis

JABOWA was created to reproduce the population dynamics (species succession, individual tree suppression and release, etc.) of the trees in a mixed species forest in northeastern North America. This implies that JABOWA is suitable to model various forest types throughout the entire New England region, but the model was originally designed to simulate tree growth at the stand level on 1/100 ha (10m × 10m) plots distributed throughout the Hubbard Brook watershed of New Hampshire. Botkin et al. (1972a) initially simulated a period of 2000 years with the model in an effort to investigate succession in a beech-birch-cherry forest after an initial clearcut in the Hubbard Brook watershed; however, the time scale suitable for use with JABOWA is anywhere from decades to thousands of years.

Tree Species Parameters

JABOWA-3 includes 25 parameters for each tree species and seven site information parameters. Users of the model who wish to add tree species that are not already included in the model source code can do so by calculating values for these parameters for their new species (Appendix A). Tree species parameters are listed below in the same order presented in the model source code:

1) (S): this is the shade tolerance class of each species. A species is either considered shade-intolerant (1), intermediate (2) or shade-tolerant (3). This shade-tolerance classification has a direct impact on regeneration of each species in the model (discussed in greater detail under "SAP" parameter).

2) (N): this parameter serves as an index of soil fertility. Trees are broken up into three separate N classifications: nitrogen-intolerant (1), intermediate (2) and nitrogen-tolerant (3). Trees considered nitrogen-intolerant (1) grow rapidly in soils with high available nitrogen amounts, but grow slowly in low-nitrogen soils. The converse is true for nitrogen-tolerant soils, while nitrogen-intermediate tree species demonstrate growth in the middle of the two latter classifications.
3) (SAP): this parameter establishes the maximum amount of saplings for each tree species that can be added to a plot during one calendar year. The model defines a sapling as a tree with a minimum height of 1.37 m. The model typically allocates a large maximum number of saplings (50-60/100 m^2 plot) to enter for early successional species, which usually are shade-intolerant. A small maximum number of saplings (1-3/100 m^2 plot) are entered for late successional species (typically shade-tolerant). Intermediate species are allotted a maximum number of saplings between 1-15/100 m^2 plot. The number added to each plot is a stochastic function, but will fall within the specified range for each shade-tolerance classification.
4) (E): this is the "able to enter" parameter. A value of "0" will keep a tree species from entering the plot and germinating while a value of "1" will allow a species to enter the plot. This parameter allows for the elimination of tree species from a plot to simulate the effects of a species-specific disease.
5) (G): this parameter scales the growth rate of each tree species under optimal conditions and was calculated by assuming that a tree under optimal

conditions should grow to two third's of its maximum height at one-half of its maximum age, beginning from an initial 0.5 cm stem.

6) (C): this parameter represents the ratio between leaf weight and diameter of a tree species (smaller values of C signify that a tree has fewer leaves).
7) (DMAX): this represents the maximum diameter in cm for each tree species.
8) (HMAX): this represents the maximum height in cm for each tree species.
9) (AMAX): this represents the maximum age for each tree species. The data comes from previously published papers on tree longevity.
10) (b_2): this is a tree height parameter and is derived using the following empirical function: $b_2 = 2(H_{max}-137)/D_{max}$ where H_{max} = the maximum height of a certain tree species, 137 = DBH in cm, and D_{max} = the maximum diameter of a tree species.
11) (b_3): this is the second tree height parameter and uses the following equation: $b_3 = (H_{max}-137)/D^2_{max}$. It should be noted that both equations for b_2 and b_3 are combined together in the following function relating height to diameter: $H = 137 + b_2D – b_3D^2$. This function is used in the model to calculate "shading" by an individual tree on a plot.
12) (AINC): this parameter is set to a value of "0.01 cm" for each tree species and is used by the model as the minimum annual diameter growth increment.
13) (DDMAX): this parameter represents the physiological degree-day value with an isopleth congruent with the tree species' northern (cold) range boundary.
14) (DDMIN): conversely, this parameter is the analogous isopleth associated with the southern (warm) boundary range. Both "DDMAX" and "DDMIN"

are used to adjust a tree species growth due to abiotic factors related to a species geographical range (temperature, light availability, etc.).

15) (DT): this parameter represents the minimum depth to the water table that each tree species requires for adequate growth. The relationship between DT and depth to bedrock is used in JABOWA-3 to differentiate between trees adapted to wet environments and those adapted to dry environments.

16) (WLTMX): this parameter indicates the maximum wilt allowable by a species under which it will remain alive. This value has been estimated as factor between 0.5 and 5.0 with species characteristic of dry sites given a value closer to 5.0 and a species characteristic of wet sites given a value closer to 0.5.

17) (LT_MIN): this parameter establishes the minimum percentage of sunlight intensity at the soil surface needed for a tree of intermediate shade tolerance to enter the plot.

Parameters 18-21 are all biomass parameters. These parameters are incorporated into the following equation to determine biomass (kg/m^2) for separate portions of a tree:

$$\text{Biomass} = \frac{(A_1 D^{A_2})}{A_3}$$

where A_1, A_2 and A_3 (Table 2) are biomass parameters and D is the DBH in cm.

Table 2. Biomass parameters used in the JABOWA-3 model for separate portions of a tree (Botkin 1992).

	Parameters		
Portion	A_1	A_2	A_3
Stem	SWA	SWB	100,000
Bark	SBA	SBB	100,000
Branch	BA	BB	100,000
Roots	RA	RB	100,000

18) (STEM): these two parameters (SWA & SWB) are used in the above biomass equation to determine the biomass (kg/m^2) for the stem of a specific tree species.

19) (BARK): these two parameters (SBA & SBB) are used in the above biomass equation to determine the biomass (kg/m^2) for the bark of a specific tree species.

20) (BRANCHES): these two parameters (BA & BB) are used in the above biomass equation to determine the biomass (kg/m^2) for the branches of a specific tree species.

21) (ROOTS): these two parameters (RA & RB) are used in the above biomass equation to determine the biomass (kg/m^2) for the roots of a specific tree species.

Site Information Parameters

1) (ELEV): this parameter represents the plot elevation in feet above sea level and is used in determining the difference in elevation between the plot and weather station from which the temperature and precipitation records for the site come from. Temperature and precipitation are adjusted according to a

standard meteorological lapse rate (decrease in temperature of approximately 1°C per 300 m elevation).

2) (LAT): this latitude parameter is required by the model in order to adjust the seasonal amount of sunlight available on a plot.
3) (SOIL_DEPTH): this parameter represents the average depth of the soil on a site and is used to determine the amount of water that can be stored in the soil. A default value of 1 m is used in situations where the soil is deeper than 1 m.
4) (WATER_TABLE_DEPTH): this parameter is the depth at which the soil is saturated with water provided this occurs in the top meter of soil, otherwise a default value of 1 m is used.
5) (TEXTURE): this is the soil texture parameter and is used as a measure of moisture-holding capacity (mm of water/m of soil depth).
6) (%_ROCK): this parameter represents the percent coverage of rocks on the soil profile surface. If percent rock is 30%, then water storage is decreased by 30%.
7) (AVAIL_N): this parameter represents the yearly amount of available nitrogen (kg/ha) through soil mineralization that is present on a site and is measured on a relative scale (-100 to +100). Zero represents a relatively poor site, and 100 represents an extremely good site.

Functional Relationships

The JABOWA-3 model uses three subroutines to predict how trees germinate, grow, compete for space, and eventually die. The subroutines are as follows: 1) Subroutine GROW, 2) Subroutine BIRTH, and 3) Subroutine KILL.

-Subroutine GROW

Subroutine GROW contains equations that calculate growth functions. The most important of these is the fundamental growth equation:

$$\delta D = \frac{GiD\,[1-(DH/D_{max}\,H_{max})]}{274 + 2b_2D - 4b_3D^2} * \sum(\text{environment})$$

where D is the DBH of a tree, H is the total height of a tree, D_{max} is the maximum known diameter for a specific tree species, H_{max} is the maximum known height for a specific tree species, G is a representative constant that determines how quickly a tree reaches one-half of its maximum size, ∑(environment) is the sum of environmental conditions on a specific site, and b_2 & b_3 are tree parameters that relate height to diameter (see Model Parameters #10 and #11 above).

The growth of each individual tree on a plot is simulated as a function of the climate, area of leaves above the tree, crowding from other trees, shading by other taller trees, and the size of the tree. It is important to note that in JABOWA-3, as with other gap models, each tree on a plot shades all shorter trees. Competition between trees on a plot is affected by the following abiotic parameters: air temperature, rainfall data, elevation of the plot, latitude of the plot, soil moisture (soil texture measured as the moisture holding capacity in mm H_2O/m of soil depth), available N in soil and percent rock in top meter of soil. These abiotic factors simultaneously affect growth of each individual tree and are combined within the model and expressed as a factor between 0 and 1. The model then uses this "environmental condition" to decrease tree growth beneath a species-specific maximum calculated in the fundamental growth equation.

-Subroutine BIRTH

Subroutine BIRTH contains equations that calculate the number of new saplings that become established in the plot. The shade tolerance of an individual tree species is directly correlated to the maximum number of saplings that can be entered for that species in one year. Shade intolerant species have a large maximum number since they are typically found in open areas and in early successional stages. Shade tolerants have relatively low maximum numbers and shade intermediates are in between. In this process of sapling recruitment, two important assumptions are made: 1) seeds of all species in the default tree list are present in the forest, and 2) germination of seeds for any given species will take place provided environmental conditions are suitable for the production of mature trees of that species. JABOWA-3 calculates the actual amount of saplings that can be included in the plot for a given year by multiplying the maximum number of saplings allowable for a species by the sum of environmental factors (light, temperature, soil moisture, and soil available N content) on that site, which typically reduces that maximum number.

-Subroutine KILL

Subroutine KILL contains equations that calculate tree mortality. The model uses two types of death processes. The first is directly correlated to the maximum longevity of an individual tree species and applies to all trees on a plot. Here the assumption is made that only 2% of trees that reach the overstory and remain in good health throughout their life will attain the maximum known age for their species. The second assumption is referred to as “competition-induced death,” which is simply the death of a poorly growing tree. Under this mortality process, the model checks each individual tree to see if the diameter growth of that tree plunges below a minimum (see Model Parameter #12 above). If diameter growth does fall below this minimum, the tree is at risk to a higher chance of mortality. At this point only 1% of these poorly growing stems will survive more than 10 consecutive years on the plot.

Model Assumptions

Computer models create a simplified version of reality so that specific phenomena and interactions can be studied, evaluated, and understood (Botkin 1993, Jim Berkson, personal communication, 2001). Models only approximate real world occurrences, which allows introduction of error. Error can be introduced when assumptions are made in an effort to oversimplify reality. The JABOWA-3 model contains a number of assumptions that influence how the model works.

The first assumption relates to how trees compete for space in shaded conditions. As mentioned previously, larger trees on the plot shade all other smaller trees at some point during the growing season. Because of this assumption, trees within the plot do not have specific *x-y* coordinates, but instead are spatially homogeneous in the *x*-y directions. Another assumption used to simplify the model is that the trees growing on the plot have no influence on soil moisture and soil nitrogen. Conversely, soil moisture and soil nitrogen have a significant impact on tree growth (see Sensitivity Analysis). The next assumption, previously mentioned under "Subroutine BIRTH," states that germination of seeds for any given species will take place provided environmental conditions are suitable for the production of mature trees of that species. This means that the probability of a species germinating on a plot is not dependent on seed source availability, but instead depends upon whether or not environmental conditions are suitable for the production of mature trees of that species. Another assumption that is made is that height of a tree of a given species is strictly based upon diameter. The following equation is used to show this relationship:

$$H(D) = 137 + b_2D - b_3D^2$$

where $H(D)$ = height in cm, 137 = DBH in cm, b_2 = tree height parameter (species specific), b_3 = second tree height parameter (species specific), and D = diameter of a tree. Finally, the model assumes that tree growth is deterministic while regeneration and mortality are stochastic.

III. METHODS

Seven upland oak old-growth stands and seven adjacent younger, managed stands of the same site and stand type were inventoried for the purpose of determining what silvicultural manipulations would best accomplish the development of old-growth forest characteristics in the younger stands (Figure 1).

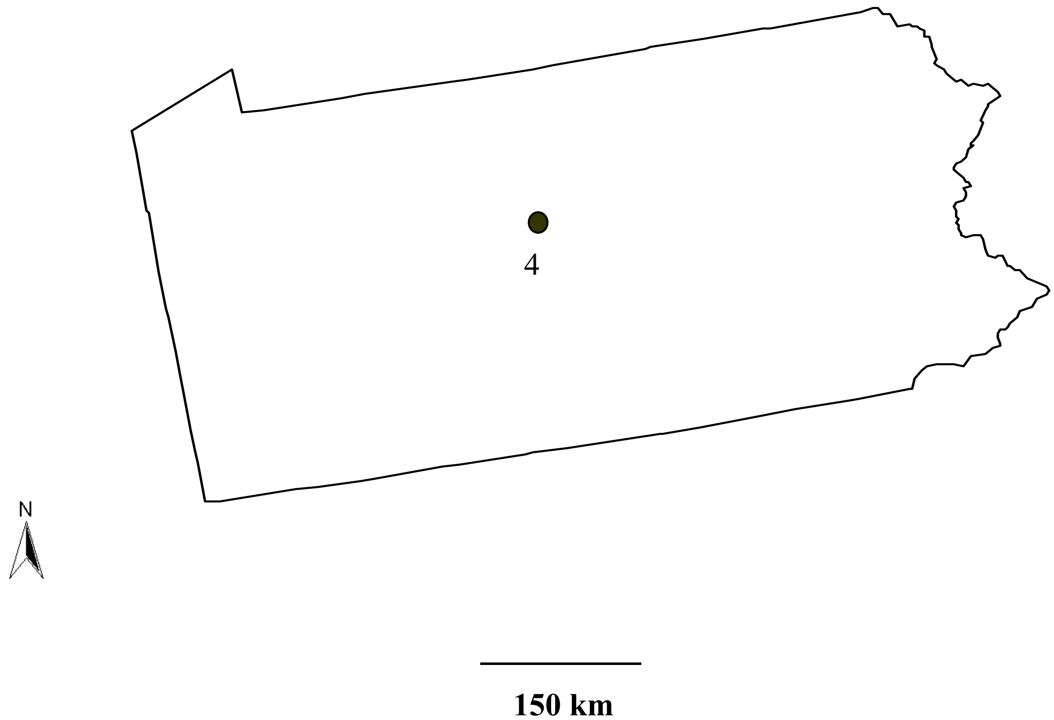

Figure 1. Location of six study sites throughout the Ridge & Valley, Blue Ridge and Piedmont of Virginia and Pennsylvania. 1 = Craig Creek Road, VA, 2 = Stony Creek, VA, 3 = Great Falls Park, VA, 4 = Detwiler Run, PA, 5 = Montpelier, VA, 6 = Turkey Ridge Natural Area, VA, 7 = Blue Ridge Parkway (Milepost 75), VA.

An average minimum age for the mature, overstory tree component of 150 years (Goebel and Hix 1996, Jesse Overcash, personal communication, 2001) was used in conjunction with the presence of old-growth characteristics to categorize the old-growth stands (Franklin et al. 1981, Oliver and Larson 1996). The specific stand characteristics required were: uneven-aged stand structure, presence of many mature trees, high structural diversity (multi-layered canopy), presence of snags, presence of coarse woody debris on the forest floor and in streams, pit-and-mound topography, and evidence of windthrow. It was my intention to accurately define these stands as "old-growth" by using both a minimum forest age threshold and old-growth stand characteristics.

A history of each old-growth stand, including previous logging and agricultural uses, was determined from past records obtained from the land owner/agency, and other sources to gain a better understanding of how the old-growth stand developed. Many land-use archives only date back 70 – 100 years, which resulted in incomplete histories for some of the older stands. The younger, managed stands proved much easier to obtain histories for due to the recentness of activity.

Study Areas

This study was conducted on seven old-growth and seven younger, managed stands throughout the Ridge and Valley, Blue Ridge, and Piedmont of Virginia and Pennsylvania (Table 3) (Duffy 1969).

Table 3. Location, jurisdiction and stand characteristics for each old-growth site. JNF = Jefferson National Forest, USFS = United States Forest Service, NPS = National Park Service, PBF = Pennsylvania Bureau of Forestry, NNLF = Natural National Landmark Forest, VDOF = Virginia Dept. of Forestry, RV = Ridge and Valley, PI = Piedmont, BR = Blue Ridge, WO = white oak, NRO = northern red oak, CO = chestnut oak, BO = black oak.

Site	Province	County, State	Area	Oldest Trees	Dom. Spp.
Craig Creek Rd, JNF (USFS)	RV	Montgomery, VA	10 ha	200+	WO
Stony Creek, JNF (USFS)	RV	Giles, VA	17 ha	200+	WO, NRO
Great Falls Park (NPS)	PI	Fairfax, VA	10 ha	200-250	WO
Detwiler Run (PBF)	RV	Centre, PA	22 ha	326	CO
Montpelier (NNLF)	PI	Orange, VA	80 ha	200-300	WO, BO
Turkey Ridge Natural Area (VDOF)	PI	Cumberland, VA	8 ha	250-280	WO
Blue Ridge Pkwy (MP 75) (USFS)	BR	Bedford, VA	6 ha	275	NRO

-Young/Managed Stands

Younger, managed stands were inventoried in conjunction with each of the old-growth stands. Criteria for selecting these younger stands were based upon the following site characteristics: soil series/type, aspect, percent slope, and species composition. Nearby, but not necessarily adjoining, stands were considered under the following conditions: they had a similar soil type (when possible), same aspect within ±25 degrees of the old-growth stand's aspect, same percent slope within ±10 % of the old-growth stand's slope, and contained upland oak species.

-Old-Growth Stands

Site 1. Craig Creek Road, Jefferson National Forest, VA

Both the 10 ha old-growth white oak stand, and the 12 ha younger/managed hardwood stand are located on the foot slope of Sinking Creek Mountain in Montgomery County, Virginia (37°21'N 80°22'W). These stands lay within the Ridge and Valley province on a relatively dry site with a gentle slope. The average slope and aspect of the old-growth stand was 13% (range 11–16%) with a southern aspect (163°), while the adjacent younger stand also had an average slope of 13% (range 9–15%) and a southwestern aspect (138°). The average annual temperature and annual precipitation for the area was 11°C and 104 cm, respectively (TWC 2002a). Soils within the study area were in the Jefferson series (Typic Hapludults) and were characterized as deep, extremely stony, well-drained soils formed in colluvium of acid sandstone, shale, and siltstone (Creggar et al. 1985). The following old-growth characteristics were observed throughout the white oak stand: large diameter white oaks (56-76 cm) aged at 200+ years (Figure 2), high structural diversity, numerous standing dead trees, coarse woody debris on the forest floor, and pit and mound topography. The stand was examined for evidence of past and/or recent fires by looking for fire scars, burned stumps, and soil charcoal, but no indication of these characteristics were observed. A few cut stumps from past logging were present on the eastern boundary of the stand.

Figure 2. Large diameter white oak present in the old-growth stand (A) and a large diameter cut stump in the adjacent younger stand (B) located just north of Craig Creek Road, Montgomery County, Virginia.

- *Land-Use History*

The previous landowner of the old-growth stand worked salvaging dead American chestnut (*Castanea dentata*) logs and his work kept him away from this property much of the year. Since the stand did not contain American chestnut, but instead had mostly oak species and some pine species, it is believed he was not interested in logging it, which left the present old-growth stand mostly intact (Jesse Overcash, personal communication, 2001). Tree-ring analysis showed that the overstory component of the younger stand was approximately 30 years old. Evidence of skid trails and a few large diameter cut stumps were also present on the younger stand (Figure 2).

Site 2. Stony Creek, Jefferson National Forest, VA

Both the 17 ha old-growth northern red oak stand, and the 15 ha younger/ managed northern red oak stand are located on the summit and shoulder of White Rock Mountain in Giles County, Virginia (37°22'N 80°37'W). These stands lay within the Jefferson National Forest in the Ridge and Valley province on a dry site with steep to flat ridgetop topography. The average slope of the old-growth stand was 24% (range 14–35%) with a northern aspect (3°), while the adjacent younger stand had an average slope of 19% (range 17–23%) and a northern aspect (353°). The average annual temperature and annual precipitation for the area was 11°C and 104 cm, respectively (TWC 2002a). Soils within the study area were in the Lehew and Wallen series (Typic Dystrochrepts) and were characterized as very stony, steep, moderately deep soils on narrow mountaintops and upper side slopes formed in material weathered from sandstone bedrock (Swecker et al. 1985). Many mid-sized rocks protruded from surface throughout both stands. The following old-growth characteristics were observed throughout the northern red oak stand: large diameter oaks (67-139 cm) aged at 200+ years (Figure 3), high structural diversity, canopy gaps, numerous standing dead trees, coarse woody debris, and an open understory. The stand was examined for evidence of past fires by looking for fire scars, burned stumps, and soil charcoal, but no indications of fire were present.

Figure 3. Large diameter northern red oak (133-cm) (A) and large coarse woody debris (B) present on the rocky ridgetop of White Rock Mountain located just south of Stony Creek, Giles County, Virginia.

- Land-Use History

It is believed that the old-growth stand was never harvested due to the steepness and rockiness of the ridgetop terrain. The cost and difficulty of extracting the large diameter trees from this steep, ridgetop position was the main deterrent that kept loggers from clearing it (Jesse Overcash, personal communication, 2001). The younger stand (Age = 75) was located slightly east of the old-growth stand on more accessible terrain. The bottom two-thirds of the north face of White Rock Mountain also showed evidence of previous logging in the form of skid trails and cut stumps.

Site 3. Great Falls Park, VA

Great Falls Park (GFP) is located in northern Virginia (Fairfax County) within the Piedmont physiographic province. A 10 ha old-growth white oak stand, and 8 ha younger/managed hardwood stand (Age = 130) were located within the park on a gently sloping ridge parallel to the Potomac River (38°50'N 77°15'W). The average slope and aspect of the old-growth stand was 13% (range 6–23%) with an eastern aspect (111°), while the adjacent younger stand had an average slope of 21% (range 10–26%) and an eastern aspect (72°). The average annual temperature and annual precipitation for the area is 13°C and 113 cm, respectively (Braun 1950, Porter et al. 1963). Soils within the study area are in the Manor and Glenig series (Typic Dystrochrepts) and are characterized as acidic, shallow, highly micaceous, and well-drained (Porter et al. 1963). The following old-growth characteristics were observed throughout the white oak stand: large diameter white oaks (65-92 cm) aged between 200 and 250 years (Abrams and Copenheaver 1999) (Figure 4), uneven-age stand structure, canopy gaps, numerous standing dead trees, pit and mound topography due to windthrow, and coarse woody debris on the forest floor. Evidence of past fires was observed from fire scars on trees, burned stumps, and soil charcoal in the old-growth stand (Figure 4).

-Land-Use History

The land-use history of Great Falls Park began when Native Americans used the area as a meeting place prior to European settlement (Abrams 1998). The family of Lord Fairfax owned the land from 1719 to 1785 at which time the area was thought to hold considerable mineral deposits. George Washington was responsible for directing the construction of numerous bypass canals on the Potomac River under the auspices of the Patowmack Canal Company between 1785 and 1830, including the canal at Great Falls, VA. The site was then utilized by a variety of companies looking to profit from manufacturing, dam building, and hydroelectric power between 1830 and 1905. A light railroad bed and an amusement park were constructed on site in 1906 and they stayed in use until 1952. The National Park Service finally purchased the land in 1966 after 10 years of conservation efforts (Abrams and Copenheaver 1999).

Figure 4. Large diameter white oak (A) and a charred stump (B) show evidence of a surface fire in the old-growth stand of Great Falls Park, Fairfax County, Virginia.

Site 4. Detwiler Run, PA

Detwiler Run consists of a 400 ha watershed located within Rothrock State Forest in the Seven Mountains region of central Pennsylvania. This watershed contains an uneven-aged 21.5 ha old-growth chestnut oak (*Q. prinus)* stand. This stand was located near the top of a sandstone ridge positioned on a talus sideslope.

Both the 21.5 ha old-growth chestnut oak stand (Age = 250 – 310), and the 20 ha younger/managed chestnut oak stand (Age = 100) were located on a relatively steep, talus sideslope of Thickhead Mountain in Huntingdon County and Centre County, Pennsylvania (40°48'N 77°15'W). These stands lay within the Rothrock State Forest in the Ridge and Valley province on a xeric site. The average slope and aspect of the old-growth stand was 35% (range 28–46%) with a southeastern aspect (150°), while the adjacent younger stand had an average slope of 34% (range 23–42%) and a southeastern aspect (141°). The average annual temperature and annual precipitation for the area was 9°C and 93 cm, respectively (Braker 1981, TWC 2002b). Soils within the study area were in the Hazleton-Dekalb association (Typic Dystrochrepts) and were characterized as deep, very steep, well-drained soils formed in residuum and colluvium from acidic sandstone (Braker 1981). The following old-growth characteristics were observed throughout the older chestnut oak stand: large diameter chestnut oaks (47-122 cm), high structural diversity, canopy gaps, numerous snags (Figure 5), pit and mound topography, and coarse woody debris including downed branches and broken tops from ice and wind damage. The stand was examined for evidence of past and/or recent fires by looking for fire scars, burned stumps, and soil charcoal, but no indication of these characteristics were observed.

Figure 5. Chestnut oak snag (A) in the old-growth stand and cut stump (B) due to gypsy moth salvage operations in the younger stand of Detwiler Run, Huntingdon and Centre Counties, Pennsylvania.

- Land-Use History

In 1902, the Kulp Lumber Company bought the land area surrounding the Detwiler Run watershed for the purpose of constructing logging railroads. Beidleheimer Logging Company utilized existing railroad lines under the jurisdiction of Kulp to log land owned by the Reichley Brothers in the headwaters area of the Detwiler Run watershed. Interestingly, the land that Kulp acquired in 1902, and the Reichley Brothers land were never linked by railways. This break between the two land parcels straddled the Centre-Huntingdon County line, and consequently the Detwiler Run old-growth area was never logged. However, the Reichley Brothers did construct a logging road that angled up the sideslope of Thickhead Mountain to take out pitch pine (*Pinus rigida*) located within 1000 m of the old-growth stand. This skid path now serves as a forest road and was used to gain access to the stand. Although the area was covered by lumber and charcoal operations at this time, the steep talus conditions (Figure 6) of the area thwarted removal of the timber resources. In 1905 and 1906 all tracts of land in the area were purchased by the Commonwealth of Pennsylvania through the Forest Reserves Act of 1897. These tracts now comprise the current Rothrock State Forest (Ruffner and Abrams 1998).

Figure 6. Extreme talus conditions present on the old-growth stand in the Detwiler Run watershed, Huntingdon & Centre Counties, Pennsylvania.

Site 5. Montpelier, VA

Montpelier, former home of President James Madison, is located north of Charlottesville, VA in the Piedmont physiographic region. An 80 ha National Natural Landmark Forest that contains a variety of old-growth upland oaks: chestnut oak, northern red oak, white oak, black oak, and scarlet oak (*Q. coccinea*), is positioned directly behind the house. The forest and homestead are under the jurisdiction of the National Trust for Historic Preservation.

Both the 80 ha old growth mixed oak-poplar stand, and the 20 ha younger/managed oak-hickory stand were located on a gently sloping section of the James Madison Estate in Orange County, Virginia (38°12'N 78°07'W). These stands lay within the Piedmont province on a mesic site with flat topography. The average slope and aspect of the old-growth stand was 9% (range 3–14%) with a northwestern aspect (338°), while the adjacent younger stand had an average slope of 13% (range 6–20%) and a northeastern aspect (37°). The average annual temperature and annual precipitation for the area is 13°C and 109 cm, respectively (TWC 2002c). Soils within the old-growth stand were in the Davidson series (Rhodic Paleudults) and were characterized as deep, well-drained, clay loams formed from dark, basic Catoctin greenstone (Carter et al. 1971). The younger/managed stand (Age = 150) contained soils in the Bucks series (Typic Hapluduts) and were characterized as deep, well-drained, silt loams formed from material weathered from red shale and conglomerate of Triassic age (Carter et al. 1971). The following old-growth characteristics were observed throughout the mixed oak stand: large diameter oak and yellow-poplar (*Liriodendron tulipifera*) (58-109 cm) aged between 200 and 300 years old (Montpelier 2001) (Figure 7), high structural diversity, canopy gaps, numerous standing dead trees, open understory, pit and mound topography, and coarse woody debris on the forest floor. The stand was examined for evidence of past fires by looking for fire scars, burned stumps, and soil charcoal, but none of these characteristics were observed.

