STAND STRUCTURE, GROWTH, AND MORTALITY IN SOUTHERN APPALACHIAN SPRUCE-FIR

by

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Dissertation submitted to the Faculty of the
Virginia Polytechnic Institute and State University
in partial fulfillment of the requirements for the degree of
Ph.D.
in
Department of Forestry

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April 1992
Blacksburg, Virginia

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(ABSTRACT)

Current stand structure and composition, biomass levels and distributions, stand level foliage surface area (LAI) estimations, and mortality and growth patterns were determined using consistent sampling methodology for a network of 142 (20 m x 20 m) permanent plots at three southern Appalachian spruce-fir sites (Mt. Rogers National Recreation Area (NRA) of Virginia, the Black Mountains of North Carolina, and the Great Smoky Mountains of Tennessee and North Carolina). Baseline conditions were documented to accommodate future efforts to determine actual phenomena of forest decline in a highly disturbed ecosystem. Information on structure, composition, and growth and mortality trends were combined to develop a model to predict forest change for the next two decades.

Past studies indicated that undisturbed spruce-fir species distribution tended to follow an elevation gradient: red spruce (*Picea rubens* Sargent) dominance changing to Fraser fir (*Abies fraseri* (Pursh) Poiret) dominance as elevation increased. Current stand composition at the Black Mountains and the Great Smokies also showed a shift from spruce to fir; however, Mt. Rogers NRA was an exception to that trend. As fir abundance increased with elevation there were increasing levels of balsam woolly adelgid-caused (*Adelgid piceae* Ratz.) mortality at the Black and Smoky Mountains where there was a greater proportion of standing dead fir than live fir. Unlike these two sites, Fraser fir on Mount Rogers still had escaped major damage from the adelgid.

Projected leaf area index (LAI)(m^2/m^2) was developed for spruce, fir and yellow birch (*Betula lutea* Michaux f.), based on predicted foliage weight from overstory biomass equations, as a quantifiable measure of forest productivity. Primarily old-growth spruce-fir stands at the Great Smoky Mountains had an average LAI (11.9) significantly greater than stands at Mt. Rogers NRA (9.1) or the Black Mountains (8.3) which both have a patchwork of disturbance histories. Some conversion to increased hardwoods may have occurred in second growth stands at lower elevations with a resulting lower leaf area capability. At higher elevations (1830-1980 m), LAI was predicted to decrease if the remaining adelgid-infested fir die for both virgin and logged sites.

Past studies have inferred information on mortality patterns from assessment of standing dead stems density. Overstory annual mortality was directly measured each year from 1985 and 1989 and found to vary among the four dominant overstory species; mountain-ash (*Sorbus americana* Marshall) had the highest rate (6.4 %), followed by fir (5.8 %), birch (2.7 %), and spruce had the lowest (2.1 %). Results suggested that enumerations of standing dead trees should not be used to assess mortality patterns since a substantial proportion (20-30 %) of all trees that died, fell to the ground in the same year, and were never part of the pool of standing dead stems. Comparisons of fir diameter distribution indicated that at sites where the balsam woolly adelgid was causing significant fir mortality, stand structure was shifting because of the elimination of larger (> 35 cm DBH) live fir stems. Prediction of individual tree mortality using logistic regression was unsuccessful for birch and mountain-ash, while equations to predict spruce and fir mortality depended on crown condition (amount of intact needles), as a predictor variable.

Since an accelerated rate of change in stand structure has been predicted to occur with increased mortality and reduced growth rates, a short-term (twenty year) projection model of forest composition and structure was developed. Individual tree basal area increment equations for red spruce, Fraser fir, and yellow birch, along with ingrowth and mortality information were combined to provide predictions starting from the year 1989 and ending in 2009. Where the adelgid has been dominating fir mortality patterns for several decades, such as in the Black Mountains, little overall change is expected. For most elevations basal area is projected to be stable while stem densities decrease. In the Smokies, where little fir is found at or below 1675 m elevation, stand structure is predicted to change little during the 20 year period. However, the highest elevations of the Smokies are predicted to eventually be similar to the current stand structure of high elevations of the Black Mountains. The adelgid infestation of the peaks of the central Smokies lagged by twenty-some years behind the Black Mountains and the model predicts a deterioration of fir as well as spruce in that area.

Acknowledgements

I would like to express my sincere gratitude to my major professor, S. M. Zedaker, for seven years of support and encouragement. I wish to express my appreciation to the other members of my graduate committee including D. W. Smith and H. E. Burkhart of the Department of Forestry, J. R. Webster of the Department of Biology, and P. S. White of the Department of Biology of the University of North Carolina at Chapel Hill. I would also like to thank several faculty members who graciously agreed to serve on my graduate committee but have since left the university on sabbatical leave or for other employment opportunities, including W. C. Johnson, E. T. Nilsen, and J. A. Scrivani. I am very appreciative of the flexibility shown to me by the School of Forestry and Wildlife Resources and for encouraging a non-forester to pursue a doctorate degree on a part-time basis.

I wish to also thank C. Eagar of the USDA Forest Service and T. Burk of the University of Minnesota as co-investigators of the Spruce-Fir Research Cooperative's *Site and stand characteristics of southern Appalachian spruce-fir* project for their helpful assistance and expertise.

This project would have been impossible without the help of the many research technicians and graduate students that assisted with the field work with a high level of professionalism, a tremen-

dous work ethic, and a terrific (and necessary) sense of humor, including: S. Adams, D. Awl, E. Barnhardt, L. Benton, T. Blount, B. Bruce, J. Burger, B. Cazell, D. Chapman, J. Cook, S. Crownover, M. Denny, S. Erwin, B. Fulcher, J. Goelz, M. James, J. McDonald, J. Montague, P. Moore, C. Murry, E. Pauley, S. Pilsk, T. Roach, L. Renfro, L. Richmond, R. Stevenson, S. Stiefel, D. Swift, K. Walter, R. Wightman, and A. Wilson. I especially want to thank A. C. Helm, P. Durr, S. Young, R. Underwood, and T. Ordway; I have been honored to work with these people. I must also acknowledge the many reliable work-study students who assisted with a large portion of the data entry and laboratory work.

I am indebted to several of the staff members of the Department of Forestry for their expertise and helpfulness throughout this research project including C. Barker, N. Chapman, B. Freyman, L. Fuller, K. Hollandsworth, P. Quarterman, S. Snow