Figure 7. Large diameter white oaks in the old-growth stand within the National Natural Landmark Forest at Montpelier, Orange County, Virginia.

-Land-Use History

President James Madison’s grandfather, Ambrose Madison, first settled Montpelier in 1723. Montpelier was originally known as Mount Pleasant and it was here that James Madison spent the early years of his childhood. In 1760, James Madison's father constructed the initial section of the current mansion. Structural changes and two major additions were later added by James Madison himself. James Madison died in 1836 and at this time his wife Dolley left the property and moved back to Washington D.C. In 1844, Dolley sold the Montpelier property to a friend in Richmond, Virginia. Between 1844 and 1901, the property passed through five additional owners. Finally, in 1901, the duPont family bought the estate and made further additions to the house that doubled its size. Marion duPont Scott was the last private owner of the Montpelier estate. In 1984, the National Trust for Historic Preservation acquired Montpelier and the old-growth National Natural Landmark Forest and manages both as a public monument (Montpelier 2001).

Site 6. Turkey Ridge Natural Area, Cumberland State Forest, VA

The 6,475 ha Cumberland State Forest is located within the Piedmont physiographic province in Cumberland County, Virginia (37°37'N 78°15'W). The Turkey Ridge Natural Area inside the Cumberland State Forest is comprised of an upland oak/hickory old-growth forest.

Both the 8 ha old-growth white oak stand within the Natural Area (Age = 250 – 280), and the 7 ha younger/managed hardwood stand (Age = 65) located nearby lay on a gently sloping ridge/shoulder above a highly productive bottomland area near the Willis River. The average slope and aspect of the old-growth stand was 11% (range 2–19%) with a northeastern aspect (63°), while the adjacent younger stand had an average slope of 8% (range 5–11%) and an eastern aspect (89°). The average annual temperature and annual precipitation for the area was 13°C and 109 cm, respectively (TWC 2002d). Soils within the old-growth area were in the Wilkes and Louisburg series (Typic Hapludalfs & Ruptic-Ultic Dystrochrepts) and were characterized as shallow, excessively drained sandy to clay loams formed from residuum of granite, gneiss, fine-grained schist, and pegmatite (Henry et al. 1948, Nicholson et al. 1980, Stan Warner, personal communication, 2002). Soils within the younger/managed stand were in the Lloyd and Cecil series (Typic Hapludults) and were characterized as fairly deep, well-drained clay loams formed from residuum of granite, schist, and gneiss (Henry et al. 1948, Stan Warner, personal communication, 2002). The following old-growth characteristics were observed throughout the Turkey Ridge Natural Area: large diameter white oaks (47-54 cm) (Figure 8), high structural diversity, standing dead trees, pit and mound topography, and coarse woody debris on the forest floor. The stand was examined for evidence of past fires by looking for fire scars, burned stumps, and soil charcoal, but none of these characteristics were observed. However, an old woods road passes through the center of the stand to an open field.

Figure 8. Large diameter oaks in the younger stand (A) and large diameter white oaks (B) present in the old-growth stand within Turkey Ridge Natural Area, Cumberland State Forest, Cumberland County, Virginia.

- Land-Use History

The old-growth stand within Turkey Ridge Natural Area was on a xeric site and was likely not harvested since it did not produce the size and quality of the trees on the adjacent bottomland site (Stan Warner, personal communication, 2001). Tree ages of some of the older oaks were between 250 and 280 years old (Dan Druckenbrod, personal communication, 2001). The younger/managed stand located upslope from Turkey Ridge represents a quality old-growth candidate stand. A crown release treatment occurred in recent years to free some of the larger oaks and hickories from competition (Figure 8). Tree diameters already equal and in some cases exceed those located within the old-growth stand.

Site 7. Blue Ridge Parkway (Milepost 75), Jefferson National Forest, VA

Both the 6 ha old-growth northern red oak stand, and the 6 ha younger/managed hardwood stand (Age = 100) were located on a gently sloping section of Thunder Ridge in Bedford County, Virginia (37°30’N 79°28’W). These stands lay within the Jefferson National Forest in the Blue Ridge province on a mesic site with flat topography. The average slope and aspect of the old-growth stand was 12% (range 8–17%) with a northern aspect (17°), while the adjacent younger stand also had an average slope of 10% (range 2–14%) and a northern aspect (26°). The average annual temperature and annual precipitation for the area is 14°C and 107 cm, respectively (McDaniel et al. 1989). Soils within the study area were in the Edneyville series (Typic Dystrochrepts) and were characterized as deep, extremely stony, fine sandy loams formed from residuum of granite and gneiss (Bailey and Arnold 1986). It should be noted that although these sites were classified as “extremely stony” soils, only scattered rock fragments were found. The following old-growth characteristics were observed throughout the northern red oak stand: large diameter northern red oaks (55-67 cm) (Figure 9) between 200 and 275 years (Abrams et al. 1997), high structural diversity, uneven-aged, canopy gaps, numerous snags, pit and mound topography, and coarse woody debris due to downed branches and broken tops from ice and wind damage. The stand was examined for evidence of past and/or recent fires by looking for fire scars, burned stumps, and soil charcoal, but no indication of these characteristics were observed.

Figure 9. Large diameter northern red oak in the old-growth stand (A) and smaller hardwoods at a higher density (B) present in the young stand located on Jefferson National Forest near Blue Ridge Parkway (Milepost 75), Bedford County, Virginia.

Plot Design and Sampling Procedures

The field measurements required by the JABOWA-3 ecosystem model dictated the sampling technique for this study. Botkin's (1993) *Forest Dynamics: An Ecological Model* outlines the data needed to run the model. The JABOWA-3 computer model was not specifically designed for old-growth forest types, nor was it specific to southern Appalachian and Piedmont forests and modifications to the recommended sampling scheme were needed to adjust for this. Old-growth stands are known to display high variability in canopy structure (Parker 1995, Peter Kapeluck, personal communication, 2001) and this variability requires a more intensive sampling procedure to gain an adequate estimate of composition and structure. The main adjustment to Botkin's recommended design was the use of 1/12 ha circular plots instead of 1/100 ha box plots. Plot sizes were increased to adjust for the larger trees that are typically found in old-growth forests and the southern Appalachians compared to northeastern hardwood forests where Botkin developed JABOWA (Shugart and West 1979).

Vegetation Sampling

Six 8.15 m circular plots arranged along two randomly stratified transects were used within each stand to inventory composition and structure. Plot centers were randomly located along the transects by using the second-hand on a wristwatch to correspond with length in meters between plot centers. The six plots within each stand covered a combined total area of 1,252 square meters, which was more than twice the upper-end of the minimal area suggested (500 square meters) for accurate vegetation sampling in temperate-zone vegetational communities (Mueller-Dombois and Ellenberg

1974) and also over twice the suggested sampling area required by JABOWA-3 to run the model sufficiently (Botkin 1993).

The following restrictions were used in selecting random plots within each stand: 1) Plots were not located on existing or previously used forest roads, 2) plots were not located in stream beds (perennial, intermittent, ephemeral) and 3) plots were not within 10 meters of a stand boundary. Plots that fell in any of these situations were randomly relocated 30 meters to the right or left at a 90-degree angle. These restrictions were implemented to allow a more accurate tree inventory and sampling of each stand.

Tree heights and DBH were tallied using an Impulse® laser hypsometer (Laser Technology, Inc., Englewood, CO) and a metric diameter tape for each tree over 1 cm DBH in each plot. The height and DBH of snags (> 7.62 cm DBH) also was recorded, along with coarse woody debris, which was inventoried using a line intercept method. Finally, the following site characteristics: aspect, percent slope, and elevation, were recorded for each stand.

Coarse Woody Debris Sampling

Coarse woody debris (downed trees and limbs > 7.62 cm in diameter) was inventoried using the line intercept sampling method (Barbour et al. 1987). This method is less time-consuming, but has been found to be nearly as accurate as traditional quadrat methods for sampling coarse woody debris.

A transect line was laid out using a standard measuring tape that ran from the northern tip of every plot to the southern tip of the plot. The entire length of this transect was 16.3 meters. All CWD crossed by the transect line was measured at right angles with a metric diameter tape. The volume of CWD found in each plot was calculated using a general volume equation:

$$V=(\pi^2 /8L) \Sigma d^2$$

where V is the volume of wood per unit ground area, L is the length of the sample line, and d is the diameter of intersected CWD at right angles to its length (Van Wagner and Wilson 1976). A two-sample t-Test assuming unequal variances was then performed between the volume of coarse woody debris found on the six old-growth plots and six younger/managed plots for each of the seven study sites in order to determine if a significant difference existed ($p > 0.05$).

Soil Sampling & Analysis

The JABOWA-3 computer model also required soil data input to estimate growth potential for the stand. Depth to water table (if < 1m), soil depth (if < 1m), percent rock amounts, and available nitrogen in the soil were necessary for background site information needed to run the model.

If the water table and/or bedrock were reached within the first meter of soil, its depth was recorded. Soil depth estimates were obtained from previously published information from Soil Surveys (Henry et al. 1948, Porter et al. 1963, Carter et al. 1971, Braker 1981, Creggar et al. 1985, Swecker et al. 1985, Bailey and Arnold 1986). At one point within each plot, a small hole (≈ 10 cm square by 30 cm deep) was dug using a shovel and/or soil trowel. The soil from this hole was collected and placed into a plastic bag. This soil was then sifted in the lab and rock fragments were separated out and then weighed in order to determine percent rock for the upper 30 cm. Percent rock for the remaining 70 cm of soil (30 cm + 70 cm = 1 m soil depth required by JABOWA) was determined from Soil Surveys. Sensitivity analysis found that a minimum of 50 kg/ha/yr of available N was required by the model in order to produce accurate growth output (Table 11). A default value of 55 kg/ha/yr of available N was used for each site during the actual modeling simulations.

Lab Analysis

Dendrochronology

A dominant or codominant oak of the same species in each 8.15 m plot was cored in all the younger, managed stands, and two of the seven old-growth stands (Craig Creek Road, Stony Creek). The other five old-growth stands (Turkey Ridge Natural Area, Detwiler Run, Great Falls Park, Blue Ridge Parkway [Milepost 75], and Montpelier) already have published chronologies that were used for overstory age estimates. In situations where no representative overstory trees within the plot were present, nearby trees located outside of plots were cored.

Individual tree cores (n = 60) were brought to the laboratory and dried and mounted on wooden core holders (Phipps 1985). Progressively finer grit sand paper was used to sand each core in order to render the cells visible under a microscope. Cores were cross-dated visually using the list year technique to locate signature years and make age determinations (Yamaguchi 1991). This technique involves locating narrow growth rings on several tree cores from the same stand in order to accurately date the cores.

Data/Modeling Analysis

Silvicultural recommendations were made for the younger, managed stands that would eventually allow them to develop into uneven-aged stands and then into old-growth. Specific recommendations for each stand were created by analyzing the results of various manipulations in JABOWA-3.

JABOWA-3

Sensitivity of JABOWA to adjustment of soil depth, percent rock, and available N was evaluated to establish the importance of varying levels of each of these site parameters on population density and basal area. Further analysis was implemented to quantify the average error created when plot size for each simulated stand was increased from 1/100 ha to 1/12 ha.

The Craig Creek Road Site was randomly selected for the site parameter and plot size sensitivity analysis. Soil depth sensitivity was tested by varying the soil depth parameter by 0.2 m from 0m to 1 m. Percent rock was investigated by adjusting values on 20% intervals from 8% to 98%. The effects of varying levels of available N were examined by increasing levels of available N by 10% from 15% to 85%. Population and basal area output were examined from 90 year simulation averages over 65 iterations for each of these three site parameters and when plot size was increased from 1/100 ha to 1/12 ha (Table 11, Table 12). It should be noted that all other parameters not being tested were kept at the same level during the sensitivity analysis.

Tree inventory data, and soil data from four of the six 8.15 m field plots was then grouped into a 1/12 ha circular plot for each stand and entered into the JABOWA-3 computer model. This grouping was accomplished by centrally aggregating plots for each stand based on basal area (m^2/ha). Data from the two extreme plots containing the highest basal area and lowest basal area were not used in the computer simulations but were retained for importance value calculations. Single trees within each of the younger, managed stands were individually removed (logged) and these "thinned" stands were projected forward in time until they structurally resembled their old-growth counterparts. This was accomplished by bringing each major tree species in the younger stand to within +/- 20% of the actual population density (#/ha) in each of the diameter classes in the old-growth stand (Tables 13-19). Minor tree species, which typically included those species present in the younger stand but not in the old-growth stand and those classified as "others" for a given site, were not included in the simulation results (Appendix B). It should also be noted that some of the shrub/small tree species found on the sites (*Amelanchier arborea*, *Celtis occidentalis*, *Ilex opaca*, *Hamamelis virginiana*, and *Lindera benzoin*) were not included during the simulations (Appendix C). Several projections were made in each of the younger stands in order to closely approximate the diameter distribution and composition of its paired old-growth stand. A success rate was then calculated for each species in each diameter class for each stand using the following formula:

$$SRRV = +/- 0.2 * OGV$$

where *SRRV* = Success Rate Range Value, +/- 0.2 = +/- 20%, and *OGV* = the actual old-growth population density value (#/ha) for a specific species in a specific diameter class (single category). After all of the *SRRV's* were calculated for the entire model run, each category was examined to determine whether or not the simulated population density value was within +/- 20% (*SRRV*) of the old-growth population density value. Simulated population density values that were within this range were considered a successful category. It should be noted that in situations where the simulated stand contained 12 stems/ha in a specific category and the old-growth stand contained eight stems/ha, the category was considered a success even though it was outside of the +/- 20% range. This adjustment was made to account for the fact that the old-growth population values were based on a 1/8 ha total size (6 plots * 208.7 m^2/plot) while the simulated stands were based on 1/12 ha total size (4 plots * 208.7 m^2/plot). The following formula was then used to determine an overall success rate (*OSR*) for the model simulation (Table 20):

$$OSR = (\text{Total Successful Categories}/\text{Total Categories}) * 100$$

The same procedure was used to determine success rates for control run simulations in which no silvicultural manipulations were enacted. The overall success rate for the control runs was then compared to the simulated stand success rate for that site at the simulated stand cut-off age in order to determine whether or not active management for old-growth stand structure proved useful (Table 20). Finally, realistic management plans were developed to carry out the silvicultural manipulations implemented in the model runs at each site (Appendix D).

Guidelines

Marquis et al's (1994) guide, *Quantitative silviculture for hardwood forests of the Alleghenies*, was used for examining methods of modifying traditional uneven-aged silviculture techniques in even-aged stands along with Erdman's (1986) guide, *Developing quality in second-growth stands*, to increase old-growth characteristics in these younger forests. The scientific literature and interviews with experienced land managers were used in an effort to make realistic and attainable management plans and goals for this conversion (Hansen et al. 1991, Runkle 1991, Lorimer and Frelich 1994, Vora 1994, Rooney 1995, Strong et al. 1995, Goebel and Hix 1996, Coates and Burton 1997, Nelson et al. 1997).

IV. RESULTS

Vegetation Analysis

Species Importance

Species richness of the old-growth sites was not consistently greater than the younger sites. Three old-growth stands (Craig Creek Road, Stony Creek, and Blue Ridge Parkway [Milepost 75]) had higher species richness than their paired younger stands, and three of the younger stands had a higher species richness than their paired old-growth stands (Great Falls Park, Montpelier, and Turkey Ridge Natural Area). Only Detwiler Run had equal species richness between old-growth and young.

The species richness of the present-day old-growth stand (n = 15) located near Craig Creek Road in Montgomery County, Virginia was higher than that of the adjacent younger stand (n = 13) (Table 4). The Jaccard Index of Similarity between the two stands was 0.750 (Jaccard 1901, Digby and Kempton 1987). The old-growth stand was dominated by white oak, red maple (*Acer rubrum*) and blackgum (*Nyssa sylvatica*). Lesser species of importance included eastern white pine (*Pinus strobus*), chestnut oak (*Quercus prinus*), and black oak. Snags showed a relatively high importance value (Rank = 3). Red maple, chestnut oak, yellow-poplar (*Liriodendron tulipifera*), black oak, and blackgum showed the highest relative importance in the bordering younger stand (Table 4). Species of lesser importance included mockernut hickory (*Carya tomentosa*), sourwood, (*Oxydendrum arboreum*) and white oak. The importance value of snags in this stand was moderate (Rank = 6).

Species richness of the contemporary old-growth stand (n = 14) located above Stony Creek in Giles County, Virginia was higher than that of the nearby younger stand (n = 13) (Table 5). The Jaccard Index of Similarity between the two stands was 0.588. Northern red oak, red maple, and chestnut oak showed the highest importance value in the old-growth stand. Species of less significance consisted of eastern hophornbeam (*Ostrya virginiana*), yellow birch, and black cherry (*Prunus serotina*). Snags displayed a moderately high importance value on this site (Rank = 4). The younger, managed stand was dominated by northern red oak and striped maple (*Acer pensylvanicum*) (Table 5). Red maple, chestnut oak, and pignut hickory (*Carya glabra*) were found to be less important in this stand. Once again, snags exhibited a moderate importance value (Rank = 5).

Great Falls Park, located in Fairfax County, Virginia, showed the highest species richness among all the old-growth sites (n = 16) and younger sites (n = 21) (Table 6). The Jaccard Index of Similarity between the two stands was also the highest among all seven study sites (0.762). Yellow-poplar, American beech, (*Fagus grandifolia*) and pawpaw (*Asimina triloba*) were of highest importance in the old-growth stand. Northern red oak, white oak, and scarlet oak (*Quercus coccinea*) were of lesser importance in this stand. The younger stand was dominated by yellow-poplar, black oak, blackgum, and white oak (Table 6). Species of lower importance consisted of flowering dogwood (*Cornus florida*), mockernut hickory, and American beech. Snags showed a moderate importance value in this stand (Rank = 5).

Species richness of the present-day old-growth stand (n = 7) in the Detwiler Run Watershed in Huntingdon and Centre Counties, Pennsylvania was equal to that of the younger, managed stand (n = 7) (Table 7). The Jaccard Index of Similarity between the two stands was 0.400. Red maple, black birch (*Betula lenta*), chestnut oak, and blackgum had the highest relative importance value in the old-growth stand. Species cited less often include eastern white pine, witch-hazel (*Hamamelis virginiana*), and black oak. Snags ranked fourth in importance for this stand. The younger managed stand resulted in high importance values for chestnut oak, red maple, and flowering dogwood (Table 7). Blackgum, northern red oak, black oak, and white oak were of lesser importance. Snags ranked second in importance on this stand.

Species richness of the old-growth stand (n = 10) located behind the Montpelier estate in Orange County, Virginia was lower than that of the adjacent younger stand (n = 15) (Table 8). The Jaccard Index of Similarity between the two stands was 0.667. The old-growth stand resulted in a high importance for yellow-poplar, pignut hickory, and flowering dogwood. White oak, green ash (*Fraxinus pennsylvanica*), and American basswood (*Tilia americana* var. *americana*) were of lesser importance in this stand. The importance value for snags found in this stand was also high (Rank = 3). The nearby younger, managed stand produced the highest relative importance for pignut hickory, flowering dogwood, and blackgum (Table 8). Yellow-poplar, white oak, and green ash were of lesser importance in the younger stand.

The species richness of the present-day Turkey Ridge Natural Area (n = 11) located on the Cumberland State Forest in Cumberland County, Virginia was lower than that of the nearby younger stand (n = 14) (Table 9). The Jaccard Index of Similarity between the two stands was 0.471. White oak, mockernut hickory, eastern red cedar (*Juniperus virginiana*), and winged elm (*Ulmus alata*) had the highest importance value on the Turkey Ridge Natural Area. Of lesser importance were green ash, American basswood, and northern red oak. Snags ranked fifth in importance for this stand.

Flowering dogwood, black oak, yellow-poplar, and white oak dominated the nearby younger stand (Table 9). Mockernut hickory, eastern white pine, and eastern red cedar were of lesser significance. Snags also ranked fifth in importance for this stand.

The species richness of the old-growth stand (n = 15) located near Milepost 75 of the Blue Ridge Parkway in Bedford County, Virginia was higher than that of the nearby younger stand (n = 14) (Table 10). The Jaccard Index of Similarity between the two stands was 0.611. The old-growth stand produced the highest importance for northern red oak, green ash, blackgum, and striped maple. Black cherry, sweet cherry (*Prunus avium*), and black locust (*Robinia pseudoacacia*) were less significant in this stand. The importance value for snags in this stand was moderate (Rank = 6). The younger stand showed the greatest importance for green ash, northern red oak, black cherry, and bitternut hickory (*Carya cordiformis*) (Table 10). Striped maple, black birch, and black locust were of lesser importance respectively. Snags were moderately important on this stand (Rank = 6).

Table 4. Total and relative density, frequency, basal area and relative importance values for tree species surveyed in the old-growth stand (top table) and younger stand (bottom table) near Craig Creek Road, Montgomery County, Virginia.

Site	Species	Density (ha-1)	Frequency (no. of plots)	Basal Area (m^2.ha-1)	Relative density	Relative frequency	Relative basal area	Relative importance
Old-growth	*Quercus alba*	103.8	6	12.53	6.5	11.8	42.1	20.1
	Acer rubrum	415.3	6	1.70	26.0	11.8	5.7	14.5
	Snags	231.6	6	3.36	14.5	11.8	11.3	12.5
	Nyssa sylvatica	247.6	6	1.21	15.5	11.8	4.1	10.4
	Pinus strobus	183.7	2	2.88	11.5	3.9	9.7	8.4
	Quercus prinus	63.9	3	3.45	4.0	5.9	11.6	7.2
	Quercus velutina	55.9	3	2.46	3.5	5.9	8.3	5.9
	Carya tomentosa	63.9	5	0.79	4.0	9.8	2.7	5.5
	Osytrya virginiana	16.0	5	0.29	1.0	9.8	1.0	3.9
	Hamamelis virginiana	111.8	1	0.09	7.0	2.0	0.3	3.1
	Oxydendrum arboreum	16.0	2	0.22	1.0	3.9	0.7	1.9
	Cornus florida	16.0	2	0.09	1.0	3.9	0.3	1.7
	Liriodendron tulipifera	31.9	1	0.10	2.0	2.0	0.3	1.4
	Carya glabra	16.0	1	0.28	1.0	2.0	0.9	1.3
	Pinus virginiana	8.0	1	0.28	0.5	2.0	0.9	1.1
	Amelanchier arborea	16.0	1	0.03	1.0	2.0	0.1	1.0
	Total	1597.4	51	29.76	100 %	100 %	100 %	100 %
Young/Managed	*Acer rubrum*	670.9	6	6.80	24.3	11.3	27.0	20.9
	Quercus prinus	303.5	5	7.48	11.0	9.4	29.6	16.7
	Liriodendron tulipifera	375.4	6	2.95	13.6	11.3	11.7	12.2
	Quercus velutina	239.6	6	3.61	8.7	11.3	14.3	11.4
	Nyssa sylvatica	455.3	6	0.66	16.5	11.3	2.6	10.1
	Snags	335.5	4	1.28	12.1	7.5	5.1	8.2
	Carya tomentosa	191.7	6	1.12	6.9	11.3	4.4	7.6
	Oxydendrum arboreum	55.9	5	0.38	2.0	9.4	1.5	4.3
	Quercus alba	47.9	4	0.50	1.7	7.5	2.0	3.7
	Cornus florida	39.9	1	0.12	1.4	1.9	0.5	1.3
	Pinus virginiana	16.0	1	0.25	0.6	1.9	1.0	1.2
	Hamamelis virginiana	16.0	1	0.01	0.6	1.9	0.0	0.8
	Robinia pseudoacacia	8.0	1	0.07	0.3	1.9	0.3	0.8
	Pinus strobus	8.0	1	0.01	0.3	1.9	0.0	0.7
	Total	2763.5	53	25.23	100 %	100 %	100 %	100 %

Table 5. Total and relative density, frequency, basal area and relative importance values for tree species surveyed in the old-growth stand (top table) and younger stand (bottom table) near Stony Creek, Giles County, Virginia.

Site	Species	Density (ha-1)	Frequency (no. of plots)	Basal Area (m^2.ha-1)	Relative density	Relative frequency	Relative basal area	Relative importance
Old-Growth	*Quercus rubra*	175.7	6	22.88	18.8	15.4	47.8	27.3
	Acer rubrum	311.5	6	8.32	33.3	15.4	17.4	22.0
	Quercus prinus	63.9	5	7.72	6.8	12.8	16.1	11.9
	Snags	95.8	5	2.12	10.3	12.8	4.4	9.2
	Ostrya virginiana	95.8	3	0.50	10.3	7.7	1.1	6.3
	Betula alleghaniensis	24.0	2	2.73	2.6	5.1	5.7	4.5
	Prunus serotina	24.0	2	1.75	2.6	5.1	3.7	3.8
	Magnolia acuminata	24.0	3	0.36	2.6	7.7	0.8	3.7
	Carya tomentosa	31.9	1	0.19	3.4	2.6	0.4	2.1
	Acer pensylvanicum	31.9	1	0.02	3.4	2.6	0.0	2.0
	Quercus alba	8.0	1	0.85	0.9	2.6	1.8	1.7
	Carya glabra	16.0	1	0.29	1.7	2.6	0.6	1.6
	Betula lenta	16.0	1	0.01	1.7	2.6	0.0	1.4
	Nyssa sylvatica	8.0	1	0.07	0.9	2.6	0.1	1.2
	Amelanchier arborea	8.0	1	0.04	0.9	2.6	0.1	1.2
	Total	934.5	39	47.84	100 %	100 %	100 %	100 %
Young/Managed	*Quercus rubra*	215.6	6	23.44	16.6	15.4	67.1	33.0
	Acer pensylvanicum	599.0	6	0.60	46.0	15.4	1.7	21.0
	Acer rubrum	111.8	5	1.91	8.6	12.8	5.5	9.0
	Quercus prinus	95.8	2	3.88	7.4	5.1	11.1	7.9
	Snags	55.9	5	1.63	4.3	12.8	4.7	7.3
	Carya glabra	71.9	5	0.64	5.5	12.8	1.8	6.7
	Magnolia acuminata	31.9	2	1.26	2.5	5.1	3.6	3.7
	Cornus florida	24.0	2	0.08	1.8	5.1	0.2	2.4
	Hamamelis virginiana	47.9	1	0.10	3.7	2.6	0.3	2.2
	Quercus alba	8.0	1	1.07	0.6	2.6	3.1	2.1
	Nyssa sylvatica	16.0	1	0.20	1.2	2.6	0.6	1.5
	Amelanchier arborea	8.0	1	0.05	0.6	2.6	0.1	1.1
	Sassafras albidum	8.0	1	0.03	0.6	2.6	0.1	1.1
	Carya tomentosa	8.0	1	0.01	0.6	2.6	0.0	1.1
	Total	1301.9	39	34.91	100 %	100 %	100 %	100 %

Table 6. Total and relative density, frequency, basal area and relative importance values for tree species surveyed in the old-growth stand (top table) and younger stand (bottom table) in Great Falls Park, Fairfax County, Virginia.

Site	Species	Density (ha-1)	Frequency (no. of plots)	Basal Area (m^2.ha-1)	Relative density	Relative frequency	Relative basal area	Relative importance
Old-growth	*Liriodendron tulipifera*	111.8	5	12.03	8.8	10.2	28.8	15.9
	Fagus grandifolia	303.5	5	0.64	23.9	10.2	1.5	11.9
	Asimina triloba	311.5	5	0.15	24.5	10.2	0.4	11.7
	Quercus rubra	63.9	3	7.73	5.0	6.1	18.5	9.9
	Quercus alba	31.9	3	8.14	2.5	6.1	19.5	9.4
	Quercus coccinea	16.0	2	9.18	1.3	4.1	22.0	9.1
	Cornus florida	135.8	4	0.34	10.7	8.2	0.8	6.6
	Nyssa sylvatica	79.9	5	0.49	6.3	10.2	1.2	5.9
	Quercus velutina	16.0	2	1.46	1.3	4.1	3.5	2.9
	Lindera benzoin	31.9	3	0.01	2.5	6.1	0.0	2.9
	Carya glabra	47.9	2	0.17	3.8	4.1	0.4	2.8
	Acer rubrum	31.9	2	0.36	2.5	4.1	0.9	2.5
	Snags	16.0	2	0.78	1.3	4.1	1.9	2.4
	Carya tomentosa	24.0	2	0.17	1.9	4.1	0.4	2.1
	Ilex opaca	24.0	2	0.05	1.9	4.1	0.1	2.0
	Celtis occidentalis	16.0	1	0.01	1.3	2.0	0.0	1.1
	Carpinus caroliniana	8.0	1	0.00	0.6	2.0	0.0	0.9
	Total	1269.9	49	41.71	100 %	100 %	100 %	100 %
Young/Managed	*Liriodendron tulipifera*	111.8	5	5.82	10.1	8.9	16.2	11.8
	Quercus velutina	71.9	3	8.33	6.5	5.4	23.2	11.7
	Nyssa sylvatica	231.6	6	1.05	21.0	10.7	2.9	11.5
	Quercus alba	63.9	5	6.74	5.8	8.9	18.8	11.2
	Snags	79.9	4	5.33	7.2	7.1	14.9	9.8
	Cornus florida	111.8	4	1.23	10.1	7.1	3.4	6.9
	Carya tomentosa	95.8	4	0.32	8.7	7.1	0.9	5.6
	Fagus grandifolia	95.8	4	0.25	8.7	7.1	0.7	5.5
	Quercus prinus	31.9	2	3.29	2.9	3.6	9.2	5.2
	Acer rubrum	71.9	4	0.39	6.5	7.1	1.1	4.9
	Quercus coccinea	8.0	1	2.57	0.7	1.8	7.2	3.2
	Sassafras albidum	24.0	3	0.14	2.2	5.4	0.4	2.6
	Asimina triloba	24.0	2	0.00	2.2	3.6	0.0	1.9
	Ilex opaca	16.0	1	0.02	1.4	1.8	0.1	1.1
	Fraxinus pennsylvanica	8.0	1	0.17	0.7	1.8	0.5	1.0
	Quercus rubra	8.0	1	0.14	0.7	1.8	0.4	1.0
	Carya glabra	8.0	1	0.04	0.7	1.8	0.1	0.9
	Amelanchier arborea	8.0	1	0.02	0.7	1.8	0.1	0.9
	Celtis occidentalis	8.0	1	0.00	0.7	1.8	0.0	0.8
	Prunus serotina	8.0	1	0.00	0.7	1.8	0.0	0.8
	Carpinus caroliniana	8.0	1	0.00	0.7	1.8	0.0	0.8
	Lindera benzoin	8.0	1	0.00	0.7	1.8	0.0	0.8
	Total	1102.2	56	35.88	100 %	100 %	100 %	100 %

Table 7. Total and relative density, frequency, basal area and relative importance values for tree species surveyed in the old-growth stand (top table) and younger stand (bottom table) on Detwiler Run, Huntingdon & Centre Counties, Pennsylvania.

Site	Species	Density (ha-1)	Frequency (no. of plots)	Basal Area (m^2.ha-1)	Relative density	Relative frequency	Relative basal area	Relative importance
Old-Growth	*Acer rubrum*	231.6	6	3.11	34.5	22.2	12.9	23.2
	Betula lenta	103.8	5	8.24	15.5	18.5	34.1	22.7
	Quercus prinus	87.9	4	6.45	13.1	14.8	26.7	18.2
	Snags	79.9	4	3.79	11.9	14.8	15.7	14.1
	Nyssa sylvatica	87.9	3	1.77	13.1	11.1	7.3	10.5
	Pinus strobus	31.9	2	0.35	4.8	7.4	1.4	4.5
	Hamamelis virginiana	39.9	2	0.06	6.0	7.4	0.2	4.5
	Quercus velutina	8.0	1	0.37	1.2	3.7	1.5	2.1
	Total	670.9	27	24.14	100 %	100 %	100 %	100 %
Young/Managed	*Quercus prinus*	103.8	5	10.98	26.5	21.7	45.0	31.1
	Snags	55.9	5	4.85	14.3	21.7	19.9	18.6
	Acer rubrum	55.9	4	1.84	14.3	17.4	7.5	13.1
	Cornus florida	79.9	3	0.46	20.4	13.0	1.9	11.8
	Nyssa sylvatica	47.9	3	1.11	12.2	13.0	4.5	9.9
	Quercus rubra	24.0	1	3.11	6.1	4.3	12.7	7.7
	Quercus velutina	8.0	1	1.64	2.0	4.3	6.7	4.4
	Quercus alba	16.0	1	0.40	4.1	4.3	1.6	3.4
	Total	391.4	23	24.40	100 %	100 %	100 %	100 %

Table 8. Total and relative density, frequency, basal area and relative importance values for tree species surveyed in the old-growth stand (top table) and younger stand (bottom table) within the National Natural Landmark Forest at Montpelier, Orange County, Virginia.

Site	Species	Density (ha-1)	Frequency (no. of plots)	Basal Area (m^2.ha-1)	Relative density	Relative frequency	Relative basal area	Relative importance
Old-Growth	*Liriodendron tulipifera*	55.9	4	21.01	6.3	8.7	35.9	17.0
	Carya glabra	183.7	6	7.53	20.7	13.0	12.9	15.5
	Snags	71.9	6	7.92	8.1	13.0	13.5	11.6
	Cornus florida	175.7	6	0.70	19.8	13.0	1.2	11.4
	Quercus alba	24.0	3	11.78	2.7	6.5	20.1	9.8
	Fraxinus pennsylvanica	103.8	5	3.13	11.7	10.9	5.3	9.3
	Tilia americana	143.8	5	0.41	16.2	10.9	0.7	9.3
	Quercus velutina	24.0	3	5.43	2.7	6.5	9.3	6.2
	Carya tomentosa	63.9	4	0.26	7.2	8.7	0.5	5.5
	Nyssa sylvatica	31.9	3	0.16	3.6	6.5	0.3	3.5
	Sassafras albidum	8.0	1	0.18	0.9	2.2	0.3	1.1
	Total	886.6	46	58.51	100 %	100 %	100 %	100 %
Young/Managed	*Carya glabra*	119.8	5	10.70	11.2	10.6	38.3	20.0
	Cornus florida	311.5	5	0.26	29.1	10.6	0.9	13.6
	Nyssa sylvatica	167.7	6	2.37	15.7	12.8	8.5	12.3
	Liriodendron tulipifera	47.9	3	4.95	4.5	6.4	17.7	9.5
	Quercus alba	31.9	3	4.30	3.0	6.4	15.4	8.2
	Fraxinus pennsylvanica	111.8	5	0.18	10.4	10.6	0.6	7.2
	Carya tomentosa	63.9	3	2.16	6.0	6.4	7.7	6.7
	Quercus prinus	55.9	4	1.25	5.2	8.5	4.5	6.1
	Quercus velutina	79.9	4	0.45	7.5	8.5	1.6	5.9
	Snags	24.0	3	0.32	2.2	6.4	1.1	3.3
	Sassafras albidum	16.0	1	0.21	1.5	2.1	0.7	1.5
	Acer saccharum	8.0	1	0.40	0.7	2.1	1.4	1.4
	Tilia americana	8.0	1	0.35	0.7	2.1	1.3	1.4
	Fagus grandifolia	8.0	1	0.05	0.7	2.1	0.2	1.0
	Carpinus caroliniana	8.0	1	0.01	0.7	2.1	0.0	1.0
	Acer rubrum	8.0	1	0.00	0.7	2.1	0.0	1.0
	Total	1070.3	47	27.96	100 %	100 %	100 %	100 %

Table 9. Total and relative density, frequency, basal area and relative importance values for tree species surveyed in the old-growth stand (top table) and younger stand (bottom table) within Turkey Ridge Natural Area, Cumberland County, Virginia.

Site	Species	Density (ha-1)	Frequency (no. of plots)	Basal Area (m^2.ha-1)	Relative density	Relative frequency	Relative basal area	Relative importance
Old-Growth	*Quercus alba*	327.5	6	9.62	17.5	13.6	43.4	24.8
	Carya tomentosa	439.3	6	5.45	23.5	13.6	24.6	20.6
	Juniperus virginiana	311.5	6	1.97	16.7	13.6	8.9	13.1
	Ulmus alata	335.5	6	0.88	17.9	13.6	4.0	11.9
	Snags	71.9	4	1.90	3.8	9.1	8.6	7.2
	Fraxinus pennsylvanica	87.9	5	0.19	4.7	11.4	0.8	5.6
	Tilia americana	151.8	3	0.16	8.1	6.8	0.7	5.2
	Quercus rubra	47.9	3	0.15	2.6	6.8	0.7	3.3
	Pinus virginiana	8.0	1	1.57	0.4	2.3	7.1	3.3
	Acer rubrum	55.9	1	0.20	3.0	2.3	0.9	2.1
	Cornus florida	24.0	2	0.03	1.3	4.5	0.1	2.0
	Prunus serotina	8.0	1	0.06	0.4	2.3	0.3	1.0
	Total	1869.0	44	22.17	100 %	100 %	100 %	100 %
Young/Managed	*Cornus florida*	311.5	6	0.76	30.0	12.2	2.8	15.0
	Quercus velutina	87.9	4	7.27	8.5	8.2	27.2	14.6
	Liriodendron tulipifera	87.9	6	4.09	8.5	12.2	15.3	12.0
	Quercus alba	79.9	5	4.49	7.7	10.2	16.8	11.6
	Snags	71.9	4	3.44	6.9	8.2	12.9	9.3
	Carya tomentosa	111.8	4	2.25	10.8	8.2	8.4	9.1
	Pinus strobus	39.9	2	1.99	3.8	4.1	7.4	5.1
	Juniperus virginiana	71.9	4	0.08	6.9	8.2	0.3	5.1
	Ulmus alata	55.9	3	0.95	5.4	6.1	3.5	5.0
	Acer rubrum	39.9	3	0.62	3.8	6.1	2.3	4.1
	Nyssa sylvatica	39.9	3	0.29	3.8	6.1	1.1	3.7
	Fraxinus pennsylvanica	16.0	2	0.42	1.5	4.1	1.6	2.4
	Oxydendrum arboreum	8.0	1	0.04	0.8	2.0	0.1	1.0
	Prunus serotina	8.0	1	0.04	0.8	2.0	0.1	1.0
	Prunus avium	8.0	1	0.01	0.8	2.0	0.0	0.9
	Total	1038.3	49	26.73	100 %	100 %	100 %	100 %

Table 10. Total and relative density, frequency, basal area and relative importance values for tree species surveyed in the old-growth stand (top table) and younger stand (bottom table) located on Jefferson National Forest near Blue Ridge Parkway (Milepost 75), Bedford County, Virginia.

Site	Species	Density (ha-1)	Frequency (no. of plots)	Basal Area (m^2.ha-1)	Relative density	Relative frequency	Relative basal area	Relative importance
Old-growth	*Quercus rubra*	175.7	6	17.70	12.3	12.5	55.2	26.7
	Fraxinus pennsylvanica	311.5	6	4.21	21.8	12.5	13.1	15.8
	Nyssa sylvatica	367.4	5	0.35	25.7	10.4	1.1	12.4
	Acer pensylvanicum	207.7	5	2.62	14.5	10.4	8.2	11.0
	Prunus serotina	55.9	3	3.23	3.9	6.3	10.1	6.7
	Snags	47.9	5	0.45	3.4	10.4	1.4	5.1
	Prunus avium	47.9	4	0.35	3.4	8.3	1.1	4.3
	Robinia pseudoacacia	39.9	3	0.54	2.8	6.3	1.7	3.6
	Acer rubrum	31.9	3	0.62	2.2	6.3	1.9	3.5
	Castanea dentata	39.9	2	0.03	2.8	4.2	0.1	2.4
	Magnolia acuminata	8.0	1	1.26	0.6	2.1	3.9	2.2
	Tilia americana	31.9	1	0.44	2.2	2.1	1.4	1.9
	Ostrya virginiana	39.9	1	0.06	2.8	2.1	0.2	1.7
	Betula lenta	8.0	1	0.14	0.6	2.1	0.4	1.0
	Hamamelis virginiana	8.0	1	0.04	0.6	2.1	0.1	0.9
	Cornus florida	8.0	1	0.00	0.6	2.1	0.0	0.9
	Total	1429.7	48	32.06	100 %	100 %	100 %	100 %
Young/Managed	*Fraxinus pennsylvanica*	774.7	6	3.17	40.9	11.1	9.5	20.5
	Quercus rubra	151.8	6	11.56	8.0	11.1	34.6	17.9
	Prunus serotina	159.7	6	8.36	8.4	11.1	25.0	14.8
	Carya cordiformis	167.7	6	4.38	8.9	11.1	13.1	11.0
	Acer pensylvanicum	271.6	5	1.29	14.3	9.3	3.9	9.2
	Snags	71.9	5	3.10	3.8	9.3	9.3	7.4
	Betula lenta	47.9	4	1.07	2.5	7.4	3.2	4.4
	Robinia pseudoacacia	31.9	4	0.02	1.7	7.4	0.1	3.1
	Castanea dentata	39.9	3	0.11	2.1	5.6	0.3	2.7
	Carya tomentosa	63.9	2	0.15	3.4	3.7	0.5	2.5
	Prunus avium	24.0	2	0.04	1.3	3.7	0.1	1.7
	Betula alleghaniensis	24.0	2	0.04	1.3	3.7	0.1	1.7
	Cornus florida	39.9	1	0.07	2.1	1.9	0.2	1.4
	Acer rubrum	16.0	1	0.03	0.8	1.9	0.1	0.9
	Ostrya virginiana	8.0	1	0.07	0.4	1.9	0.2	0.8
	Total	1892.9	54	33.45	100 %	100 %	100 %	100 %

Density Diameter Distributions

Characteristic of an uneven-aged old-growth forest, the diameter distribution of the old-growth stand located near Craig Creek Road in Montgomery County, Virginia approximated an inverse-J pattern (Figure 10) (Smith 1986). White oak, black oak, chestnut oak, and eastern white pine comprised most of the larger diameter classes (45 + cm DBH) (Figure 10, Table 13). Black oak, chestnut oak, and white oak also dominated the upper middle diameter classes (30 – 45 cm). These species plus mockernut and pignut hickory dominated the lower middle diameter classes (15 – 30 cm). The smallest diameter classes (<15 cm) were composed mostly of red maple, blackgum, and eastern white pine. The younger stand exhibited a negative linear pattern from the 5 – 10 cm diameter class to the 30 –35 cm class (Figure 10). Black oak and chestnut oak dominated the largest diameter classes (30 – 45 cm) (Figure 10, Table 13). Black oak, chestnut oak, and red maple comprised the majority of the middle diameter classes (15 – 30 cm). The smallest diameter classes (< 15 cm) were dominated by red maple, blackgum, black oak, and chestnut oak respectively.

The uneven-aged old-growth forest located above Stony Creek in Giles County, Virginia displayed a diameter distribution that typified an inverse-J pattern except for the smallest DBH class (Figure 11). Northern red oak dominated the largest (60 + cm) and upper middle diameter classes (40 – 60 cm) (Figure 11, Table 14). The lower middle diameter classes (20 – 40 cm) were dominated by northern red oak and red maple equally. Red maple made up approximately 40% of the smallest diameter classes (< 20 cm). Northern red oak covered the majority of the largest diameter classes (40 – 60 cm) and the middle diameter classes (20 – 40 cm) in the younger stand (Figure 11, Table 14).

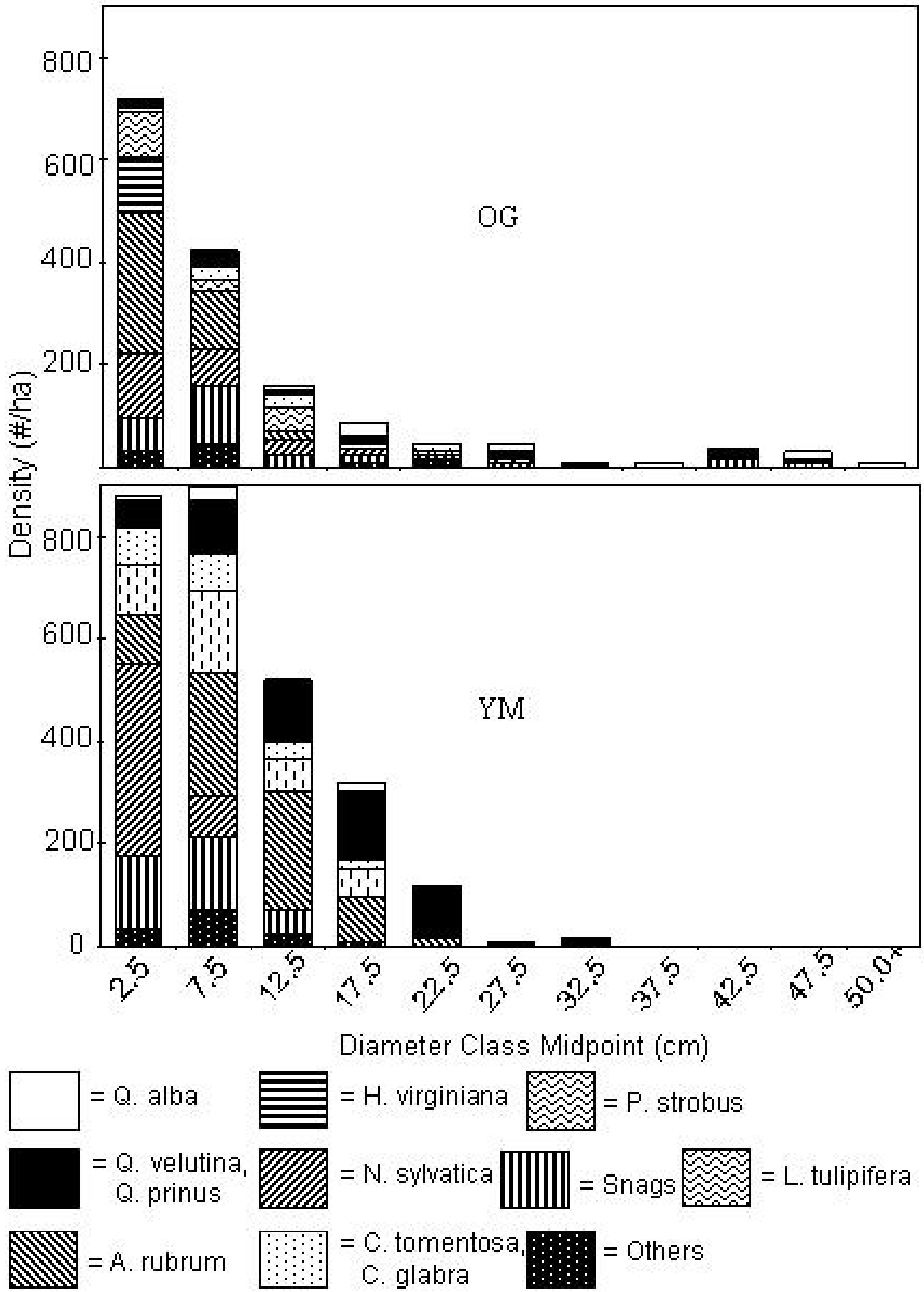

Figure 10. Density diameter distributions for the old-growth (top tier) and younger/ managed (bottom tier) stands near Craig Creek Road, Montgomery County, VA.

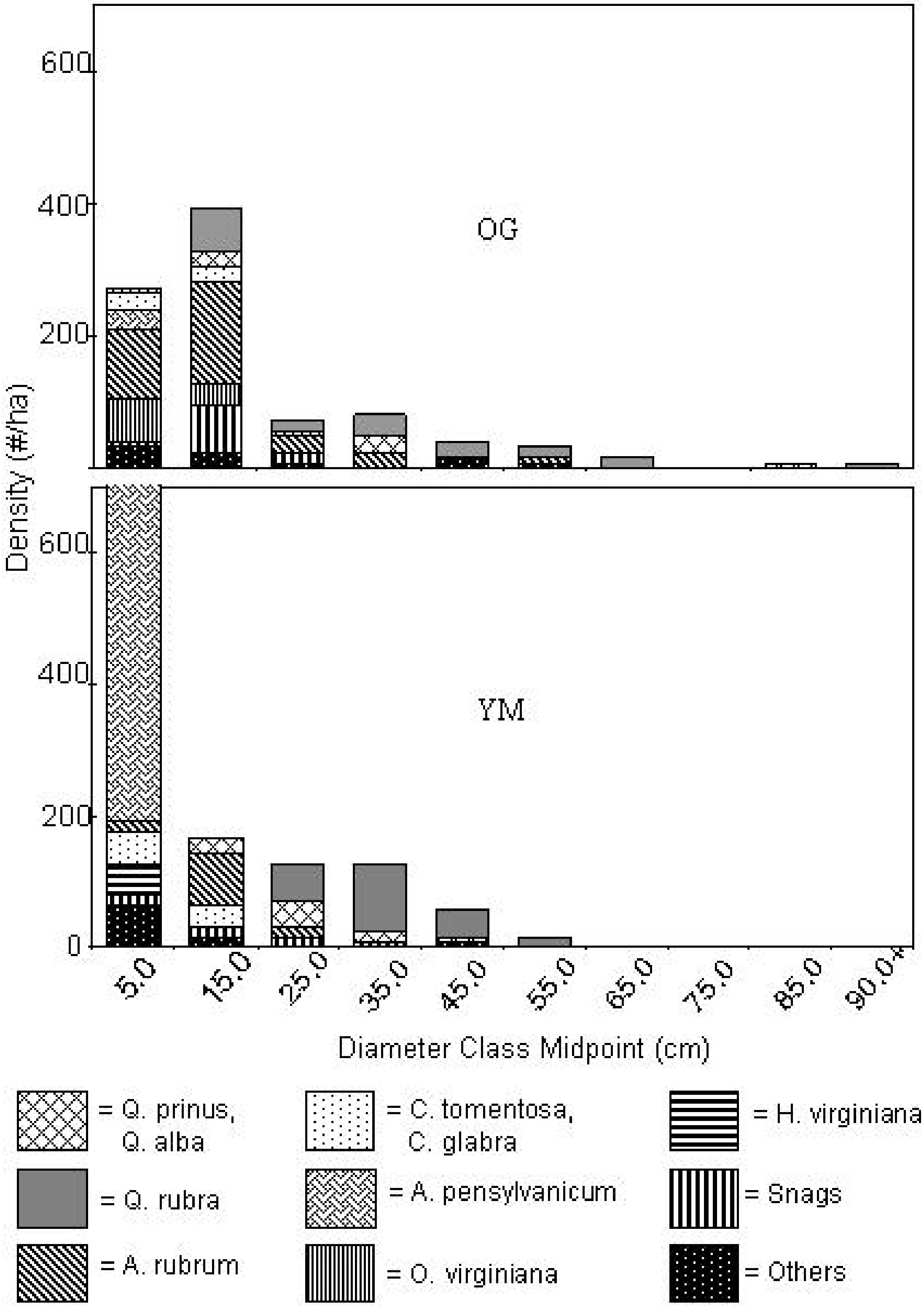

Figure 11. Density diameter distributions for the old-growth (top tier) and younger/ managed (bottom tier) stands near Stony Creek, Giles County, VA.

The smallest diameter classes (< 20 cm) were dominated by striped maple, which comprised 67%.

The old-growth stand on Great Falls Park in Fairfax County, Virginia also exhibited an inverse-J diameter distribution characteristic of an uneven-aged old-growth forest (Figure 12). Black oak, northern red oak, and scarlet oak comprised most of the larger diameter classes (60 + cm DBH) (Figure 12, Table 15). Yellow-poplar dominated the upper middle (40 – 60 cm) and lower middle diameter classes (20 – 40 cm). The smallest diameter classes (<20 cm) were composed mostly of pawpaw and American beech, which together made up 58%. The younger stand exhibited a negative linear pattern from the 1 – 5 cm diameter class to the 25 –30 cm class (Figure 12). At this point the pattern was relatively flat until a small spike in the largest diameter classes (60 + cm). White oak and chestnut oak dominated the largest diameter classes (60 + cm) (Figure 12, Table 15). Black oak, northern red oak, and scarlet oak composed the majority of the upper middle diameter classes (40 – 60 cm). Yellow-poplar dominated the lower middle diameter classes (20 – 40 cm). The smallest diameter classes (< 20 cm) were dominated by blackgum and red maple.

The uneven-aged old-growth forest located at Detwiler Run in Huntingdon and Centre Counties, Pennsylvania displayed a negative linear pattern from diameter class 5 – 10 cm to the largest diameter class (45 + cm) with the exception of a significant spike at diameter class 20 – 25 cm (Figure 13). Chestnut oak and black birch dominated the largest (45 + cm) and upper middle diameter classes (30 – 45 cm) (Figure 13, Table 16). The lower middle diameter classes (15 – 30 cm) were dominated by red maple and chestnut oak. Red maple made up approximately 50% of the smallest diameter classes (<

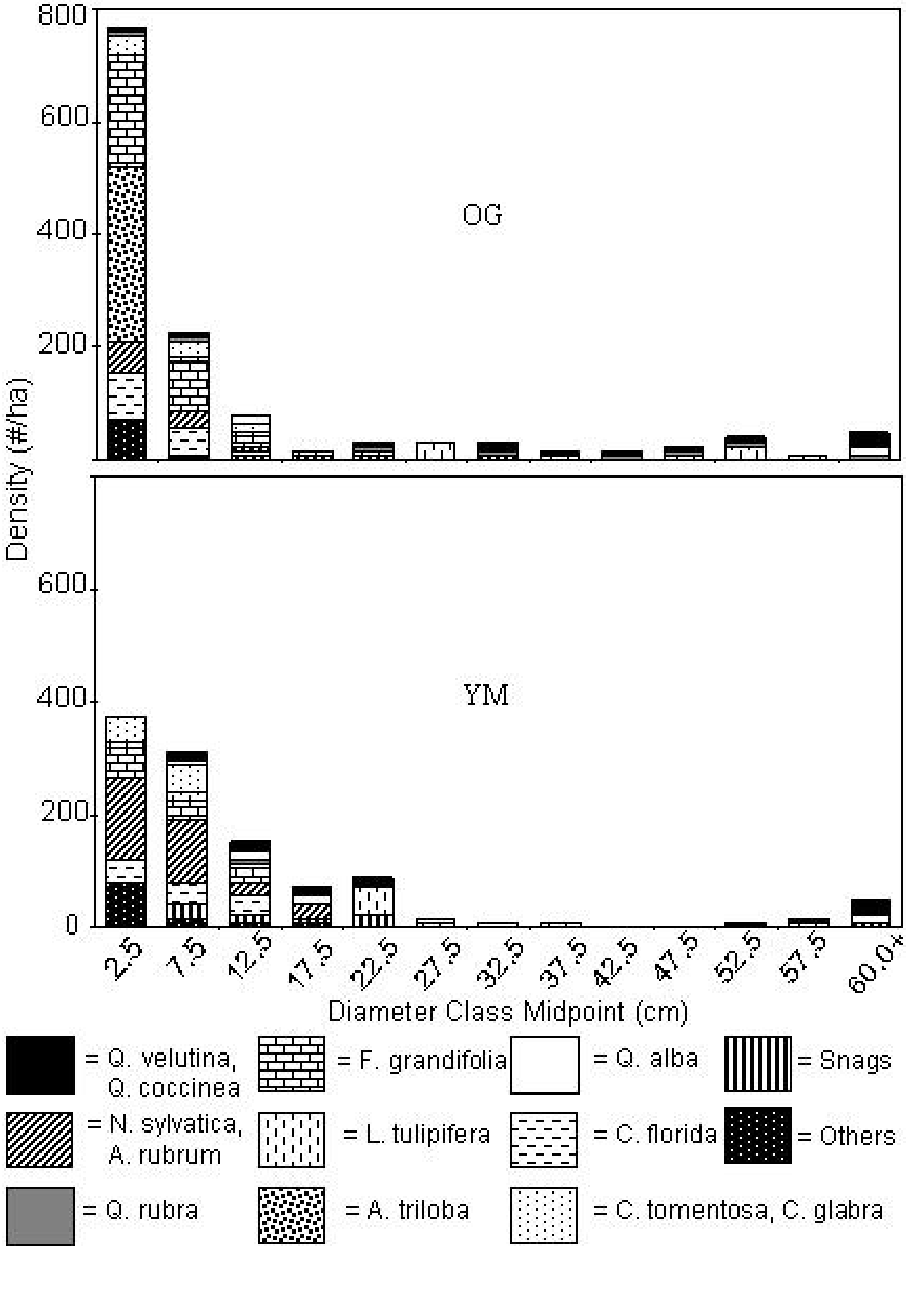

Figure 12. Density diameter distributions for the old-growth (top tier) and younger/ managed (bottom tier) stands of Great Falls Park, Fairfax County, VA.

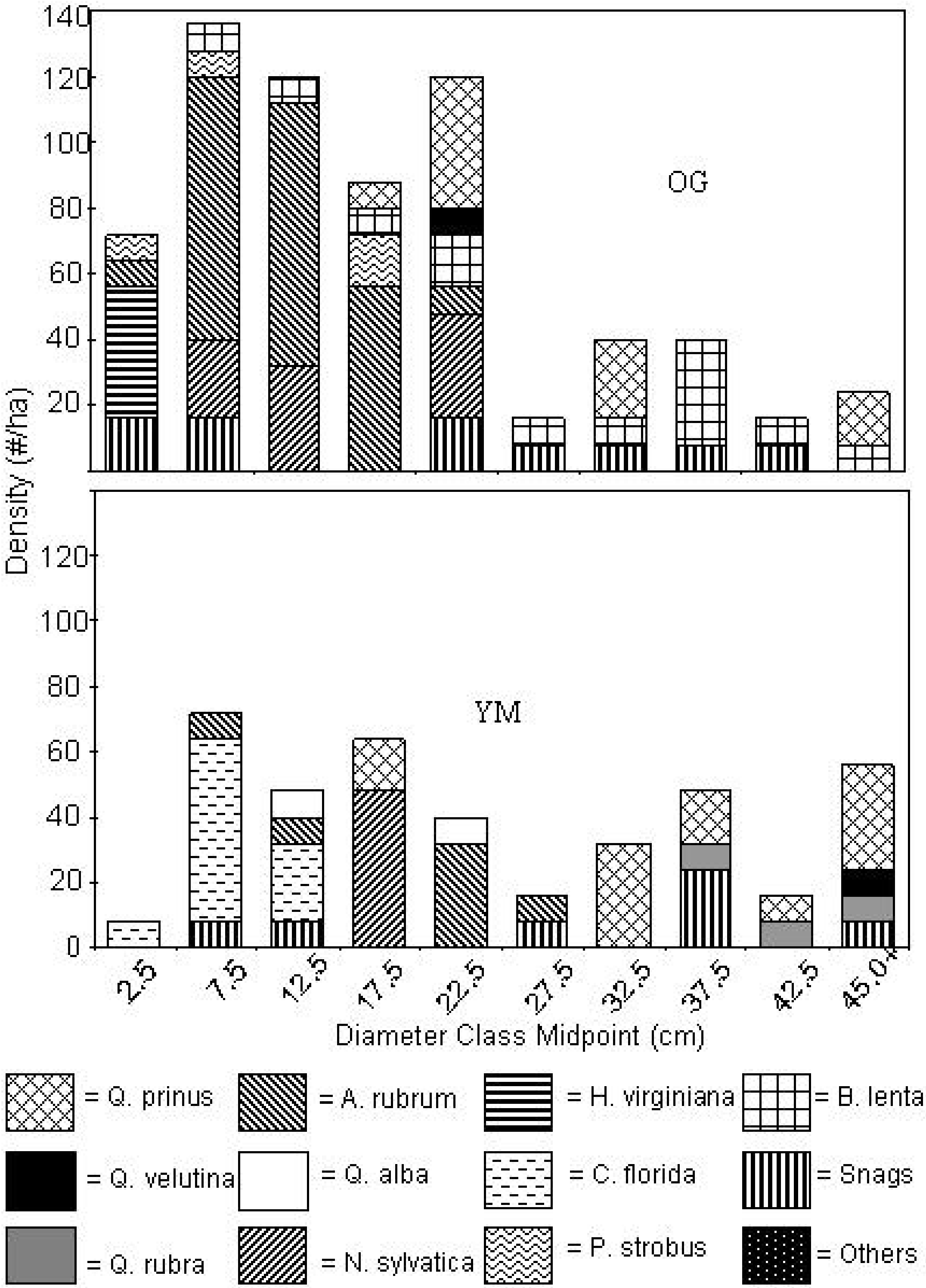

Figure 13. Density diameter distributions for the old-growth (top tier) and younger/ managed (bottom tier) stands of Detwiler Run Watershed in Rothrock State Forest, Huntingdon & Centre Counties, PA.

15 cm). The diameter distribution in the younger stand at Detwiler Run did not show any patterns or trends as a result of a recent salvage cut (Figure 13). Chestnut oak covered the majority of the largest diameter classes (45 + cm) and the upper middle diameter classes (30 – 45 cm) (Figure 13, Table 16). The lower middle diameter classes (15 – 30 cm) were dominated by blackgum and red maple (80%). The smallest diameter classes (< 15 cm) were dominated by flowering dogwood, which comprised 65%.

The old-growth stand behind the Montpelier estate in Orange County, Virginia displayed an inverse-J diameter distribution representative of an uneven-aged old-growth forest (Figure 14). Five diameter classes were used to characterize this stand due to the large size of some of the hardwood species. Yellow-poplar, white oak, black oak, and chestnut oak comprised most of the larger diameter classes (80 + cm DBH) (Figure 14, Table 17). White oak, black oak, and chestnut oak dominated the upper middle diameter classes (60 – 80 cm) while yellow-poplar, mockernut hickory and pignut hickory dominated the middle diameter classes (40 – 60 cm). The lower middle diameter classes (20 – 40 cm) were composed mostly of mockernut hickory and pignut hickory. Mockernut hickory, pignut hickory, flowering dogwood, and American basswood dominated the smallest diameter classes (<20 cm). The younger stand also exhibited an inverse-J distribution (Figure 14). Although not considered an old-growth stand by age thresholds, some of the dominant oak species were aged at 130 years. Mockernut and pignut hickory dominated both the largest diameter classes (40 - 60 cm) and middle diameter classes (20 – 40 cm) (Figure 14, Table 17). The smallest diameter classes (< 20 cm) were composed mostly of flowering dogwood (37%).

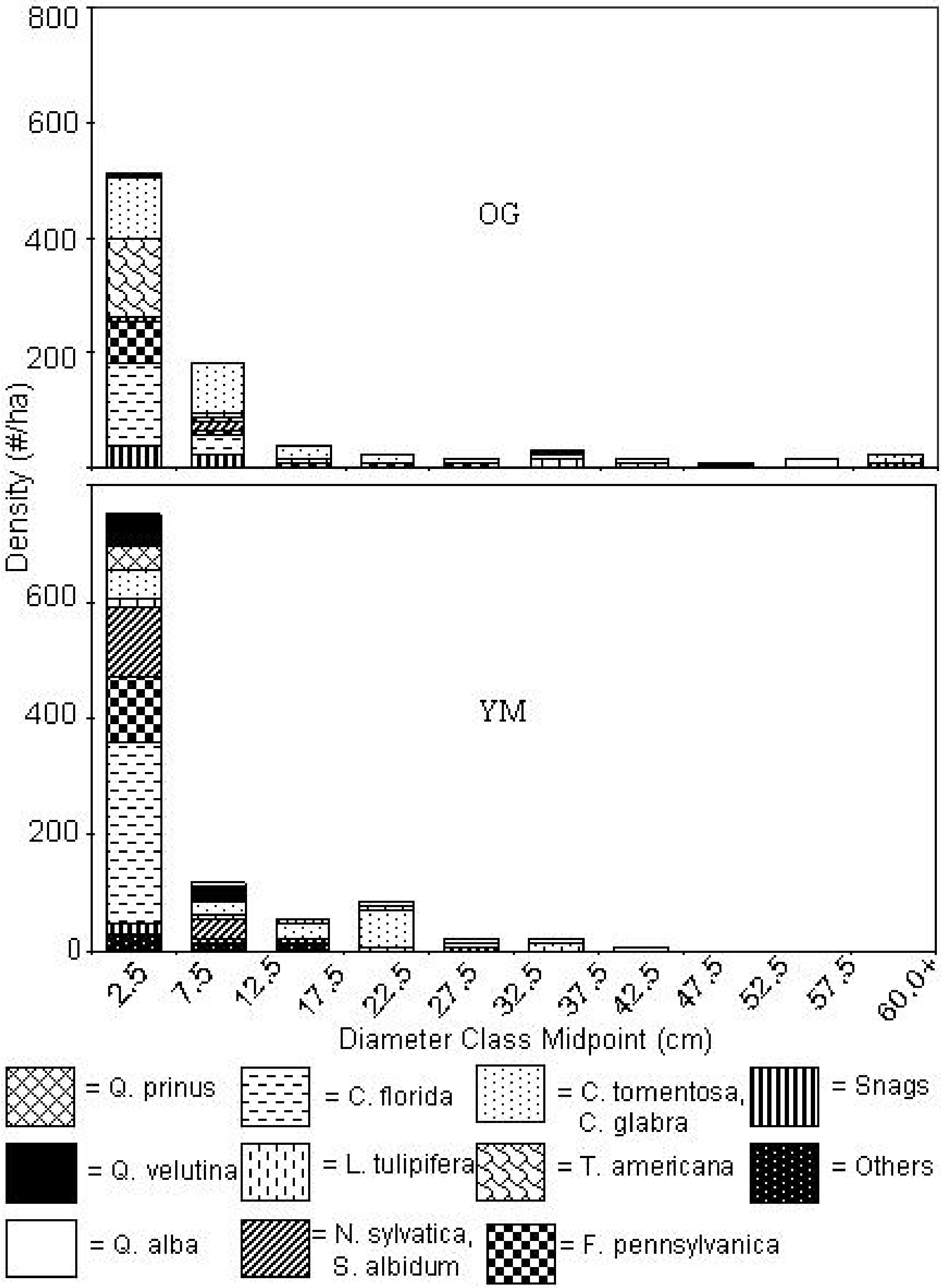

Figure 14. Density diameter distributions for the old-growth (top tier) and younger/ managed (bottom tier) stands of James Madison's Montpelier, Orange County, VA.

The uneven-aged Turkey Ridge Natural Area located on the Cumberland State Forest in Cumberland County, Virginia also exhibited an inverse-J pattern (Figure 15). White oak, northern red oak, and black oak dominated the largest (45 + cm) and upper middle diameter classes (30 – 45 cm) (Figure 15, Table 18). The lower middle diameter classes (15 – 30 cm) were dominated by eastern red cedar, eastern white pine, white oak, northern red oak, and black oak. Mockernut hickory and winged elm comprised 44% of the smallest diameter classes (< 15 cm), while white oak, northern red oak, and black oak made up 17%. The diameter distribution in the nearby younger stand also showed an inverse-J pattern although overall densities were much lower in the smallest diameter classes (< 15 cm) as compared with the old-growth stand (Figure 15). White oak, northern red oak, and black oak also dominated the largest (45 + cm) and upper middle diameter classes (30 – 45 cm) (Figure 15, Table 18). The lower middle diameter classes (15 – 30 cm) were dominated by mockernut hickory, eastern red cedar, and eastern white pine. The smallest diameter classes (< 15 cm) were white oak, northern red oak, and black oak.

The old-growth stand near Milepost 75 of the Blue Ridge Parkway in Bedford County, Virginia approximated an inverse-J diameter distribution also representative of an uneven-aged old-growth forest (Figure 16). Northern red oak dominated the larger (45 + cm) and upper middle diameter classes (30 - 45 cm DBH) (Figure 16, Table 19). Striped maple and green ash equally dominated the lower middle diameter classes (15 – 30 cm). Red maple, blackgum, and striped maple dominated the smallest diameter classes (<15 cm). The younger stand also exhibited an inverse-J distribution (Figure 16). Once again, this stand was not considered an old-growth stand by age thresholds,

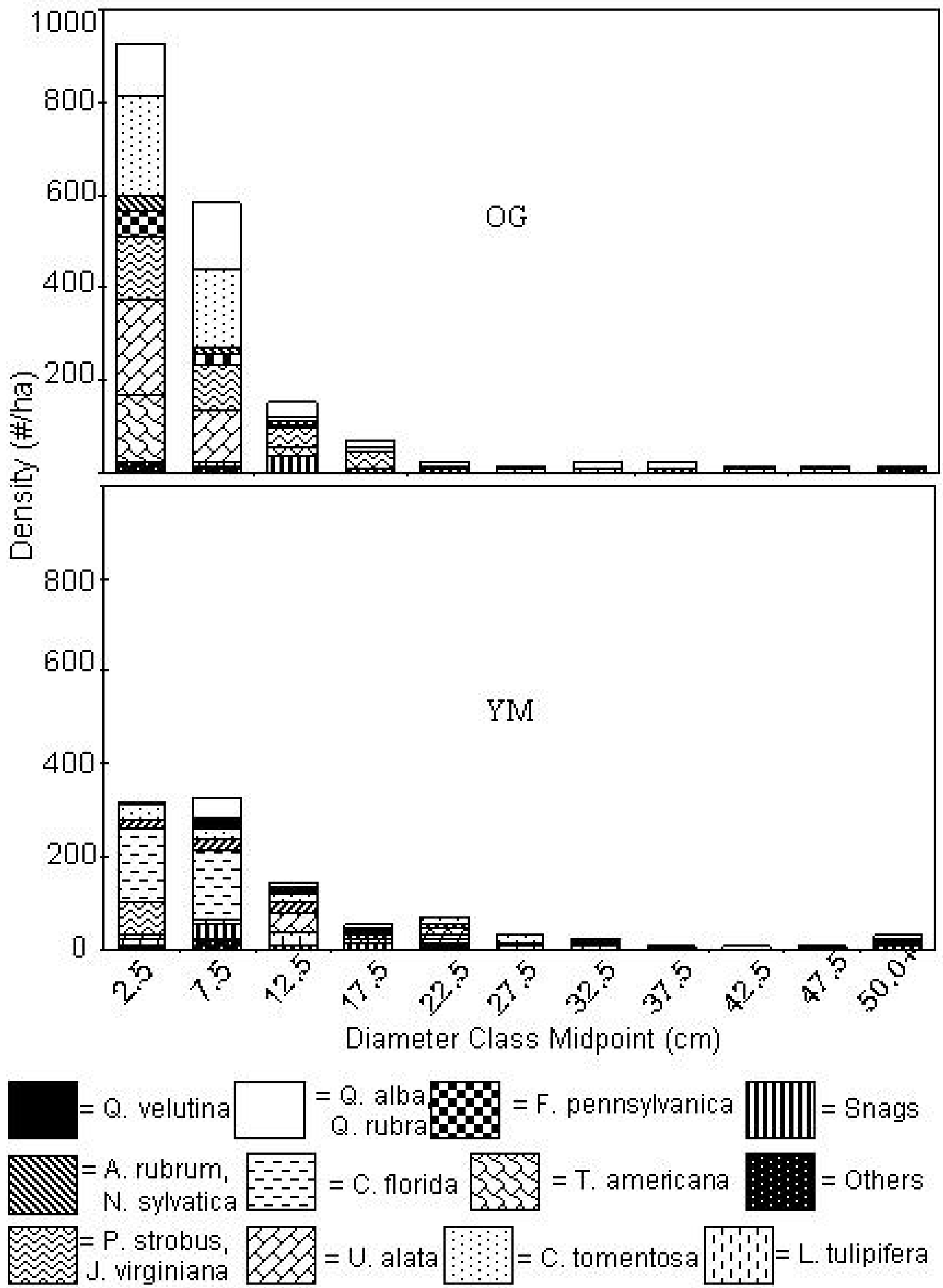

Figure 15. Density diameter distributions for the old-growth (top tier) and younger/ managed (bottom tier) stands of Turkey Ridge Natural Area in Cumberland State Forest, Cumberland County, VA.

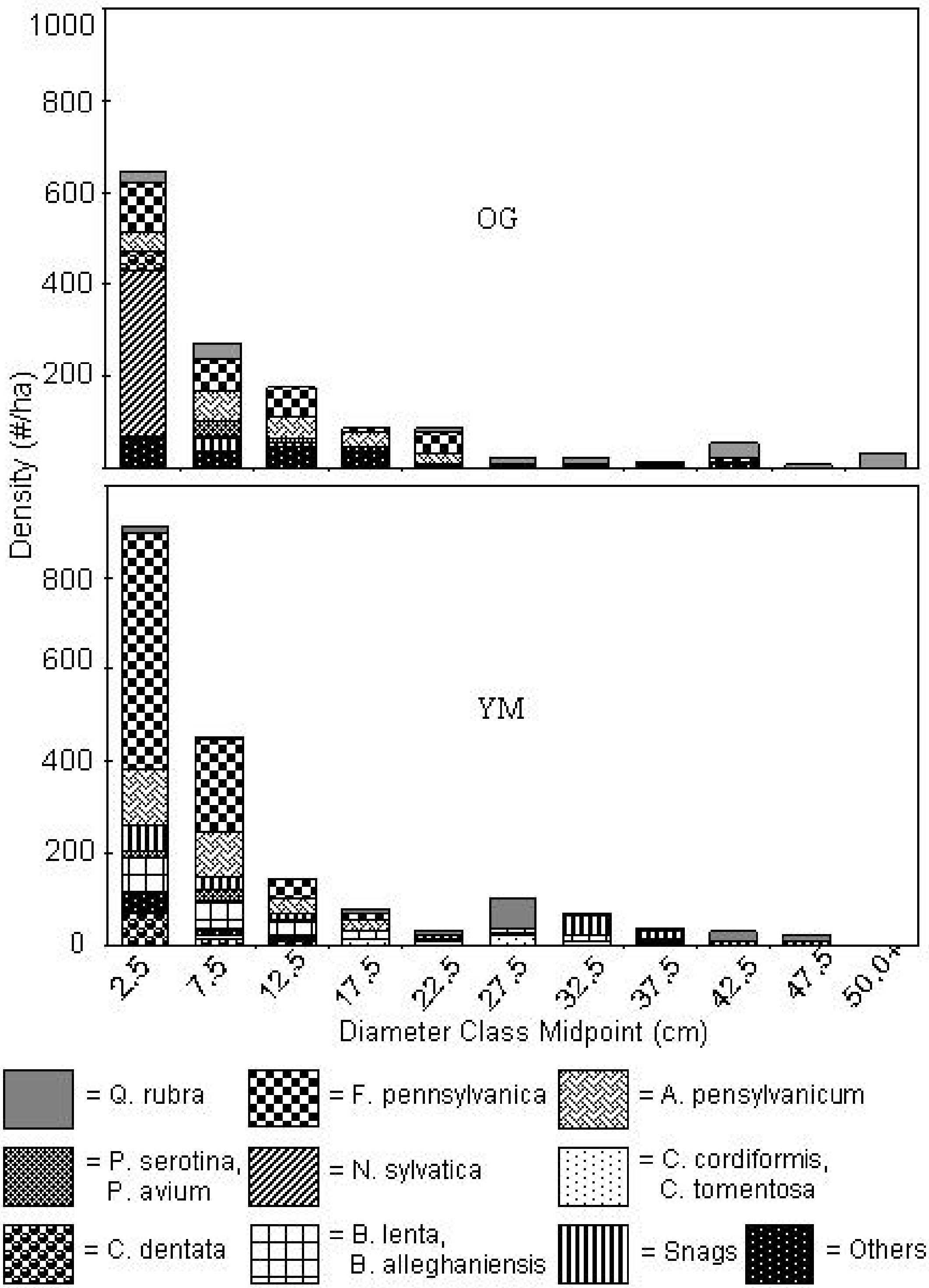

Figure 16. Density diameter distributions for the old-growth (top tier) and younger/ managed (bottom tier) stands near Milepost 75 of the Blue Ridge Parkway in Bedford County, VA.

although some of the dominant oak species were aged at 100 years. Northern red oak composed most of the largest diameter classes (45 + cm) (Figure 16, Table 19). Black cherry and sweet cherry dominated the upper middle diameter classes (30 – 45 cm). The lower middle diameter classes (15 – 30 cm) were represented by northern red oak most abundantly. The smallest diameter classes (< 15 cm) were composed mostly of green ash (64%).

Canopy Strata Distributions

The canopy strata distribution for the old-growth Craig Creek Road stand reveals that white oak dominates the emergent strata class (22 + m) and composes the highest percentage in the overstory strata class (13 – 22 m) (Figure 17). Red maple and blackgum dominated the midstory strata class (4.5 – 13 m), while blackgum and snags compose the majority of the understory strata class (< 4.5 m). The adjacent younger stand is approximately 30 years old and did not contain any trees in the emergent class. Black oak, chestnut oak, and red maple dominated the overstory (13 – 22 m). Red maple and snags dominated the midstory class (4.5 – 13 m), while blackgum made up the majority of the understory class (51%).

The emergent class (24.5 + m) of the old-growth stand near Stony Creek was dominated by northern red oak (Figure 18). This species along with red maple made up most of the overstory (15 – 24.5 m). Red maple comprised the highest percentages in both the midstory (4.5 – 15 m) and understory (< 4.5 m). The neighboring younger stand is entirely dominated by northern red oak in the emergent class (24.5 + m) and it made up the majority in the overstory (15 – 24.5 m). The midstory was dominated by striped

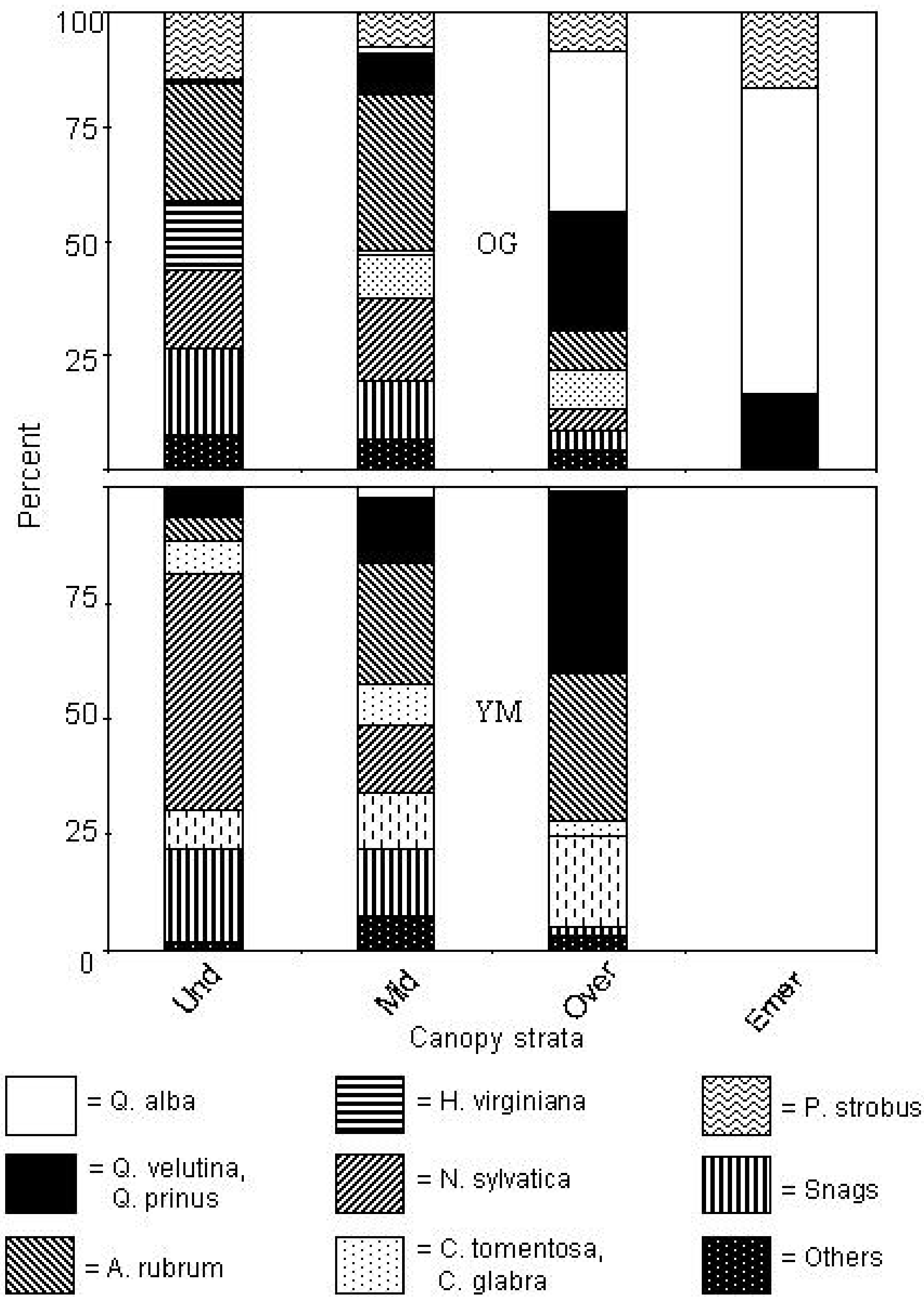

Figure 17. Canopy strata distributions for the old-growth (top tier), simulated (middle tier) and younger/managed (bottom tier) stands near Craig Creek Road, Montgomery County, VA.

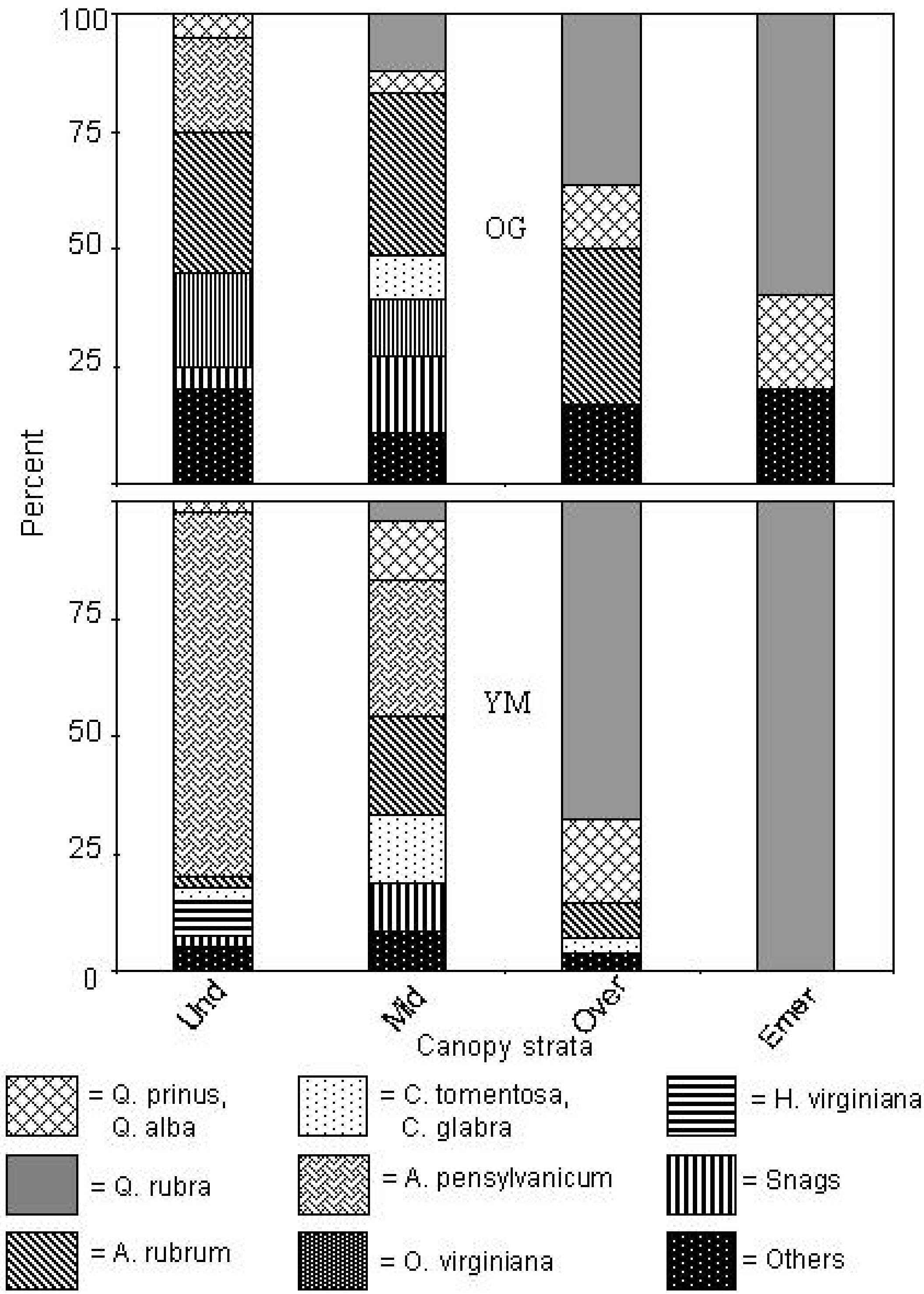

Figure 18. Canopy strata distributions for the old-growth (top tier), simulated (middle tier) and younger/managed (bottom tier) stands near Stony Creek, Giles County, VA.

maple and red maple respectively, while striped maple made up the highest percentage in the understory (77%).

The canopy strata distribution for the old-growth stand located in Great Falls Park shows that mockernut hickory, pignut hickory, black oak, and scarlet oak dominated the emergent class (30 + m) and the overstory class (15 – 30) (Figure 19). American beech dominated the midstory (4.5 – 15 m), while pawpaw dominated the understory (< 4.5 m). Only one chestnut oak stem was observed in the emergent class (30 + m) within the plots taken on the younger stand. Mockernut and pignut hickory composed the highest percentage in the overstory (15 – 30 cm). Blackgum and red maple dominated the midstory (4.5 – 15 m). These two species along with those classified as "others" (black cherry, American beech, chestnut oak, downy serviceberry (*Amelanchier arborea*), green ash, hackberry (*Celtis occidentalis*), American holly (*Ilex opaca*), ironwood (*Carpinus caroliniana*), pawpaw, sassafras (*Sassafras albidum*), and spicebush (*Lindera benzoin*) composed the majority of the understory (< 4.5 m).

The emergent class (20 + m) of the old-growth stand located on the Detwiler Run watershed was composed of chestnut oak and black birch in equal proportions (Figure 20). Black birch, blackgum, and red maple made up most of the overstory (12.5 – 20 m). The midstory class (4.5 – 12.5 m) was dominated by flowering dogwood and red maple. Witch-hazel and snags made up approximately 80% of the understory (<4.5 m). The nearby younger, managed stand gave chestnut oak the highest emergent class (20 + m) percentage. The overstory (12.5 – 20) was also dominated by chestnut oak in conjunction with blackgum. Flowering dogwood displayed the highest percentages in both the midstory (4.5 – 12.5 m) and understory (< 4.5 m).

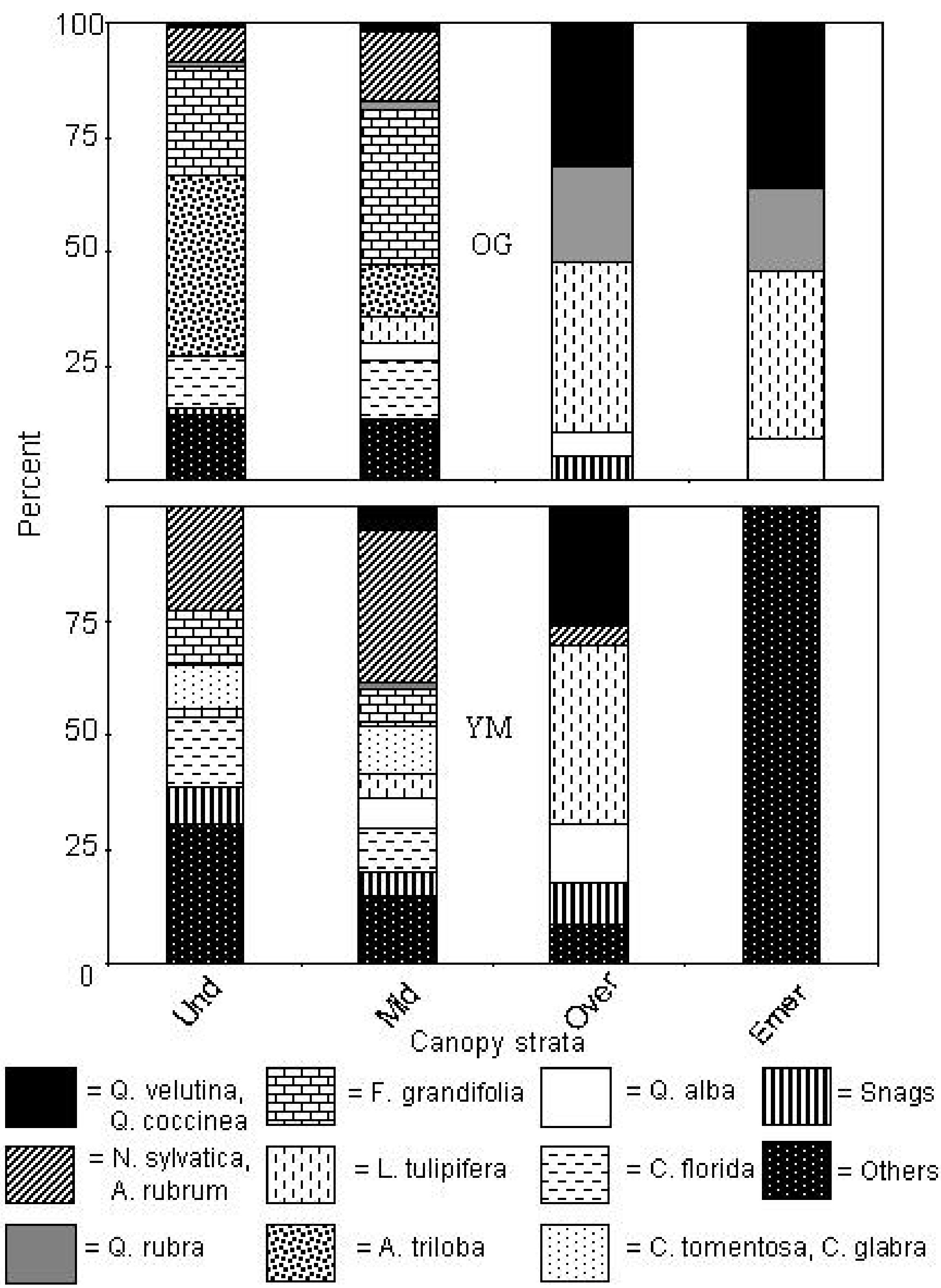

Figure 19. Canopy strata distributions for the old-growth (top tier), simulated (middle tier) and younger/managed (bottom tier) stands of Great Falls Park, Fairfax County, VA.

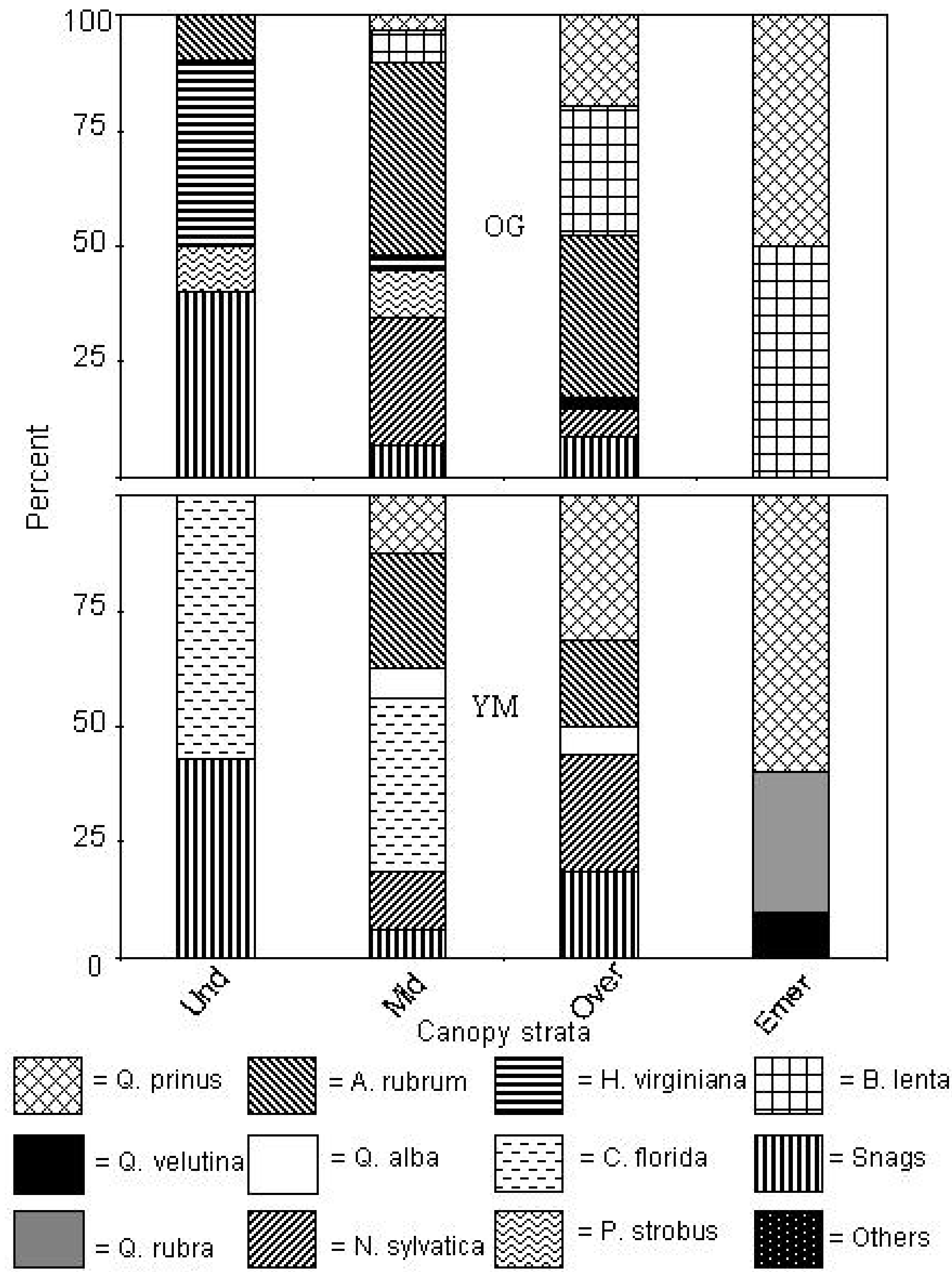

Figure 20. Canopy strata distributions for the old-growth (top tier), simulated (middle tier) and younger/managed (bottom tier) stands of Detwiler Run Watershed in Rothrock State Forest, Huntingdon & Centre Counties, PA.

The canopy strata distribution for the old-growth stand located behind the Montpelier estate shows that yellow-poplar dominated the emergent class (30 + m) (Figure 21). Mockernut and pignut hickory made up the majority of the overstory (15 – 30 m). Both yellow-poplar and the previously mentioned hickories accounted for the majority of the midstory (4.5 – 15 m). The understory was mostly composed of American basswood, mockernut hickory, pignut hickory, and green ash. Mockernut and pignut hickory comprised the entire emergent class (30 + m) of the younger stand. These species also made up the highest percentage of the overstory (15 – 30 m). The midstory (4.5 - 15) was dominated by blackgum, sassafras, mockernut hickory, and pignut hickory. Flowering dogwood made up approximately 59% of the understory in this stand.

The emergent class (26 + m) and overstory (15 – 26 m) of the old-growth stand located on Turkey Ridge Natural Area were dominated by white oak and mockernut hickory (Figure 22). Mockernut hickory, eastern white pine, eastern red cedar, and white oak comprised most of the midstory (4.5 – 15 m). Winged elm, eastern white pine, eastern red cedar, and mockernut hickory dominated the understory (<4.5 m). The nearby younger, managed stand showed that mockernut hickory and black oak composed most of the emergent class (26 + m). The overstory (15 – 26 m) was dominated by eastern white pine, eastern red cedar and mockernut hickory. Mockernut hickory displayed the highest percentage in both the midstory (4.5 – 15 m) and understory (< 4.5 m).

The canopy strata distribution for the old-growth stand located near Milepost 75 of the Blue Ridge Parkway in Bedford County, Virginia shows that northern red oak dominated the emergent class (19.5 + m) and the overstory class (13 – 19.5m) (Figure

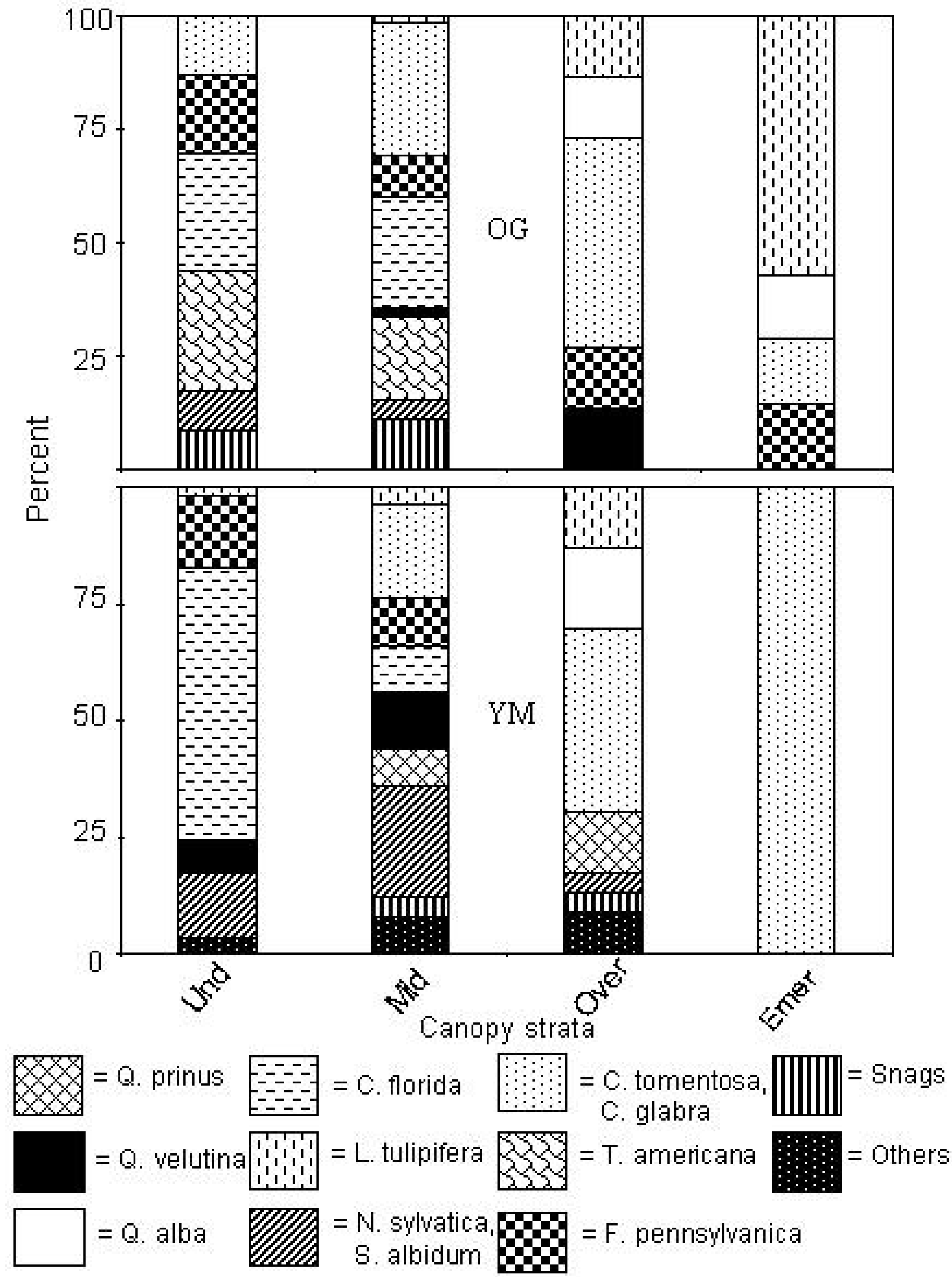

Figure 21. Canopy strata distributions for the old-growth (top tier), simulated (middle tier) and younger/managed (bottom tier) stands of James Madison's Montpelier, Orange County, VA.

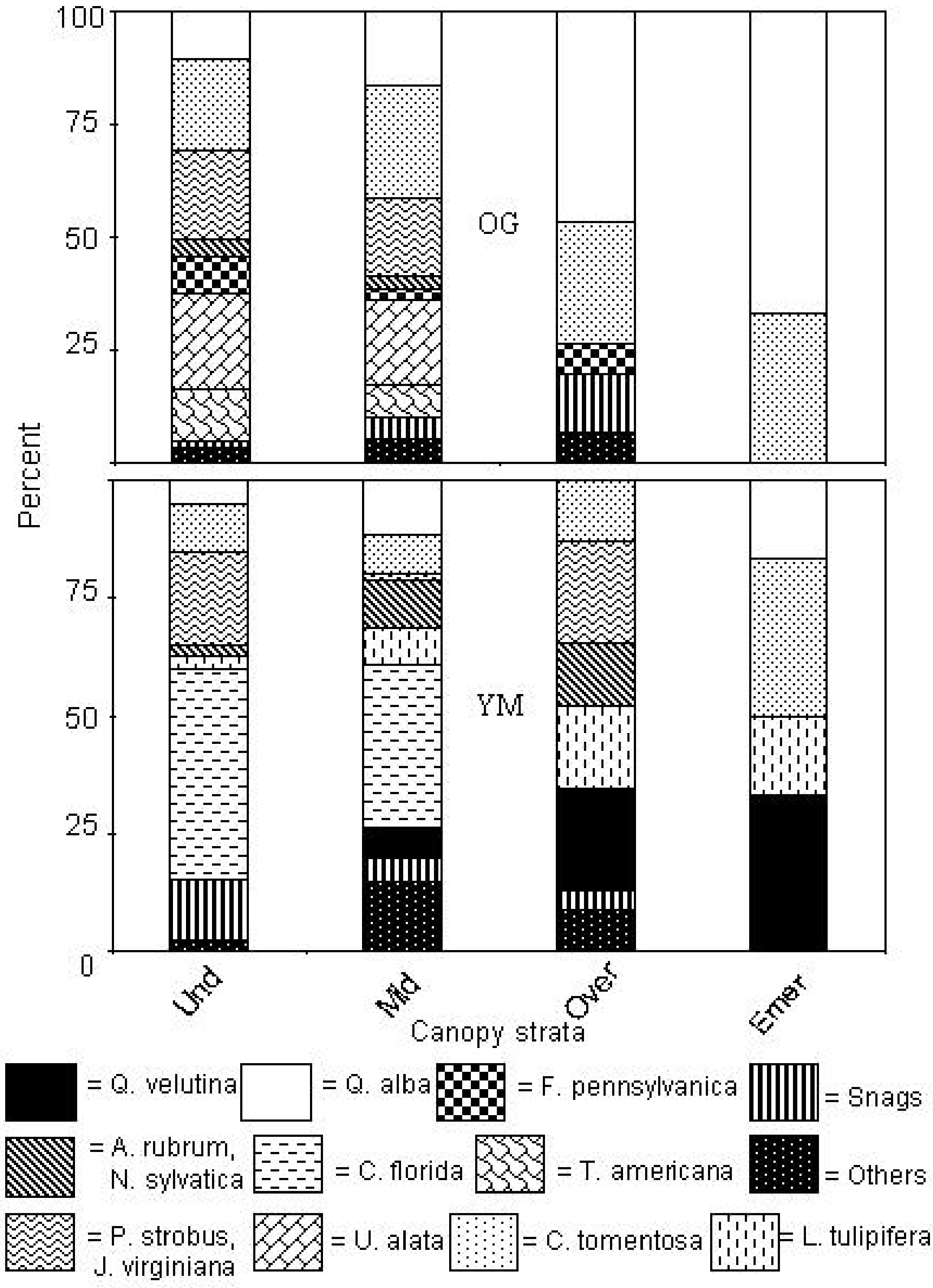

Figure 22. Canopy strata distributions for the old-growth (top tier), simulated (middle tier) and younger/managed (bottom tier) stands of Turkey Ridge Natural Area in Cumberland State Forest, Cumberland County, VA.

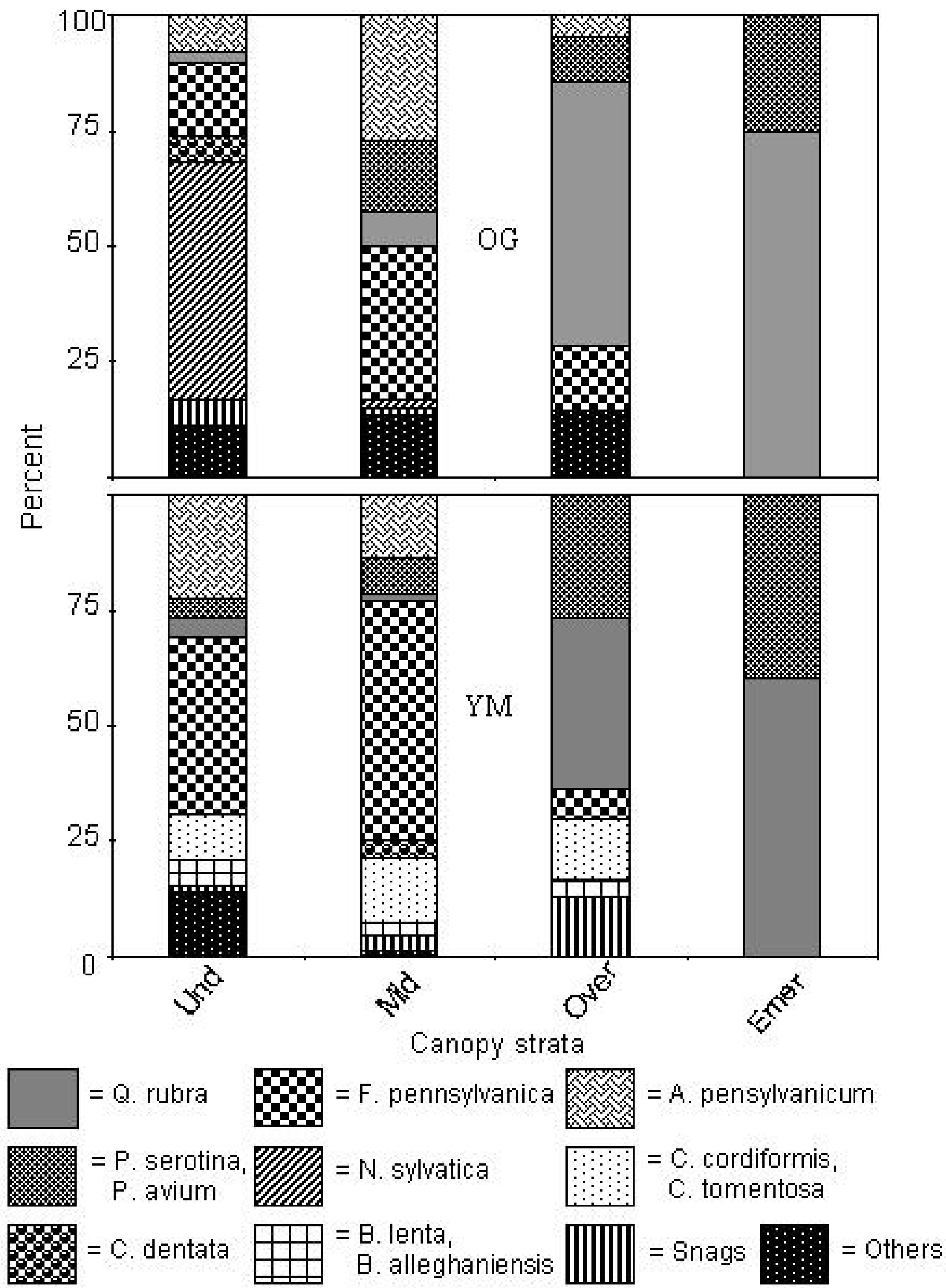

Figure 23. Canopy strata distributions for the old-growth (top tier), simulated (middle tier) and younger/managed (bottom tier) stands near milepost 75 of the Blue Ridge Parkway, Bedford County, VA.

23). Green ash dominated the midstory (4.5 – 13 m), while blackgum made up the majority of the understory (< 4.5 m). Northern red oak, black cherry, and sweet cherry dominated most of the emergent class (19.5 + m) and overstory (13 – 19.6 m). Green ash made up the majority of the midstory (4.5 - 13 m) and the understory (< 4.5 m).

Coarse Woody Debris Results

Average volumes of coarse woody debris among the seven study sites ranged from 79.43 m^3/ha (Blue Ridge Parkway [Milepost 75] old-growth stand) to 1.52 m^3/ha (Craig Creek Road managed stand). None of the old-growth stands showed a statistically significant difference between CWD volumes as compared to their adjacent younger/managed stand ($p > 0.05$). The Craig Creek Road, Virginia site contained an average CWD volume for the old-growth stand of 30.68 m^3/ha compared to 1.53 m^3/ha found on the adjacent younger stand (p-value = 0.09). The Stony Creek, Virginia site produced a CWD volume of 31.60 m^3/ha on its old-growth stand compared to 23.47 m^3/ha found on its younger stand (p-value = 0.42). Great Falls Park, Virginia contained an old-growth CWD volume of 49.82 m^3/ha measured against 48.40 m^3/ha located on the younger stand (p-value = 0.94). Sampling on the Detwiler Run, Pennsylvania stands resulted in an old-growth CWD volume of 36.93 m^3/ha, while the younger stand had a CWD volume of 36.76 m^3/ha (p-value = 0.99).

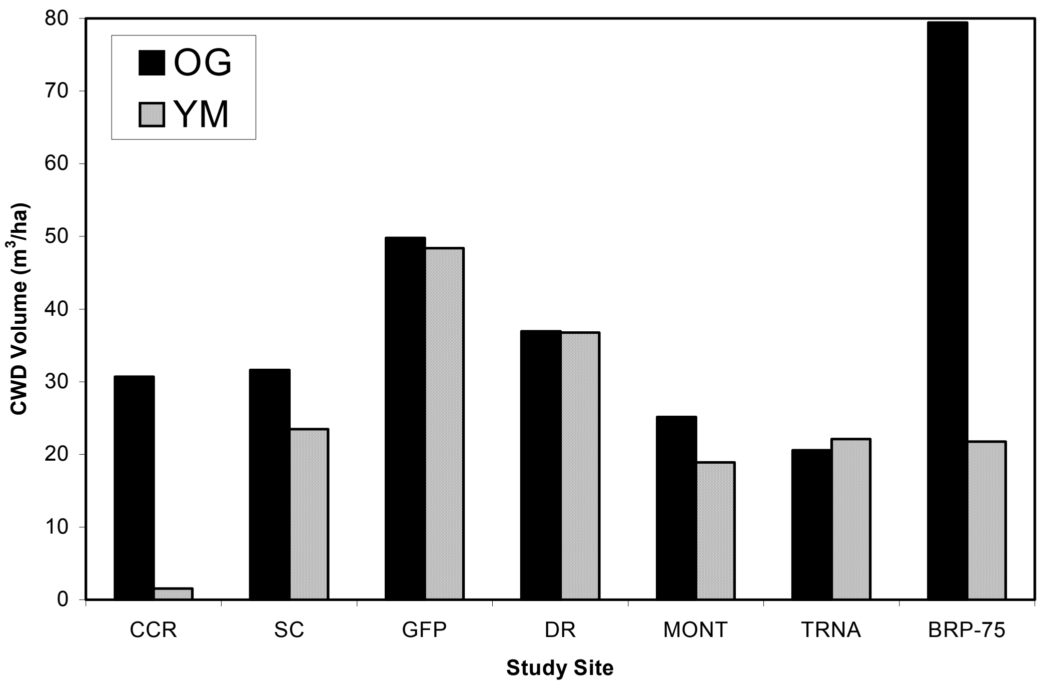

Figure 24. Average volume of coarse woody debris (m^3/ha) between seven old-growth stands and seven younger/managed stands in Virginia and Pennsylvania. CCR = Craig Creek Road, VA, SC = Stony Creek, VA, GFP = Great Falls Park, VA, DT = Detwiler Run, PA, MONT = Montpelier, VA, TRNA = Turkey Ridge Natural Area, VA, and BRP-75 = Blue Ridge Parkway (Milepost 75), VA.

Montpelier's old-growth stand contained 25.12 m^3/ha while the younger stand was measured at a CWD volume of 18.88 m^3/ha (p-value = 0.78). The Turkey Ridge Natural Area produced an average CWD volume of 20.55 m^3/ha while a volume of 22.12 m^3/ha was found on the younger stand (p-value = 0.92). Finally, the Blue Ridge Parkway (Milepost 75) stand contained 79.43 m^3/ha of CWD volume while the younger nearby stand contained 21.75 m^3/ha (p-value = 0.25)

Modeling Analysis

Sensitivity Analysis

Sensitivity of JABOWA to adjustment of soil depth, percent rock, and available N was evaluated to establish the importance of varying levels of each of these site parameters on population density and basal area. Soil depth proved to be a limiting factor at all levels below 0.8 m. By year 90, basal area was reduced from 29.7 m^2/ha at the 1.0 m level to 6.0 m^2/ha at the 0.6 m level. Basal area results decreased even further at lower soil depths. At the 0.2 m soil level, basal area was 4.2 m^2/ha, which was approximately 707% smaller than the 1.0 m level. Population values showed relatively the same trend. However, starting at year 70, populations simulated from runs where soil depth was between 0.6 m and 0.0 m actually started to increase. Percent rock showed relatively similar results for basal area and population when percent rock was between 8% and 58%. At year 90 on the 98% rock level, basal area decreased by 864% from the 8% rock level, and population actually increased 337%. There was an overall increase in both population and basal area when available N was increased from 15% to 85% at all levels.

Further analysis was implemented to quantify the average error created when plot size for each simulated plot was increased from 1/100 ha to 1/12 ha (Table 12). Across all seven younger, managed stands, basal area remained very close at both plot sizes during simulations. Difference in population densities remained relatively similar for three of the seven sites (Craig Creek Road, Montpelier, and Turkey Ridge Natural Area). The four remaining sites (Stony Creek, Great Falls Park, Detwiler Run, and Blue Ridge Parkway [Milepost 75]) showed between a 26% and 48% decrease in population by year 90.

Table 11. Soil depth, percent rock, and available N sensitivity analysis results over a 90 year simulation with 65 iterations per simulation for the Craig Creek Road, Montgomery County, Virginia site. POP = population density, BA = Basal area. Soil Depth is in meters, and available N is in kg/ha/yr.

	POP	BA	POP	BA	POP	BA	POP	BA	POP	BA	POP	BA
Soil Depth	**Year 1**	**Year 1**	**Year 10**	**Year 10**	**Year 30**	**Year 30**	**Year 50**	**Year 50**	**Year 70**	**Year 70**	**Year 90**	**Year 90**
1.0	186.2	24.0	146.3	26.9	96.5	32.4	67.1	33.8	47.0	32.4	34.5	29.7
0.8	183.0	26.4	100.4	24.3	49.5	26.2	26.6	25.3	14.4	22.9	11.4	20.9
0.6	176.2	26.2	83.0	18.4	35.6	15.9	16.2	12.5	10.2	9.3	29.7	6.0
0.4	174.3	26.1	80.5	17.8	35.8	15.3	15.4	11.2	11.0	8.0	25.4	3.5
0.2	174.3	26.0	81.1	17.7	36.6	15.2	17.4	11.3	11.6	8.2	33.1	4.2
0.0	174.3	26.0	81.2	17.5	33.8	14.3	15.2	11.4	15.5	8.2	42.1	4.1
Percent Rock	**1**	**1**	**10**	**10**	**30**	**30**	**50**	**50**	**70**	**70**	**90**	**90**
98.0	119.5	16.3	58.3	2.5	107.4	2.5	134.0	2.5	122.7	2.8	119.6	2.8
78.0	177.6	25.6	126.0	24.0	81.3	23.4	56.4	22.1	40.7	20.8	28.2	19.3
58.0	183.7	26.1	133.8	26.9	88.7	29.6	62.1	30.1	45.1	28.4	31.7	26.2
38.0	182.9	26.2	137.9	27.9	89.2	32.5	62.1	33.5	45.5	31.5	30.7	22.1
18.0	186.2	24.0	146.3	26.9	96.5	32.4	67.1	33.8	47.0	32.4	34.5	29.7
8.0	182.7	26.3	140.1	29.0	90.8	34.7	64.3	36.3	45.4	34.5	35.4	24.2
Available N	**1**	**1**	**10**	**10**	**30**	**30**	**50**	**50**	**70**	**70**	**90**	**90**
85.0	183.6	26.6	143.2	32.2	98.1	42.2	67.5	44.7	49.2	44.7	38.2	41.7
75.0	183.6	26.5	144.6	31.4	95.2	40.0	66.3	42.2	48.1	40.7	34.2	38.1
65.0	182.8	26.4	139.6	30.1	95.2	36.8	65.0	38.5	47.5	38.8	37.7	36.1
55.0	186.2	24.0	146.3	26.9	96.5	32.4	67.1	33.8	47.0	32.4	34.5	29.7
45.0	182.8	26.1	135.7	27.1	88.5	30.1	61.2	31.0	42.5	28.9	31.1	26.7
35.0	171.3	25.7	113.8	24.5	77.1	24.6	53.5	22.8	38.1	20.7	28.1	18.5
25.0	140.4	19.7	49.3	10.0	28.4	11.6	16.4	11.8	9.8	11.0	6.0	9.6
15.0	140.5	19.4	50.1	8.8	28.8	8.3	17.0	7.5	10.9	6.6	8.1	5.3

Table 12. Plot size sensitivity analysis results over a 90 year simulation with 65 iterations per simulation. POP = population density (#/ha), BA = Basal area (m^2/ha), Diff = Factor difference between 1/12 ha plot and 1/100 ha plot.

Site	Plot Size	POP 0	BA 0	POP 10	BA 10	POP 30	BA 30	POP 50	BA 50	POP 70	BA 70	POP 90	BA 90
BRP-75	**1/12**	152.0	12.5	103.7	8.9	104.6	9.1	108.1	10.1	105.0	11.5	102.4	12.6
BRP-75	1/100	19.0	12.5	12.8	9.4	14.6	9.5	16.4	9.7	16.4	10.9	17.4	12.2
	Diff:	8.0	1.0	8.1	0.9	7.2	1.0	6.6	1.0	6.4	1.1	5.9	1.0
CCR	**1/12**	192.0	26.2	162.9	27.2	139.6	30.7	121.6	31.8	113.0	31.9	105.3	31.9
CCR	1/100	24.0	26.2	19.7	27.4	17.0	30.2	14.7	32.8	13.2	32.3	11.8	32.0
	Diff:	8.0	1.0	8.3	1.0	8.2	1.0	8.3	1.0	8.6	1.0	8.9	1.0
TRNA	**1/12**	80.0	8.0	237.8	1.5	553.8	3.1	446.0	9.0	374.4	17.3	313.4	24.1
TRNA	1/100	10.0	8.0	28.8	1.4	60.6	3.1	54.0	8.8	45.6	16.7	38.2	23.0
	Diff:	8.0	1.0	8.3	1.1	9.1	1.0	8.3	1.0	8.2	1.0	8.2	1.0
GFP	**1/12**	80.0	39.7	63.7	37.2	68.0	35.1	76.1	32.6	81.1	30.6	85.4	30.0
GFP	1/100	10.0	39.7	8.1	40.3	11.1	35.2	13.4	35.0	13.5	33.9	14.7	34.4
	Diff:	8.0	1.0	7.9	0.9	6.1	1.0	5.7	0.9	6.0	0.9	5.8	0.9
MONT	**1/12**	80.0	11.4	105.2	11.6	117.1	13.2	124.2	17.1	124.6	22.5	120.0	27.7
MONT	1/100	10.0	11.4	13.8	12.7	15.9	14.9	15.8	18.6	16.9	25.4	14.4	28.5
	Diff:	8.0	1.0	7.6	0.9	7.4	0.9	7.9	0.9	7.4	0.9	8.3	1.0
PBF	**1/12**	32.0	9.7	39.8	9.7	56.3	6.8	80.4	5.9	94.0	6.4	93.0	7.4
PBF	1/100	4.0	9.7	5.1	10.0	11.9	6.8	21.6	4.7	23.7	6.2	22.2	8.9
	Diff:	8.0	1.0	7.8	1.0	4.7	1.0	3.7	1.3	4.0	1.0	4.2	0.8
SC	**1/12**	88.0	42.4	49.7	39.0	50.3	34.7	57.2	30.6	65.3	27.3	74.5	24.8
SC	1/100	11.0	42.4	5.7	40.9	5.4	37.0	6.6	31.6	9.4	26.7	13.7	23.9
	Diff:	8.0	1.0	8.7	1.0	9.3	0.9	8.7	1.0	6.9	1.0	5.4	1.0

Ecologically Important Species Results

The overall success rate of the model simulation on the Craig Creek Road younger, managed stand was 71% as compared to the control simulation success rate of 25% (Table 20). Since the density of the major species in the smallest diameter classes (< 15 cm) in the old-growth stand (910.6 trees/ha) was much lower than the density of trees in the younger stand (1509.5 trees/ha), thinnings were implemented in order to produce a simulated stand with a density closer to that of the older stand (Table 13, Appendix D). With the exception of eastern white pine, all major species present in the younger stand were also present in the old-growth stand. At year one of the simulation, all red maple and yellow-poplar (minor species) were removed from the younger stand across all diameter classes. The stand was then grown to year 80 to allow for adequate growth of the dominant oak trees into the next size classes. At year 80, 48 black oak seedlings/ha, 60 mockernut hickory seedlings/ha, 264 blackgum seedlings/ha, and 300 eastern white pine seedlings/ha were planted. Simultaneously, 12 lower middle diameter class (15 - 30 cm) chestnut oaks/ha, 24 upper middle class (30 – 45 cm) chestnut oaks/ha, and 36 large class (> 45 cm) chestnut oaks/ha were removed. The simulated stand was then projected another 10 years to year 90. At this point, twelve large class (> 45 cm) chestnut oaks/ha were removed and a total of 12 lower middle class (15 – 30 cm) chestnut oaks and black oaks/ha were also removed (Table 13, Appendix D). This brought the younger stand to on old-growth stand structure in 120 years total (30 year current age + 90 years of simulation). The present-day old-growth stand on this site is between 200 – 225 years old.

The Stony Creek younger, managed stand model simulation had an overall success rate of 75% while the control simulation success rate was only 50% (Table 20). Once again, the density of the major species in the smallest diameter classes (< 20 cm) of the old-growth stand (431.3 trees/ha) was much lower than the density of trees in the younger stand (814.7 trees/ha). Thinnings were implemented in order to produce a simulated stand with a density closer to that of the older stand (Table 14, Appendix D). All major species present in the younger stand were also present in the old-growth stand. At year one of the simulation, striped maple in the smallest diameter class (< 20 cm) of the younger stand was reduced by 95% (468 of 492 stems/ha). Twelve chestnut oak stems/ha in the smallest diameter classes (< 20 cm) and in the upper middle diameter classes (40 – 60 cm) also were removed. Finally, 72 northern red oak seedlings/ha were planted in the stand. The stand was then grown for 25 years. At year 25, thinnings were implemented again. Red maple was reduced from 444 stems/ha to 240 stems/ha in the smallest diameter class (< 20 cm). Northern red oak was reduced from 72 trees/ha to 36 trees/ha in the upper middle diameter classes (40 – 60 cm) and by 12 trees/ha in the lower middle diameter classes (20 – 40 cm). 60 mockernut hickory seedlings/ha were also planted to finish the simulation (Table 14, Appendix D). This brought the younger stand to on old-growth stand structure in 100 years total (75 year current age + 25 years of simulation). The present-day old-growth stand on this site is over 200 years old.

The overall success rate of the model simulation on the Great Falls Park younger, managed stand was the highest of all the simulations (81%) (Table 20). The control simulation success rate was 56%. The younger stand contained all of the species present in the old-growth stand. The younger stand also contained some fairly large oak trees similar to the old-growth stand. Since the density of the major species in the smallest diameter classes (< 20 cm) in the old-growth stand (982.4 trees/ha) was higher than the density of trees in the younger stand (750.8 trees/ha), seedlings were planted for four species in order to increase overall density (Table 15, Appendix D). The following amounts and types of seedlings were planted: northern red oak = 36/ha, American beech = 192/ha, and pawpaw = 648/ha. 80% of the red maple stems (48/ha) present in the smallest diameter classes (< 20 cm) were removed along with 25% of the blackgum stems (60/ha). The stand was then projected five years. At year five of the simulation, the following species were thinned in the smallest diameter classes (< 20 cm): black oak, northern red oak and scarlet oak = 68/ha (combined for all three), white oak and chestnut oak = 32/ha (combined for both), mockernut hickory and pignut hickory = 36/ha (combined for both), and blackgum and red maple = 76/ha (combined for both). 24 stems/ha in the lower middle diameter classes (20 – 40 cm) and 12 stems/ha of white oaks were removed in the largest diameter classes (> 60 cm) (Table 15, Appendix D). This brought the younger stand to on old-growth stand structure in 135 years total (130 year current age + five years of simulation). The contemporary old-growth stand on this site is between 200 – 250 years old.

The model simulation of the younger, managed stand on the Detwiler Run younger, managed had an overall success rate below 50% and proved unsuccessful. Population densities at four diameter classes are available for the young and old-growth stand on this site (Table 16).

The Montpelier younger, managed stand model simulation had an overall success rate of 74% compared to 43% for the control simulation (Table 20). With the exception of the two largest diameter classes (60 – 80 cm, > 80 cm) overall population density was higher among major species in the younger stand compared to the old-growth stand. Thinnings were implemented in the smallest (< 20 cm), lower middle (20 – 40 cm), and middle diameter classes (40 – 60 cm) in order to produce a simulated stand with a density closer to that of the older stand (Table 17, Appendix D). All major species present in the younger stand were also present in the old-growth stand except for American basswood. At year one, 132 blackgum stems/ha, 12 sassafras stems/ha, 12 red maple stems/ha, 156 pignut hickory stems/ha, and 72 yellow-poplar stems/ha were removed from the smallest diameter classes (< 20 cm). In both the lower middle diameter classes (20 – 40 cm) and middle diameter classes (40 – 60 cm), 12 blackgum trees/ha were removed along with 12 upper middle diameter class (60 – 80 cm) pignut hickories/ha. The stand was then grown for 40 years to allow movement of oak species into larger diameter classes. At year 40, the following thinnings were implemented in the smallest diameter classes (< 20 cm): 36 yellow-poplar stems/ha, all but 12 blackgum stems/ha, all but 12 sassafras stems/ha, all silver maple stems, 72 black oak stems/ha, and 36 chestnut oak stems/ha. At the same time, the following species were planted: 108 dogwood stems/ha, 72 green ash stems/ha, 48 pignut hickory stems/ha, and 252 American basswood stems/ha. 24 pignut hickory stems/ha were removed from the lower middle diameter classes (20 – 40 cm) along with 12 pignut hickory stems/ha from the middle diameter classes (40 – 60 cm). Finally, 24 lower middle diameter class chestnut oaks/ha were removed (Table 17, Appendix D). This brought the younger stand to on old-growth stand structure in 190 years total (150 year current age + 40 years of simulation). The contemporary old-growth stand on this site is between 200 – 300 years old.

The overall success rate of the model simulation for the younger, managed stand near the Turkey Ridge Natural Area was 75% compared to 42% for the control simulation (Table 20). The younger stand contained all of the major species present in the old-growth stand with the exception of winged elm and American basswood. Both thinnings and plantings were implemented for various species in the smallest diameter classes (< 15 cm) at year one (Table 18, Appendix D). 84 seedlings/ha of yellow poplar, 96 dogwood seedlings/ha, and all red maple stems were removed. Simultaneously, 336 mockernut hickory seedlings/ha, 224 eastern red cedar seedlings/ha, and 240 white oak seedlings/ha were planted. In the lower middle diameter classes (15-30 cm), all yellow-poplar and red maple stems were removed. Finally, 12 yellow-poplar trees/ha were removed from the upper middle diameter classes (30 – 45 cm). The stand was then grown for 25 years. At year 25, 228 American basswood stems/ha, 372 winged elm stems/ha, and 108 eastern red cedar stems/ha were planted. At the same time, eight stems/ha of white oak, northern red oak, and black oak in the largest diameter classes (> 45 cm) were killed and 52 stems/ha of blackgum and red maple (combined) were removed (< 15 cm) (Table 18, Appendix D). This brought the younger stand to on old-growth stand structure in 90 years total (65 year current age + 25 years of simulation). The present-day old-growth stand is between 200 – 300 years old.

The Blue Ridge Parkway (Milepost 75) younger, managed stand model simulation had an overall success rate of 67% while the control simulation success rate was only 46% (Table 20). With the exception of blackgum and red maple, all species in the younger stand were present in the old-growth stand. At year one, both thinnings and plantings were implemented (Table 19, Appendix D). Green ash showed a very large population (750.8) in the smallest diameter classes (< 15 cm) so 276 stems/ha were removed. 60 northern red oak seedlings/ha were planted in this same diameter class. 60 northern red oak seedlings were then removed from the lower middle diameter classes (15 – 30 cm). The stand was grown for five years. At year five, striped maple was reduced by 50 % (103 stems/ha) and 16 stems/ha of northern red oak was removed from the smallest diameter classes (< 15 cm). 12 more stems/ha of northern red oak was removed from the lower middle diameter classes (15 – 30 cm) (Table 19, Appendix D). This brought the younger stand to an old-growth stand structure in 105 years total (100 year current age + five years of simulation). The present-day old-growth stand is approximately 275 years old.

Table 13. Population density results for the younger/managed (YM), computer simulated (SIM) and old-growth (OG) stands at four diameter classes for major species found on the Craig Creek Road, Montgomery County, Virginia site. Numerical values are on a per hectare basis. * Asterisks denote successful category simulations.

Species	Diam Class (< 15 cm)			Diam Class (15.1-30 cm)			Diam Class (30.1-45 cm)			Diam Class (> 45 cm)		
	YM	**SIM**	**OG**	**YM**	**SIM**	**OG**	**YM**	**SIM**	**OG**	**YM**	**SIM**	**OG**
Quercus alba	31.9	12.0*	8.0	16.0	12.0	39.9	0.0	12.0	16.0	0.0	0.0	24.0
Q. velutina, Q. prinus	279.5	47.9*	56.0	247.6	35.9*	32.0	16.0	24.0*	24.0	0.0	12.0*	8.0
C. tomentosa, C. glabra	175.7	59.9*	55.9	16.0	24.0*	24.0	0.0	0.0*	0.0	0.0	0.0*	0.0
Pinus strobus	0.0	167.7*	159.7	0.0	0.0	16.0	0.0	0.0*	0.0	0.0	0.0	8.0
Acer rubrum	567.1	431.3*	399.3	103.8	0.0	16.0	0.0	0.0*	0.0	0.0	0.0*	0.0
Nyssa sylvatica	455.3	191.7*	231.6	0.0	0.0	16.0	0.0	0.0*	0.0	0.0	0.0*	0.0
Total	1509.5	910.5	910.6	383.4	71.9	143.8	16.0	36.0	40.0	0.0	12.0	39.9

Table 14. Population density results for the younger/managed (YM), computer simulated (SIM) and old-growth (OG) stands at four diameter classes for major species found above the Stony Creek, Giles County, Virginia site. Numerical values are on a per hectare basis. * Asterisks denote successful category simulations.

Species	Diam Class (< 20 cm)			Diam Class (20.1-40 cm)			Diam Class (40.1-60 cm)			Diam Class (> 60 cm)		
	YM	**SIM**	**OG**	**YM**	**SIM**	**OG**	**YM**	**SIM**	**OG**	**YM**	**SIM**	**OG**
Quercus rubra	0.0	59.9*	63.9	159.7	48.0*	47.9	55.9	35.9*	39.9	0.0	12.0	24.0
Q. prinus, Q. alba	39.9	24.0	31.9	55.9	35.9*	31.9	8.0	0.0*	0.0	0.0	0.0	8.0
C. tomentosa, C. glabra	79.9	47.9*	47.9	0.0	0.0*	0.0	0.0	0.0*	0.0	0.0	0.0*	0.0
Acer pensylvanicum	599.0	35.9*	31.9	0.0	0.0*	0.0	0.0	0.0*	0.0	0.0	0.0*	0.0
Acer rubrum	95.8	239.6*	255.6	16.0	12.0	47.9	0.0	0.0	8.0	0.0	0.0*	0.0
Total	814.7	407.3	431.3	231.6	95.9	127.8	63.9	35.9	47.9	0.0	12.0	31.9

Table 15. Population density results for the younger/managed (YM), computer simulated (SIM) and old-growth (OG) stands at four diameter classes for major species found at the Great Falls Park, Fairfax County, Virginia site. Numerical values are on a per hectare basis. * Asterisks denote successful category simulations.

Species	Diam Class (< 20 cm)			Diam Class (20.1-40 cm)			Diam Class (40.1-60 cm)			Diam Class (> 60 cm)		
	YM	**SIM**	**OG**	**YM**	**SIM**	**OG**	**YM**	**SIM**	**OG**	**YM**	**SIM**	**OG**
Q. velutina, Q. rubra, Q. coccinea	47.9	16.0*	16.0	0.0	24.0	31.9	16.0	12.0	24.0	16.0	24.0*	24.0
Q. alba, Q. prinus	47.9	16.0*	16.0	24.0	0.0*	0.0	0.0	0.0*	0.0	24.0	16.0*	16.0
C. tomentosa, C. glabra	103.8	72.0*	71.9	0.0	0.0*	0.0	0.0	0.0*	0.0	0.0	0.0*	0.0
Liriodendron tulipifera	39.9	24.0*	24.0	63.9	47.9*	47.9	8.0	12.0	39.9	0.0	0.0*	0.0
Fagus grandifolia	95.8	12.0	303.5	0.0	0.0*	0.0	0.0	0.0*	0.0	0.0	0.0*	0.0
N. sylvatica, A. rubrum	303.5	104.0*	103.8	0.0	12.0*	8.0	0.0	0.0*	0.0	0.0	0.0*	0.0
Cornus florida	111.8	83.9	135.8	8.0	0.0*	0.0	0.0	0.0*	0.0	0.0	0.0*	0.0
Asimina triloba	0.0	239.6	311.5	0.0	0.0*	0.0	0.0	0.0*	0.0	0.0	0.0*	0.0
Total	750.8	567.5	982.4	95.8	107.8	87.9	24.0	24.0	63.9	39.9	47.9	39.9

Table 16. Population density results for the younger/managed (YM) and old-growth (OG) stands at four diameter classes for major species found at the Detwiler Run site in Huntingdon and Centre Counties, Pennsylvania. Numerical values are on a per hectare basis. The computer simulation for this site proved unsuccessful, thus values are not available.

	Diam Class (< 15 cm)			Diam Class (15.1-30 cm)			Diam Class (30.1-45 cm)			Diam Class (> 45 cm)		
Species	**YM**	**SIM**	**OG**	**YM**	**SIM**	**OG**	**YM**	**SIM**	**OG**	**YM**	**SIM**	**OG**
Quercus prinus	0.0	----	0.0	16.0	----	47.9	55.9	----	24.0	31.9	----	16.0
Quercus velutina	0.0	----	0.0	0.0	----	8.0	0.0	----	0.0	8.0	----	0.0
Acer rubrum	16.0	----	167.7	39.9	----	63.9	0.0	----	0.0	0.0	----	0.0
Nyssa sylvatica	0.0	----	55.9	47.9	----	31.9	0.0	----	0.0	0.0	----	0.0
C.florida, H. virginiana	87.9	----	39.9	0.0	----	0.0	0.0	----	0.0	0.0	----	0.0
Betula lenta	0.0	----	16.0	0.0	----	31.9	0.0	----	47.9	0.0	----	8.0
Snags	16.0	----	31.9	8.0	----	24.0	24.0	----	24.0	8.0	----	0.0
Total	119.8	N/A	311.5	111.8	N/A	207.7	79.9	N/A	95.8	47.9	N/A	24.0

Table 17. Population density results for the younger/managed (YM), computer simulated (SIM) and old-growth (OG) stands at five diameter classes for major species found near the Montpelier estate in Orange County, Virginia. Numerical values are on a per hectare basis. * Asterisks denote successful category simulations.

Species	Diam Class (< 20 cm)			Diam Class (20.1-40 cm)			Diam Class (40.1-60 cm)		
	YM	SIM	OG	YM	SIM	OG	YM	SIM	OG
Liriodendron tulipifera	24.0	12.0*	8.0	8.0	12.0*	8.0	16.0	0.0	16.0
Q. alba, Q. velutina, Q. prinus	127.8	12.0*	8.0	24.0	0.0*	0.0	16.0	12.0*	8.0
C. tomentosa, C. glabra	71.9	203.7*	191.7	87.9	24.0	39.9	24.0	12.0	16.0
Fraxinus pennsylvanica	111.8	83.9*	79.9	0.0	0.0	16.0	0.0	0.0	8.0
Cornus florida	311.5	167.7*	175.7	0.0	0.0*	0.0	0.0	0.0*	0.0
Tilia americana	0.0	143.8*	143.8	0.0	0.0*	0.0	0.0	0.0*	0.0
N. sylvatica, S. albidum	151.8	24.0*	24.0	8.0	0.0*	0.0	8.0	0.0*	0.0
Total	798.7	647.0	631.0	127.8	35.9	63.9	63.9	24.0	47.9

Species	Diam Class (60.1-80 cm)			Diam Class (> 80 cm)		
	YM	SIM	OG	YM	SIM	OG
Liriodendron tulipifera	0.0	0.0	8.0	0.0	0.0	16.0
Q. alba, Q. velutina, Q. prinus	0.0	12.0	16.0	0.0	0.0	16.0
C. tomentosa, C. glabra	0.0	0.0*	0.0	0.0	0.0*	0.0
Fraxinus pennsylvanica	0.0	0.0*	0.0	0.0	0.0*	0.0
Cornus florida	0.0	0.0*	0.0	0.0	0.0*	0.0
Tilia americana	0.0	0.0*	0.0	0.0	0.0*	0.0
N. sylvatica, S. albidum	0.0	0.0*	0.0	0.0	0.0*	0.0
Total	0.0	12.0	24.0	0.0	0.0	31.9

Table 18. Population density results for the younger/managed (YM), computer simulated (SIM) and old-growth (OG) stands at four diameter classes for major species found at the Turkey Ridge Natural Area in Cumberland County, Virginia. Numerical values are on a per hectare basis. * Asterisks denote successful category simulations.

Species	Diam Class (< 15 cm)			Diam Class (15.1-30 cm)			Diam Class (30.1-45 cm)			Diam Class (> 45 cm)		
	YM	**SIM**	**OG**	**YM**	**SIM**	**OG**	**YM**	**SIM**	**OG**	**YM**	**SIM**	**OG**
Q. alba, Q. rubra, Q. velutina	95.8	263.6*	287.5	16.0	12.0	31.9	16.0	24.0	39.9	31.9	16.0*	16.0
J. virginiana, P. strobus	71.9	287.5*	271.6	31.9	0.0	39.9	8.0	0.0*	0.0	0.0	0.0*	0.0
Carya tomentosa	71.9	395.4*	391.4	39.9	12.0	24.0	0.0	12.0	16.0	0.0	0.0	8.0
N. sylvatica, A. rubrum	63.9	56.0*	55.9	16.0	0.0*	0.0	0.0	0.0*	0.0	0.0	0.0*	0.0
Ulmus alata	0.0	347.4*	335.5	0.0	0.0*	0.0	0.0	0.0*	0.0	0.0	0.0*	0.0
Tilia americana	0.0	131.8*	151.8	0.0	0.0*	0.0	0.0	0.0*	0.0	0.0	0.0*	0.0
Total	303.5	1481.7	1493.6	103.8	24.0	95.8	24.0	35.9	55.9	31.9	16.0	24.0

Table 19. Population density results for the younger/managed (YM), computer simulated (SIM) and old-growth (OG) stands at four diameter classes for major species found at the Blue Ridge Parkway (Milepost 75) site in Bedford County, Virginia. Numerical values are on a per hectare basis. * Asterisks denote successful category simulations.

Species	Diam Class (< 15 cm)			Diam Class (15.1-30 cm)			Diam Class (30.1-45 cm)			Diam Class (> 45 cm)		
	YM	**SIM**	**OG**	**YM**	**SIM**	**OG**	**YM**	**SIM**	**OG**	**YM**	**SIM**	**OG**
Quercus rubra	24.0	56.0*	55.9	79.9	24.0*	24.0	31.9	24.0	55.9	16.0	12.0	39.9
P. serotina, P. avium	103.8	24.0	39.9	8.0	0.0	8.0	63.9	0.0*	0.0	8.0	0.0*	0.0
Acer pensylvanicum	247.6	152.0*	151.8	24.0	24.0	55.9	0.0	0.0*	0.0	0.0	0.0*	0.0
Fraxinus pennsylvanica	750.8	239.6*	247.6	16.0	24.0	55.9	8.0	12.0*	8.0	0.0	0.0*	0.0
Castanea dentata	39.9	24.0	39.9	0.0	0.0*	0.0	0.0	0.0*	0.0	0.0	0.0*	0.0
A. rubrum, N. sylvatica	0.0	24.0	367.4	0.0	0.0*	0.0	0.0	0.0*	0.0	0.0	0.0*	0.0
Total	1166.1	519.5	902.5	127.8	71.9	143.8	103.8	35.9	63.9	24.0	12.0	39.9

Table 20. Success rate results for JABOWA-3 model simulations, control simulations, and ages for young, old-growth, and simulated stands. All simulations were successful to some degree except for the Detwiler Run (DR) simulation. * Overall success rate for model simulations and control simulations only takes into account those model simulations in which there was some degree of success (DR excluded).

Site	Simulated Success Rate (%)	Control Success Rate (%)	% Difference	Young Stand Age	Old Stand Age	Simulated Age
CCR	71.0	25.0	46.0	30	200-225	110
SC	75.0	50.0	25.0	75	200+	100
GFP	81.3	55.6	25.7	130	200-250	135
DR	N/A	N/A	N/A	100	250-310	N/A
MONT	74.0	42.5	31.5	150	200-300	190
TRNA	75.0	41.7	33.3	65	250-280	90
BRP-75	66.7	46.4	20.3	100	275	105
Average	73.8*	43.5*	30.3			

V. DISCUSSION

Stand Structure Analysis

The density of mature trees (#/ha) found on each of the seven old-growth stands showed a mixed range of values without many trends. Largest tree diameters varied from a 109 cm yellow-poplar found on the Montpelier old-growth stand to a 50 cm black birch found on the Detwiler Run old-growth stand. Martin (1992) recommended a minimum density criterion of seven trees/ha ≥ 75 cm DBH for mixed mesophytic old-growth forests. Three of the seven old-growth stands sampled in this study met this criteria (Stony Creek, Great Falls Park, and Montpelier), while four did not (Craig Creek Road, Detwiler Run, Turkey Ridge Natural Area, and Blue Ridge Parkway Milepost-75). In the cases of Craig Creek Road, Detwiler Run and Turkey Ridge Natural Area, all sites were on extremely dry and/or rocky areas, which inhibited large diameter tree growth and thus prevented the criterion from being met. Although vegetation sampling of the Blue Ridge Parkway old-growth stand did not show seven trees/ha ≥ 75 cm in this study, Abrams (1997) found approximately 15 trees/ha ≥ 80 cm DBH during a more intensive sampling of the same stand. In a Massachusetts old-growth hardwood stand on Wachusett Mountain, Orwig et al. (2001), recorded a density of approximately seven trees/ha ≥ 70 cm DBH. In contrast, Abrams et al. (2001) found an approximate mean density of only two trees/ha ≥ 70 cm in DBH for a Pennsylvania old-growth bog forest.

Snag densities (#/ha) displayed high variability within the old-growth sites. The highest density of snags was 232/ha found on the Craig Creek Road old-growth stand, while the lowest density was 16/ha found on the Great Falls Park old-growth stand. The Craig Creek Road stand had a much higher snag density than the rest of the old-growth stands, which all fell below 100 snags/ha and averaged 88 snags/ha. Roovers and Shifley (1997) observed an average snag density of 113 snags/ha with some stands exceeding 300 snags/ha in an old-growth forest in Central Illinois. In contrast, Hale et al. (1999) sampled 21 old-growth hardwood stands in Minnesota and found snag densities averaging 34/ha with none of the stands exceeding 88/ha. Goodburn and Lorimer (1998) also found a much lower snag density (avg = 39/ha) in on old-growth hardwood stand located near Lake Superior in Michigan. Differences in site characteristics and species composition both play a central role in tree mortality on a given site, which in turn with rate of decay determines snag density (Harmon 1982, Runkle 1982, Matlack et al. 1993, Hardt and Swank 1997).

Coarse woody debris volumes on the old-growth stands ranged from 79.43 m^3/ha (Blue Ridge Parkway [Milepost 75] old-growth stand) to 1.53 m^3/ha (Craig Creek Road managed stand) with an average volume of 39.16 m^3/ha. The high volume of CWD on the Blue Ridge Parkway stand was attributed to its exposed ridgetop location, high amounts of wind and ice damage, and slower decay rates characteristic of higher elevation/cooler temperature sites (Harmon 1982). None of the old-growth stands showed a statistically significant difference between CWD volumes when compared with its adjacent younger/managed stand ($p > 0.05$). This was attributed to the high variances rendered during the statistical analysis. The small number of plots ($n = 6$) that CWD was measured on for each stand was the main factor causing these high variances. Future CWD sampling efforts should increase the number of plots sampled, but even then, there is no assurance that statistically significant difference would be found.

CWD volumes in other eastern old-growth forest proved comparatively higher than that found on most of the stands in this study with the exception of the Blue Ridge Parkway old-growth stand. Muller and Liu (1991) measured CWD volumes on three old-growth deciduous stands within the Cumberland Plateau in Kentucky at 94, 79, and 75 m^3/ha. Harmon et al. (1986) found volumes of 132, 94, 82 m^3/ha for three old-growth hardwood stands in Tennessee. More similar to CWD volumes calculated during this study, MacMillan (1981) determined an average volume of 46 m^3/ha in an Indiana old-growth stand. Once again, the small number of plots sampled on each old-growth stand (n = 6) and short length of transect line (10 m) for each plot may have been a factor in the low volumes found on these stands.

Simulation Analysis

The overall success rate for simulated stands was 74% as compared to 44% for stands in which no silvicultural implementations were modeled (Table 20). This 30% difference in overall success between simulated stands and control stands provides a worthy argument for the benefits of active old-growth management versus leaving a stand unmanaged. Further success in future stand simulations may be gained through an examination of unsuccessful diameter class categories.

Various trends that caused diameter class categories to be unsuccessful (those outside of the +/- 20 % range) in the simulated stands were observed throughout the model runs on most sites. One trend that came up in two of the six modeled stands involved finding a different iteration of the same model run that actually met the criteria for old-growth population density for a specific species in a specific diameter class, while the one used did not. In JABOWA, reproduction and mortality are a stochastic process, therefore each model run or iteration can be different thus producing some iterations in which the criteria was met, and some iterations in which it was not met. For instance, in the smallest diameter classes (< 20 cm) of the Stony Creek simulation, the white oak/chestnut oak category was 24 stems/ha in the simulated stand and 32 stems/ha in the old-growth stand. The iteration used for this simulation did not meet the +/- 20 % criteria for old-growth population density, but other iterations did. Another example was found during the Blue Ridge Parkway simulation. In this instance, the model placed the population of the black cherry/sweet cherry category at 24 stems/ha for the smallest diameter class (< 15 cm), which was out of the +/- 20% range of success for the 32 stems/ha old-growth population value. A different iteration of the simulated stand put the value of this same category at 48 stems/ha. More iterations would produce more variable density values as a result of stochasticity and it is likely that one of these iterations would have fallen within the +/- 20% success range.

Another issue encountered amongst unsuccessful categories was that of finding densities of tree species within the original discarded plots that would have placed a category into a successful range. The Stony Creek simulation resulted in 0 stems/ha in the chestnut oak/white oak density category for the largest diameter class (> 60 cm) while the old-growth class contained eight stems/ha. Data from one of the discarded outlier plots in the younger stand would have resulted in a density of 12 stems/ha for this same class if it had been used. In the Montpelier simulation, there were no yellow-poplar stems in the 40 – 60 cm diameter classes, while 24 stems/ha were actually found on one of the discarded plots. This is not necessarily an error, but was simply due to a limitation of the plot size used in the model (1/12 ha) compared with the total area measured during vegetation sampling (1/8 ha).

The next general pattern found in unsuccessful simulation categories involved a tree species that would not grow into the next size class. During the Craig Creek Road simulation, eastern white pine in the smallest diameter class (< 15 cm) did not survive into any larger diameter classes. The old-growth stand contained eastern white pine in both the lower middle diameter classes (15 – 30 cm) (16 stems/ha) and the largest diameter classes (> 45 cm) (eight stems/ha) so it safe to conclude that while the model would not allow for succession of this species in the simulated stand, its succession is evident in the old-growth stand. Another situation under this same pattern arose with American beech in the Great Falls Park simulation. During this simulation, American beech was planted in high abundance (192 seedlings/ha) in conjunction with the 108 stems/ha that were already present in this diameter class (< 20 cm). By year five, only 12 stems/ha of the initial 300/ha remained. This occurred in all iterations. One more instance where this trend was present was in the Turkey Ridge Natural Area simulation. Eastern white pine was present in the younger stand in the lower and upper middle diameter classes (15 – 30 cm, 30 – 45 cm). Within five years, the model killed off all 40 stems/ha present in these classes. One possible reason for these anomalies, at least in the case of eastern white pine, could be the low population density of this species as compared to other species found on the plot. Oaks and hickories, which were found in higher abundance on these plots, may have a competitive advantage over lower density species during model simulations. It is most likely that American beech was outcompeted by red maple and blackgum, which were already established on the plot in the < 20 cm diameter class (304 stems/ha).

The last major problem that resulted in unsuccessful categories was not a problem with the model, but instead a conflict with the research objective. The goal of this exercise was to silviculturally modify the younger stands into a stand structure similar to its old-growth counterpart in a shorter time frame than natural processes would allow. In order to meet this time requirement, some trees in smaller diameter classes simply did not have enough time to grow into larger diameter classes. During the Craig Creek Road simulation, red maple was initially removed at year one and prevented from establishing itself within the stand during the first 80 years of simulations in an effort to allow oak species to grow unencumbered by shade-tolerant species. At year 80, red maple was allowed back into the stand, but did not have enough time to grow into the next larger size diameter class (15 – 30 cm) before the simulation was stopped. In the younger stand near Montpelier, the largest white oak present was in the 40 – 60 cm diameter class. It would have taken another 155 years to grow this tree into the > 80 cm diameter class to match that category's old-growth density value. At this point the stand would have already been in an old-growth state (150 year original age + 155 years of simulation = 305 year final age). One more example of this issue is present with mockernut hickory in the Turkey Ridge Natural Area simulation. In this case, mockernut hickory is present in all diameter classes in the old-growth stand, but only in the first two of the younger stand. It would have taken approximately 145 years to grow the largest mockernut hickories in the younger stand into the largest diameter class (> 45 cm) thus failing to meet the research objective.

The Detwiler Run model simulation proved to be entirely unsuccessful. The contemporary old-growth stand on this extremely talus site (52 % rock coverage) was a unique chestnut oak/black birch stand. Black birch was present in each of the four diameter classes (< 15 cm, 15 - 30 cm, 30 - 45 cm, and > 45 cm) on the old-growth stand, but the younger stand contained no black birch. Attempts to add black birch seedlings to the simulated stand proved unsuccessful. The model would not allow these seedlings to live past age 30 and even then they had not grown into the next diameter class (15-30 cm). This is most likely due to the fact that black birch is shade-intolerant and was being shaded by all larger trees in the plot. Ecologically, black birch on poor soils is usually partially or completely replaced by oaks, which is what happened during model runs, but occasionally this species is abundant on rocky mountains in Pennsylvania, which proved to be the case on Detwiler Run (Burns and Honkala 1990). The model simply cannot simulate the unique species dynamics present in this old-growth stand. Another problem that occurred in the attempted Detwiler Run simulation was the extremely slow growth rate (3 cm over 50 years) of eastern white pine. Eastern white pine comprised approximately 10% of both the < 15 cm and 15-30 cm diameter classes and the model would not allow a sufficient number of seedlings to grow from the smallest diameter class (< 15 cm) into the 15-30 diameter class.

Old-Growth Modeling Concerns

The question of “what is old-growth” and “how do we quantify it” is an important factor to be considered when attempting to model the dynamics of uneven-aged old-growth forests. Old-growth structural characteristics, such as uneven-age stand structure, having many large, mature trees, high vertical diversity, the presence of snags, the presence of CWD on the forest floor, pit and mound topography, steady-state nutrient and energy cycling, and steady-state volume growth (Franklin et al. 1981, Oliver and Larson 1996) are not easily simulated in any type of growth model that is littered with simplifying assumptions. This proves to be the case with many of the JABOWA-derived gap models where it is assumed that the foliage of each individual tree on a plot is distributed uniformly over the entire gap (Kimmins 1997). This "opaque blanket" approach was mainly a result of computer limitations in the late 1960's and is less accurate in modeling species-specific interactions between tree species than individual tree growth models like SORTIE and FORCEE particularly at larger plot sizes (Pacala et al. 1996, Kimmins 2000). Another issue along these same lines is that individual trees do not always follow the average trend of height increasing monotonically with DBH on a plot due to microsite conditions, genetics, unexplained variation, etc. Most gap models, including JABOWA, predict tree heights from a fitted average height versus diameter relationship. Since this height/diameter function is monotonically increasing, the smallest DBH trees always have the smallest heights and the largest DBH trees always have the largest heights regardless of what was measured in the field. This may result in an inaccurate representation of vertical structure within a stand unless field-measured trees fall along the empirical curve designated by that species' average height - diameter function. Snags and CWD are another important aspect of old-growth forests that gap models fail to measure. Output lists of killed trees are readily obtainable by a model user, but this does not specify whether a dead tree is still standing or has fallen on the ground.

It can be argued that horizontal structure is a defining attribute of old-growth, but is very difficult to quantify (Parker 1995). A model that is spatially explicit in tree location and height (ZELIG, SORTIE, SPACE) may be more suited to simulate horizontal structure, but still may not be capable of modeling old-growth stand structure (Phil Radtke, personal communication, 2002). JABOWA assumes spatial homogeneity over the plot, which does not make it ideal for modeling horizontal structure. This spatial ambiguity disallowed the simulation of group selection cuts during the model runs, which is one of the recommended prescriptions for converting younger, managed stands into old-growth forests (Rooney 1995). However, JABOWA does a satisfactory job in simulating overall competition and shading among mixed-species, uneven-aged stands and it allowed the implementation of other previously recommended silvicultural prescriptions in the computer simulations (single-tree selection, culling larger diameter stems and planting seedlings) (Burns 1983, Runkle 1991, Lorimer and Frelich 1994, Marquis et al. 1994). Most importantly, this model proved successful with the goals of the planning agenda set forth at the beginning of this project with the only exception being the unsuccessful Detwiler Run model simulation. Here, the objective of using local old-growth structure as a goal for modeling the growth response to silvicultural treatments in adjacent younger, managed stands was met. Further possibilities exist for land managers in other parts of North America who want to manage their younger stands for old-growth characteristics, but do not have the time or money to do so or do not have readily available or preexisting old-growth stands to use as a benchmark. In these situations, preexisting old-growth data sets or models of old-growth stand structure may be used just as easily as a target for old-growth structural and management objectives.

Future efforts in modeling old-growth forests should focus on adapting gap models to answer specific questions about other aspects of old-growth forests. Concentration should be given to accurately modeling uneven-aged canopy structure (based on independent height functions), snag and CWD density and volume, and moving away from the spatial homogeneity approach that has served as the primary foundation behind many JABOWA-derived gap models.

LITERATURE CITED

Abrams, M.D., and Orwig, D.A. 1996. A Review of Dendroecology and Successional Dynamics of Old-Growth and Second-Growth Oak and Pine Forests in the Eastern United States. *RADIOCARBON*. 1996: 343-352.

Abrams, M.D., Orwig, D.A., Dockry, M. J. 1997. Dendroecology and successional status of two contrasting old-growth oak forests in the Blue Ridge Mountains, USA. *Canadian Journal of Forest Research* 27: 994-1002.

Abrams, M.D. 1998. The composition and dendroecology of a mixed-oak old-growth forest at Great Falls Park, Virginia. Report to the National Park Service.

Abrams, M.D., and Copenheaver, C.A. 1999. Temporal variation in species recruitment and dendroecology of an old-growth white oak forest in the Virginia Piedmont, USA. *Forest Ecology and Management* 124: 275-284.

Abrams, M.D., Copenheaver, C.A., Black, B.A., S. van de Gevel. 2001. Dendroecology and climatic impacts for a relict, old-growth, bog forest in the Ridge and Valley Province of central Pennsylvania, U.S.A. *Canadian Journal of Botany* 79: 58-69.

Bailey, T.W., and Arnold, T.L. 1986. Soil interpretation report for the Jefferson National Forest – northern part. USDA Forest Service, Natural Bridge Station, Natural Bridge, VA.

Barbour, M.G., Burk, J.H., Pitts, W.D. 1987. *Terrestrial Plant Ecology*. Benjamin/Cummings Publishing Co. Inc. pp. 182-208.

Barbour, M.G., Burk, Pitts, Gilliam, Schwartz. 1999. *Terrestrial Plant Ecology*. 3rd Ed. Benjamin/Cummings Publishing Co. Inc. 649 p.

Bonan, G.B. and Korzuhin, M.D. 1989. Simulation of moss and tree dynamics in the boreal forests of interior Alaska. *Vegetatio* 84(1): 31-44.

Botkin, D.B., Janak, J.F., Wallis, J.R. 1972a. Rationale, Limitations, and Assumptions of a Northeastern Forest Growth Simulator. *IBM Journal of Research and Development* 16: 101-116.

Botkin, D.B., Janak, J.F., Wallis, J.R. 1972b. Some Ecological Consequences of a Computer Model of Forest Growth. *Journal of Ecology* 60(3): 849-872.

Botkin, D.B. 1992. Manual for JABOWA-II: The Forest Growth Model. Oxford University Press. 60 p.

Botkin, D.B. 1993. *Forest Dynamics: An Ecological Model*. Oxford University Press. 309 p.

Braker, W.L. 1981. Soil Survey of Centre County, Pennsylvania. USDA Soil Conservation Service. 162 pages plus maps.

Braun, E.L. 1950. *Deciduous forests of eastern North America*. The Free Press, NY, 596 p.

Burns, R.M. (tech. comp.). 1983. Silvicultural systems for the major forest types of the United States. Agriculture Handbook 445. USDA Forest Service. 191 p.

Burns, R.M., and Honkala, B.H., (tech. coords.). 1990. *Silvics of North America: 1. Conifers; 2. Hardwoods*. Agriculture Handbook 654. USDA Forest Service, Washington, DC. Vol.2, 877 p.

Carey, A.B. 1989. Wildlife associated with old-growth forests in the Pacific Northwest. *Natural Areas Journal* 9: 151-162.

Carter, J.B., Wills, J.W., Cummins, W.E. 1971. Soil Survey of Orange County, Virginia. USDA Soil Conservation Service. 168 pages plus maps.

Coates, K.D., and Burton, P.J. 1997. A gap-based approach for development of silvicultural systems to address ecosystem management objectives. *Forest Ecology and Management* 99: 337-354.

Coffin, D.P., and Lauenroth, W.K. 1990. A gap dynamics simulation model of succession in a semiarid grassland. *Ecological Modelling* 50: 107-132.

Creggar, W. H., Hudson, H.C., Porter, H.C. 1985. Soils Survey of Montgomery County, Virginia. USDA Soil Conservation Service. 158 pages plus maps.

Crow, T.R., Haney, A., Waller, D.M. 1993. Report on the scientific roundtable on biological diversity convened by the Chequamegon and Nicolet National Forests. TP-R9-CNF/NNF-93-1, USDA Forest Service, Milwaukee, WI.

Dale, V.H. and Franklin, J.F. 1989. Potential effects of climate change on stand development in the Pacific Northwest. *Canadian Journal of Forest Research* 19(12): 1581-1590.

Davis, M.B., and Botkin, D.B. 1985. Sensitivity of cool-temperate forests and their fossil pollen record to rapid temperature change. *Quaternary Research* 23(3): 327-340.

Digby, P.G.N., Kempton, R.A. 1987. *Multivariate analysis of ecological communities*. Chapman and Hall. 206 p.

Duffy, I.T. 1969. A forest atlas of the South. New Orleans, LA: USDA Forest Service, Southern Forest Experiment Station. and Asheville, NC: Southeastern Forest Experiment Station, 27 p.

Erdmann, G.G. 1986. Developing quality in second-growth stands. *In* The northern hardwood resource: management and potential. Mich. Tech. Univ. Houghton. pp. 206-22.

Forcier, L.K. 1975. Reproductive Strategies and the Co-occurrence of Climax Tree Species. *Science* 189: 808-810.

Franklin, J.F., Cromack, K.Jr., Denison, W., McKee, A., Maser, C., Sedell, J., Swanson, F., Juday, G. 1981. Ecological characteristics of old-growth Douglas-fir forests. *Gen. Tech. Rep.* PNW-118. Portland, OR: USDA Forest Service, Pacific Northwest Forest Experiment Station. 46 p.

Franklin, J.F. 1993. Preserving biodiversity: species, ecosystems, or landscapes? *Ecological Applications* 3: 202-205.

Goebel, P.C., and Hix D.M. 1996. Development of mixed-oak forests in southeastern Ohio: a comparison of second-growth and old-growth forests. *Forest Ecology and Management* 84: 1-21.

Goodburn, J.M., and Lorimer, C.G. 1998. Cavity trees and coarse woody debris in old-growth and managed northern hardwood forests in Wisconsin and Michigan. *Canadian Journal of Forest Research* 28: 427-438.

Gutierrez, R.J., and Carey, A.B. 1985. Ecology and Management of the Spotted Owl in the Pacific Northwest. *Gen. Tech. Rep.* PNW-185. Portland, OR: USDA Forest Service, Pacific Northwest Forest Experiment Station. 119 p.

Hale, C.M., Pastor, J., Rusterholz, K.A. 1999. Comparison of structural and compositional characteristics in old-growth and mature, managed hardwood forests of Minnesota, U.S.A. *Canadian Journal of Forest Research* 29: 1479-1489.

Haney, J.C. 1997. Spatial Incidence of Barred Owl (*Strix varia*) Reproduction in Old-Growth Forest of the Appalachian Plateau. *Journal of Raptor Research* 31(3): 241-252.

Hansen, A.J., Spies, T.A., Swanson, F.J., Ohman, J.L. 1991. Conserving biodiversity in managed forests. *BioScience* 41: 382-392.

Hardt, R.A., and Newman, D.H. 1995. Regional Policies for National Forest Old-Growth Planning. *Journal of Forestry* 93(6): 32-35.

Hardt, R.A., and Swank, W.T. 1997. A Comparison of Structural and Compositional Characteristics of Southern Appalachian Young Second-Growth, Maturing Second-Growth, and Old-Growth Stands. *Natural Areas Journal* 17: 42-52.

Harmon, M.E. 1982. Decomposition of Standing Dead Trees in the Southern Appalachian Mountains. *Oecologia* 52: 214-215.

Harmon, M.E., Franklin, J.F., Swanson, F.J., Sollins, S.V., Gregory, J.D., Lattin, N.H., Anderson, S.P., Cline, S.P., Aumen, N.G., Sedell, J.R., Lienkaemper, G.W., Cromack Jr., K., Cummings, K.W. 1986. Ecology of Coarse Woody Debris in Temperate Ecosystems. *Advanced Ecological Research* 15: 133-302.

Henry, E.F., Welch, W.J., Fussell, K.E., Bailey, H.H., Smith, G.K., Sbar, A.H. 1948. Soil Survey of Prince Edward County, Virginia. USDA Soil Conservation Service. 57 pages plus maps.

Hof, J. and Bevers, M. 2000. Optimizing Forest Stand Management with Natural Regeneration and Single-Tree Choice Variables. *Forest Science* 46(2): 168-175.

Hunter, M.L. Jr. and White, A.S. 1997. Ecological thresholds and the definition of old-growth forest stands. *Natural Areas Journal* 17: 292-296.

Hunter, M.L. Jr. 1989. What constitutes and old growth stand? *Journal of Forestry* 87: 33-35.

Jaccard, P. 1901. Distribution de la flore alpine dans le Bassin des Dranses et dans quelques regions voisines. *Bull. Soc. Vand. Sci. Nat.* 37: 241-272.

Kimmins, J.P. 1997. *Forest ecology: a foundation for sustainable management*. Prentice Hall. 596 p.

Kimmins, J.P. 2000. Respect for Nature and the Role of Modeling in the Definition of Sustainable Forest Management. Last Updated: Sept 2000. Accessed: 24 Sept 2002 <http//:www.forsonline.org/comphk.pdf>.

Lamson, N.I., Smith, H.C., Perkey, A.N., Brock, S.M. 1990. Crown release increases growth of crop trees. *Res. Pap.* NE-635. USDA Forest Service. Northeastern Forest Experiment Station.

Loehle, C. 1988. Tree life history strategies: the role of defenses. *Canadian Journal of Forest Research* 18: 209-222.

Lorimer, C.G., and Frelich, L.E. 1994. Natural disturbance regimes in old-growth northern hardwoods: Implications for restoration efforts. *Journal of Forestry* 92: 33-38.

MacMillan, P.C. 1981. Log decomposition in Donaldson's Woods, Spring Mill State Park, Indiana. *American Midland Naturalist* 106: 335-344.

Marquis, D.A., Ernst, R.L., Stout, S.L. 1984. Prescribing silvicultural treatments in hardwood stands of the Alleghenies. *Gen. Tech. Rep*. NE-96. Upper Darby, PA: USDA Forest Service. Northeastern Forest Experiment Station. 90 p.

Marquis, D.A., ed. 1994. Quantitative silviculture for hardwood forests of the Alleghenies. *Gen. Tech. Rep.* NE-183. Radnor, PA: USDA Forest Service. Northeastern Forest Experiment Station. 376 p.

Martin, W.H. 1992. Characteristics of old-growth mixed mesophytic forests. *Natural Areas Journal* 12: 127-135.

Matlack, G.R., Gleeson, S.K., Good, R.E. 1993. Treefall in a mixed oak-pine coastal plain forest: immediate and historical causation. *Ecology* 74: 1559-1566.

McCarthy, B.C. 1995. Eastern old-growth forests. *Ohio Woodland Journal* 1: 8-10.

McDaniel, J.C., Bullard, C.F. Jr., Parker, C.D. III, Whitley, G.F., Dove, J.E. 1989. Soils Survey of Bedford County, Virginia. USDA Soil Conservation Service. 208 pages plus maps.

Montpelier (Montpelier Website). The James Madison Landmark Forest. Last Updated: Jan 2001. Accessed: 18 August 2001 <http//:www.montpelier.org>.

Mueller-Dombois, D., Ellengerg, H. 1974. *Aims and methods of vegetation ecology*. Wiley, Inc., New York. 547 p.

Muller, R.N, and Liu, Y. 1991. Coarse woody debris in an old-growth deciduous forest on the Cumberland Plateau, southeastern Kentucky. *Canadian Journal of Forest Research* 21: 1567-1572.

Nelson, B., Nowak, C., Reitz, S., deCalesta, D., Wingate, S. 1997. Communicating old-growth forest management on the Allegheny National Forest. *Gen. Tech. Rep.* NE-238. Upper Darby, PA: USDA Forest Service. Northeastern Forest Experiment Station. pp. 85-89.

Nicholson, J.C., Burruss, T.R., Jones, D.L. 1980. Soil Survey of Goochland County, Virginia. USDA Soil Conservation Service. 137 pages plus maps.

Noss, R.F. 1991. Sustainability and wilderness. *Conservation Biology* 5: 120-122.

Nyland, R.D. 2002. *Silviculture: concepts and applications*. Second Edition. McGraw-Hill. 682 p.

Oliver, C.D., and Larson, B.C. 1996. *Forest Stand Dynamics*. Update Edition. John Wiley & Sons, Inc., New York. 520 p.

Orwig, D.A., Cogbill, C.V., Foster, D.R., O'Keefe, J.F. 2001. Variations in Old-Growth Structure and Definitions: Forest Dynamics on Wachusett Mountain, Massachusetts. *Ecological Applications* 11(2): 437-452.

Pacala, S.W., Canham, C.D., Saponara, J., Silander, J.A.Jr., Kobe, R.K., Ribbens, E. 1996. Forest Models Defined by Field Measurements: Estimation, Error Analysis and Dynamics. *Ecological Monographs* 66(1): 1-43.

Parker, G.G. 1995. Structure and microclimate of forest canopies. *In* M.D. Lowman and N.M. Nadkarni (eds), Forest Canopies: a Review of Research on a Biological Frontier, Academic Press, San Diego, pp. 73-106.

Phipps, R.L. 1985. Collecting, preparing, crossdating, and measuring tree increment cores. US Geological Survey. Water-Resources Investigations Report 85-4148. 48 p.

Porter, H.C., Derting, J.F., Elder, J.H., Henry, E.F. 1963. Soil Survey of Fairfax County, Virginia. USDA Soil Conservation Service. 103 pages plus maps.

Rominske, R., and Busch, P. 1991. Management of a northern hardwood stand to provide for characteristics resembling old-growth (abstract). *In* Management of old-growth ecosystems conference. Ottawa Nat. Forest. Ironwood, MI. pp. 39-41.

Rooney, T.P. 1995. Restoring landscape diversity and old growth to Pennsylvania's northern hardwood forest. *Natural Areas Journal* 15: 274-278.

Ruffner, C.M., and Abrams, M.D. 1998. Relating land-use history and climate to the dendroecology of a 326-year-old Quercus prinus talus slope forest. *Canadian Journal of Forest Research* 28: 347-358.

Runkle, J.R. 1982. Gap regeneration in some old-growth forests of the eastern United States. *Ecology* 63: 1533-1546.

Runkle, J.R. 1991. Gap dynamics of old growth eastern forests: management implications. *Natural Areas Journal* 11: 19-25.

Sander, I.L. 1977. Manager's handbook for oaks in the north central states. *Gen. Tech. Rep*. NC-37. St. Paul, MN: USDA Forest Service, North Central Forest Experiment Station. 35 p.

Sander, I.L., Johnson, P.S, Rogers, R. 1984. Evaluating oak advance reproduction in the Missouri Ozarks. *Res. Pap*. NC-251. Saint Paul, MN: USDA Forest Service. North Central Forest Experiment Station. 16 p.

Shugart, H.H., and West, D.C. 1977. Development of an Appalachian Deciduous Forest Succession Model and its Application to Assessment of the Impact of the Chestnut Blight. *Journal of Environmental Management* 5: 161-179.

Shugart, H.H., and West, D.C. 1979. Size and Pattern of Simulated Forest Stands. *Forest Science* 25: 120-122.

Shugart, H.H. 1984. *A Theory of Forest Dynamics: The Ecological Implications of Forest Succession Models.* Springer-Verlag, New York. 278 p.

Shugart, H.H. 2000. Forest Dynamics in the Montpelier Forest (Program Abstract). Managing to Create the Ancient Forest Conference, 18-20 May 2000, Sweet Briar, Virginia. Sweet Briar College, Sweet Briar, Virginia. Last Updated: 4 July 2000. Accessed: 31 May 2001 <http://nature.sbc.edu/forestconference/forestabstracts.html>.

Singer, M.T., and Lorimer, C.G. 1997. Crown release as a potential old-growth restoration approach in northern hardwoods. *Canadian Journal of Forest Research* 27: 1222-32.

Slocombe, D.S. 1993. Environmental planning, ecosystem science and ecosystem approaches for integrating environment and development. *Environmental Management* 17: 289-303.

Smith, D.M. 1986. *The Practice of Silviculture.* Eighth Edition. John Wiley & Sons, Inc., New York. 526 p.

Smith, H.C., and Miller, G.W. 1991. Releasing 75 to 80 year-old Appalachian hardwood sawtimber trees: 5-year DBH response. *Edited by* L.H. McCormick and K.W. Gottschalk. *In* Proceedings of the 8th Central Hardwood Conference, University Park, PA. *Gen. Tech. Rep*. NE-148. USDA Forest Service. Northeastern Forest Experiment Station. pp. 402-413.

Smith, H.C., Miller, G.W., Lamson, N.I. 1994. Crop-tree release thinning in 65-year-old commercial cherry-maple stands (5-year results). *Res. Pap.* NE-694. Radnor, PA: USDA Forest Service. Northeastern Forest Experiment Station. 11 p.

Stransky, J.J. 1990. Quercus stellata Wangenh. post oak. *In*: Burns, R.M., Honkala, B.H., (tech. Cords). Agricultural. Handbook. 654. Silvics of North America. Vol. 2. Hardwoods. Washington, DC: USDA Forest Service: 738-743.

Strong, T.F., Erdmann, G.G., Niese, J.F. 1995. Forty years of alternative management practices in second-growth, pole-size northern hardwoods. 1. Tree quality development. *Canadian Journal of Forest Research* 25: 1173-1179.

Swecker, P.L., Cauley, P.M., Van Dine, J.W., Conner, R.K. 1985. Soil Survey of Giles County, Virginia. USDA Soil Conservation Service. 136 pages plus maps.

TWC (The Weather Channel Website). 2002a. Averages and Records for Blacksburg, Virginia. Last Updated: 31 Mar 2002. Accessed: 31 Mar 2002 <http//:www. weather.com/weather/climatology/24060>.

TWC (The Weather Channel Website). 2002b. Averages and Records for State College, Pennsylvania. Last Updated: 31 Mar 2002. Accessed: 31 Mar 2002 <http:// www.weather.com/weather/climatology/monthly/USPA1575>.

TWC (The Weather Channel Website). 2002c. Averages and Records for Montpelier Station, Virginia. Last Updated: 17 Jun 2002. Accessed: 17 Jun 2002 <http//:www.weather.com/weather/climatology/monthly/USVA0516>.

TWC (The Weather Channel Website). 2002d. Averages and Records for Cumberland, Virginia. Last Updated: 17 Jun 2002. Accessed: 17 Jun 2002 <http://www. weather.com/weather/climatology/monthly/USVA0201>.

Tubbs, C.H. 1977. Manager's handbook for northern hardwoods in the north central states. *Gen. Tech. Rep*. NC-39. St. Paul MN: USDA Forest Service. North Central Forest Experiment Station. 29 p.

Tyrell, L.E., Nowacki, G.J., Crow, T.R., Buckley, D.S., Navertz, E.A., Niese, J.N., Rollinger, J.L., Zasada, J.C. 1998. Information About Old Growth for Selected Forest Type Groups in the Eastern United States. *Gen. Tech. Rep.* NC-197. St. Paul, MN: USDA Forest Service. North Central Forest Experiment Station. 507 p.

Urban, D.L. 1990. A Versatile Model to Simulate Forest Pattern: A User's Guide to ZELIG version 1.0. University of Virginia. 108 p.

USFS (United States Forest Service). 1998. Old Growth Forest Vegetation. Last Updated: 17 Apr 1998. Accessed: 20 Sep 2000 <http//:www.fs.fed.us/land/ fm/oldgrow/oldgrow.htm>.

Van Wagner, C.E., and Wilson, A.L. 1976. Diameter Measurement in the Line Intersect Method. *Forest Science* 22(2): 230-232.

Vanclay, J.K. 1994. *Modelling Forest Growth and Yield: Applications to Mixed Tropical Forests.* CAB International. 312 p.

Virginia Big Tree Program. 2001. Average and Maximum Life Spans for Virginia Trees. Last Updated: 28 Feb 2001. Accessed: 2 Jun 2001 <http//:www.fw.vt.edu/4h/bigtree/TreeAge.htm>.

Vora, R.S. 1994. Integrating old-growth forest into managed landscapes: A northern Great Lakes perspective. *Natural Areas Journal* 14: 113-123.

Welsh, J.E., Healy, W.M., DeGraaf, R.M. 1992. Cavity-Nesting Bird Abundance in Thinned Versus Unthinned Massachusetts Oak Stands. *Northern Journal of Applied Forestry* 9: 6-9.

White, D.L., and Lloyd, F.T. 1998. An Old-Growth Definition for Dry and Dry-Mesic Oak-Pine Forests. *Gen. Tech. Rep.* SRS-23. Asheville, NC: USDA Forest Service. Southern Research Station. 42 p.

Yamaguchi, D.K. 1991. A simple method for cross-dating increment cores from living trees. *Canadian Journal of Forest Research* 21: 414-416.

APPENDICES

Appendix A. Tree Parameters.

SCIENTIFIC NAME	S	N	SAP	E	G	C	DMAX	HMAX	AMAX	B2	B3	AINC	DDMIN	DDMAX	DT	WLTMX	LT_MIN
Acer pensylvanicum*	3	2	2	1	109.8	1.750	23	1002	30	76.7	1.700	0.01	2000	6300	0.5667	0.274	0.0
Acer rubrum***	3	3	3	1	213.8	1.570	151	3677	150	47.0	0.156	0.01	2000	12400	0.3222	0.450	0.9
Acer saccharinum*	2	1	2	0	164.8	1.570	122	3961	125	62.7	0.257	0.01	2200	9000	0.4000	0.187	0.9
Acer saccharum**	3	2	3	0	118.7	1.570	170	3355	400	37.8	0.111	0.01	2000	6300	0.5667	0.350	0.0
Asimina triloba****	3	2	3	0	227.2	1.750	30	1801	45	110.9	1.848	0.01	4200	9000	0.5667	0.274	0.0
Betula alleghanensis*	2	2	15	1	143.6	0.486	100	3057	300	58.3	0.291	0.01	2000	5300	0.6000	0.245	0.9
Betula lenta****	2	2	15	1	173.6	0.486	100	3057	250	58.3	0.291	0.01	2000	5300	0.6000	0.245	0.9
Carya cordiformis**	1	2	7	1	90.0	1.390	122	3651	200	57.7	0.237	0.01	3686	9461	0.9333	0.300	0.0
Carya glabra**	1	2	6	0	98.1	1.390	130	3349	300	49.4	0.190	0.01	4105	12652	0.9333	0.450	0.0
Carya tomentosa**	1	2	6	1	98.1	1.390	130	3349	300	49.4	0.190	0.01	4105	12652	0.9333	0.450	0.0
Castanea dentata***	2	3	0	0	195.2	1.750	122	2742	200	42.7	0.175	0.01	3686	8499	0.9333	0.450	0.9
Cornus florida**	3	2	3	1	88.7	3.200	38	914	100	40.8	0.536	0.01	3686	10947	0.4889	0.274	0.0
Fagus grandifolia***	3	2	3	0	87.7	2.200	161	3670	366	44.0	0.137	0.01	2100	6000	0.4889	0.350	0.0
Fraxinus pennsylvanica****	2	1	10	1	147.5	1.750	150	2447	300	30.7	0.102	0.01	2414	10947	0.4000	0.245	0.9
Juniperus virginiana***	1	3	3	0	88.7	2.000	60	1521	250	46.1	0.384	0.01	2966	10204	0.7000	0.450	0.0
Liriodendron tulipifera**	1	1	9	0	174.8	1.430	368	6083	300	32.4	0.044	0.01	3686	10947	0.7000	0.450	0.0
Magnolia acuminata****	2	2	9	1	174.8	1.430	368	6083	250	32.4	0.044	0.01	3686	10947	0.7000	0.450	0.0
Nyssa sylvatica**	3	2	2	1	56.2	1.310	92	1831	300	37.0	0.202	0.01	3686	12652	0.4889	0.274	0.0
Ostrya & Carpinus*	1	2	3	1	144.4	0.486	30	1526	150	92.2	1.530	0.01	2750	10300	0.9333	0.450	0.0
Oxydendrum arboreum**	3	2	3	0	133.4	1.310	91	3040	200	63.6	0.348	0.01	5526	8499	0.4889	0.274	0.0
Pinus strobus***	2	3	4	0	141.2	2.000	101	4567	450	87.8	0.435	0.01	2100	6000	1.0000	0.450	0.9
Pinus virginiana**	1	3	8	0	105.6	2.000	91	3658	300	77.0	0.421	0.01	5526	7366	1.2500	0.500	0.0
Prunus avium****	2	2	10	1	166.7	2.450	91	3046	258	64.0	0.352	0.01	3899	10945	0.5667	0.378	0.9
Prunus serotina***	2	2	10	1	166.7	2.450	91	3046	258	64.0	0.352	0.01	3899	10945	0.5667	0.378	0.9
Quercus alba***	2	3	10	0	72.0	1.750	121	3022	600	47.8	0.198	0.01	2966	10204	0.9333	0.450	0.9
Quercus coccinea***	2	2	10	0	66.6	1.750	147	2996	400	39.0	0.133	0.01	4105	8499	0.9333	0.450	0.9

Quercus prinus**	2	3	10	0	102.2	1.750	213	3044	400	27.3	0.064	0.01	3686	7756	0.9333	0.450	0.9
Quercus rubra***	2	3	10	1	107.7	1.750	100	3057	400	58.3	0.291	0.01	2400	9600	0.9333	0.450	0.9
Quercus velutina**	2	3	10	0	99.7	1.750	214	4591	200	41.6	0.097	0.01	3313	9461	0.9333	0.450	0.9
Robinia pseudoacacia**	1	2	2	1	239.5	0.486	152	4135	200	52.6	0.173	0.01	5526	7366	0.7000	0.450	0.0
Sassafras albidum**	3	2	2	0	107.5	1.430	61	2440	200	75.5	0.619	0.01	3686	10947	0.4889	0.274	0.0
Tilia americana*	3	1	3	1	169.8	1.600	137	4269	140	60.3	0.220	0.01	2300	6000	0.5667	0.290	0.0
Tsuga Canadensis*	3	3	3	0	86.0	2.000	151	3677	600	47.0	0.156	0.01	2416	6559	0.4889	0.245	0.0
Ulmus alata****	2	1	3	0	146.5	0.486	65	2999	200	88.1	0.678	0.01	5300	10000	0.4000	0.378	0.9

* = Tree species already included in the JABOWA model.
** = Tree species included in the FORET model.
*** = Tree species found in both JABOWA and FORET.
**** = Tree species not found in JABOWA or FORET (Parameter values for these species were determined by consulting *Silvics of North America* and through direct correlations with species of a similar genus and site type).

Please note that the biomass parameters (STEM, BARK, BRANCHES, ROOTS) were not included in the above tree parameter list because they were not used in the computer simulations.

Appendix B. Minor Species Modeling Results.

Craig Creek Road Site, Montgomery County, Virginia

	Diam Class (1-15 cm)			Diam Class (15.1-30 cm)			Diam Class (30.1-45 cm)			Diam Class (45.1+ cm)		
Species	**YM**	**SIM**	**OG**	**YM**	**SIM**	**OG**	**YM**	**SIM**	**OG**	**YM**	**SIM**	**OG**
Liriodendron tulipifera	319.5	0.0	0.0	55.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Others	127.8	12.0	79.9	8.0	0.0	24.0	0.0	0.0	0.0	0.0	0.0	0.0

Stony Creek Site, Giles County, Virginia

	Diam Class (1-20 cm)			Diam Class (20.1-40 cm)			Diam Class (40.1-60 cm)			Diam Class (60.1+ cm)		
Species	**YM**	**SIM**	**OG**	**YM**	**SIM**	**OG**	**YM**	**SIM**	**OG**	**YM**	**SIM**	**OG**
Carpinus caroliniana	0.0	0.0	95.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Others	79.9	35.9	55.9	0.0	0.0	8.0	8.0	0.0	24.0	0.0	0.0	0.0

Great Falls Park Site, Fairfax County, Virginia

Species	Diam Class (1-20 cm)			Diam Class (20.1-40 cm)			Diam Class (40.1-60 cm)			Diam Class (60.1+ cm)		
	YM	**SIM**	**OG**	**YM**	**SIM**	**OG**	**YM**	**SIM**	**OG**	**YM**	**SIM**	**OG**
Others	111.8	47.9	79.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Montpelier Site, Orange County, Virginia

Species	Diam Class (1-20 cm)			Diam Class (20.1-40 cm)			Diam Class (40.1-60 cm)			Diam Class (60.1-80 cm)			Diam Class (80.1 cm)		
	YM	**SIM**	**OG**	**YM**	**SIM**	**OG**	**YM**	**SIM**	**OG**	**YM**	**SIM**	**OG**	**YM**	**SIM**	**OG**
Others	47.9	12.0	0.0	16.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Turkey Ridge Natural Area Site, Cumberland County, Virginia

Species	Diam Class (1-15 cm)			Diam Class (15.1-30 cm)			Diam Class (30.1-45 cm)			Diam Class (45.1+ cm)		
	YM	**SIM**	**OG**	**YM**	**SIM**	**OG**	**YM**	**SIM**	**OG**	**YM**	**SIM**	**OG**
Liriodendron tulipifera	55.9	0.0	0.0	16.0	0.0	0.0	8.0	0.0	0.0	0.0	0.0	0.0
Cornus florida	311.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Others	79.9	47.9	119.8	16.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	8.0

Blue Ridge Parkway (Milepost 75) Site, Bedford County, Virginia

Species	Diam Class (1-15 cm)			Diam Class (15.1-30 cm)			Diam Class (30.1-45 cm)			Diam Class (45.1+ cm)		
	YM	**SIM**	**OG**	**YM**	**SIM**	**OG**	**YM**	**SIM**	**OG**	**YM**	**SIM**	**OG**
B. lenta, B. alleghaniensis	64.0	0.0	0.0	0.0	0.0	0.0	8.0	0.0	0.0	0.0	0.0	0.0
C. cordifomis, C. tomentosa	167.7	0.0	0.0	39.9	0.0	0.0	24.0	0.0	0.0	0.0	0.0	0.0
Others	0.0	119.8	151.8	0.0	0.0	47.9	0.0	12.0	31.9	0.0	0.0	0.0

Appendix C. Species Parameterization Percentages.

Site	Species on 1/12 ha	Species Simulated	% Parameterized
CCR	11	11	100.0
SC	10	8	80.0
GFP	17	14	82.4
DR	7	7	100.0
MONT	13	13	100.0
TRNA	13	13	100.0
BRP-75	13	13	100.0
Average			94.6

Appendix D. Management Plan & Silvicultural Suggestions.

<u>Craig Creek Road Site, Montgomery County, Virginia</u>

Year 1: **- Kill all red maple and yellow-poplar in stand (herbicides & logging).**

Year 80: **- Plant the following:**

- 48 black oak seedlings/ha
- 60 mockernut hickory seedlings/ha
- 264 blackgum seedlings/ha
- 300 eastern white pine seedlings/ha

- Log the following:

- 12 chestnut oaks/ha (15 - 30 cm)
- 24 chestnut oaks/ha (30 – 45 cm)

- Cull the following trees for wildlife habitat:

- 36 large class (45 + cm) chestnut oaks/ha

Year 90: **- Log the following:**

- 12 chestnut oaks and/or black oaks/ha (combined total) (15 – 30 cm)

- Cull the following trees for wildlife habitat:

- 12 chestnut oaks/ha (45 + cm)

Other considerations:

During the first 80 year growth period, red maple and yellow-poplar will need to be killed on a regular 10-15 year basis using herbicides (hack & squirt) for smaller diameter stems and single-tree logging for larger sized stems.

At year 1, instead of planting 264 blackgum/ha to match the composition and density of that species in the old-growth stand, planting of oak species (white, black, etc.) may be more beneficial over the long-term for successfully insuring the succession of oak species within this stand. This decision will be based on landowner objectives.

Logged/killed trees should be left on-site to provide adequate CWD for wildlife habitat, soil stabilization, water storage and nutrient storage.

Stony Creek Site, Giles County, Virginia

Year 1: **- Plant the following:**

- 72 northern red oak seedlings/ha

- Herbicide (hack & squirt) the following:

- 468 striped maple stems/ha (< 20 cm)
- 12 chestnut oak stems/ha (< 20 cm)

- Log the following:

- 12 chestnut oak stems/ha (40 – 60 cm)

Year 25: **- Plant the following:**

- 60 mockernut hickory seedlings/ha

- Herbicide (hack & squirt) the following:

- 204 red maple stems/ha (< 20 cm)

- Log the following:

- 12 northern red oak trees/ha (20 – 40 cm)
- 36 northern red oak trees/ha (40 – 60 cm)

Other considerations:

96 stems/ha of eastern hophornbeam exist in the old-growth stand in the (< 15 cm) diameter class. Rather than planting this amount to match the composition and density of this species in the old-growth stand, planting oak species (northern red, white, black, etc.) may be more beneficial over the long-term for successfully insuring the succession of oak species within this stand. This decision will be based on landowner objectives.

Logged/killed trees should be left on-site to provide adequate CWD for wildlife habitat, soil stabilization, water storage and nutrient storage.

Great Falls Park, Fairfax County, Virginia

Year 1: - Plant the following:

- 36 northern red oak seedlings/ha
- 192 American beech seedlings/ha
- 648 pawpaw seedlings/ha.

- Herbicide (hack & squirt) the following:

- 48 red maple stems/ha (< 20 cm)
- 60 blackgum stems/ha (< 20 cm)

Year 5: - Herbicide (hack & squirt) the following:

- 68 black oak/northern red oak/scarlet oak stems/ha (< 20 cm)
- 32 white oak/chestnut oak stems/ha (< 20 cm)
- 36 mockernut hickory/pignut hickory stems/ha (< 20 cm)
- 76 blackgum/red maple stems/ha (< 20 cm)

- Cull the following:

- 12 white oaks/ha (60.1 + cm)

Other considerations:

Chestnut oak and white oak are entirely absent in the lower middle diameter class (15 – 30 cm) in the old-growth stand but are present (24/ha) in the same diameter class in the younger stand. Logging these stems would allow this stand to better resemble its old-growth counterpart, but might not be the best decision if the landowner wants to insure succession of oak species within this stand into larger diameter classes.

Logged/killed trees should be left on-site to provide adequate CWD for wildlife habitat, soil stabilization, water storage and nutrient storage.

<u>Montpelier Estate Site, Orange County, Virginia</u>

Year 1: **- Herbicide (hack & squirt) the following:**

- 132 blackgum stems/ha (< 20 cm)
- 12 sassafras stems/ha (< 20 cm)
- 12 red maple stems/ha (< 20 cm)
- 156 pignut hickory stems/ha (< 20 cm)
- 72 yellow-poplar stems/ha (< 20 cm)

- Log the following:

- 12 blackgum stems/ha (20 – 40 cm)

- Cull or log the following:

- 12 blackgum stems/ha (40 – 60 cm)
- 12 pignut hickories stems/ha (60 – 80 cm)

Year 40: **- Plant the following:**

- 108 dogwood stems/ha
- 72 green ash stems/ha
- 48 pignut hickory stems/ha
- 252 American basswood stems/ha

- Herbicide the following:

- 36 yellow-poplar stems/ha
- 72 black oak stems/ha
- 36 chestnut oak stems/ha.
- all but 12 blackgum stems/ha
- all but 12 sassafras stems/ha
- all silver maple stems

- Log the following:

- 24 pignut hickory stems/ha (20 – 40 cm)
- 24 chestnut oaks stems/ha (20 – 40 cm)

- Cull or log the following

- 12 pignut hickory stems/ha (40 – 60 cm)

Other considerations:

At year 1, instead of planting blackgum, sassafras and red maple to match the composition and density of this species in the old-growth stand, planting oak species (northern red, white, black, etc.) may be more beneficial over the long-term for successfully insuring the succession of oak species within this stand. This same scenario occurs at year 40 with the planting of dogwood. The decision to plant oaks in lieu of the various shade tolerant species just listed will be based entirely on landowner objectives.

Logged/killed trees should be left on-site to provide adequate CWD for wildlife habitat, soil stabilization, water storage and nutrient storage.

<u>Turkey Ridge Natural Area Site, Cumberland County, Virginia</u>

Year 1: **- Plant the following:**

- 336 mockernut hickory seedlings/ha
- 224 eastern red cedar seedlings/ha
- 240 white oak seedlings/ha

- Herbicide (hack & squirt) the following:

- 84 yellow-poplar stems/ha (< 15 cm)
- 96 dogwood seedlings/ha (< 15 cm)
- all red maple stems were removed (< 15 cm)

- Log the following:

- all yellow-poplar stems (15-30 cm)
- all red maple stems (15-30 cm)
- 12 yellow-poplar stems/ha (30 – 45 cm)

Year 25: **- Plant the following:**

- 228 American basswood stems/ha
- 372 winged elm stems/ha
- 108 eastern red cedar stems/ha

- Herbicide (hack & squirt) the following:

- 52 blackgum/red maple stems/ha (< 15 cm)

- Cull the following:

- 8 white oak/northern red oak/black oak stems/ha (45 + cm)

Other considerations:

Logged/killed trees should be left on-site to provide adequate CWD for wildlife habitat, soil stabilization, water storage and nutrient storage.

<u>Blue Ridge Parkway (Milepost 75) Site, Bedford County, Virginia</u>

Year 1: **- Plant the following:**

- 60 northern red oak seedlings/ha

- Herbicide (hack & squirt) the following:

- 276 green ash stems/ha (< 15 cm)

- Log the following:

- 60 northern red oak stems/ha (15 – 30 cm).

Year 5: **- Herbicide (hack & squirt) the following:**

- 103 striped maple stems/ha (<15 cm)
- 16 northern red oak stems/ha (< 15 cm)

- Log the following:

- 12 northern red oak stems/ha (15 – 30 cm)

Other considerations:

Logged/killed trees should be left on-site to provide adequate CWD for wildlife habitat, soil stabilization, water storage and nutrient storage.

VITA – Lawton E. Grinter

Lawton E. Grinter was born February 25, 1976 in Alexandria, Virginia to Barbara M. and Lawrence E. Grinter. He has an older sister, Elizabeth N. Grinter of Orlando, Florida. Lawton spent the majority of his childhood in Gaffney, South Carolina. After graduation from Gaffney High School in 1994, Lawton attended Clemson University in South Carolina in pursuit of a Bachelor of Science degree in Forest Resource Management with a Minor in Aquaculture, Fisheries and Wildlife Biology. During his senior year at Clemson, Lawton interned with the United States Forest Service in Waldport, Oregon. He also worked under Dr. David Van Lear at Clemson University to complete his Senior Honors Thesis project, which involved characterizing the composition and structure of an old-growth hardwood stand in the Piedmont of South Carolina. It was this project that sparked an interest to pursue a graduate degree in the field of Forest Ecology. In December of 1998, he graduated from Clemson University cum laude with General and Departmental Honors. Upon graduation, he fulfilled a lifelong dream of hiking the entire length of the 2,160 Appalachian Trail in one continuous journey from March 21, 1999 to August 26, 1999. In the spring of 2000, he took a job with Ceimic Corporation in Narragansett, Rhode Island as a control scientist. In August of 2000, he started work at Virginia Polytechnic and State University towards a Master's of Science degree in Forestry (Forest Ecology) under Dr. Carolyn A. Copenheaver and Dr. Shepard M. Zedaker.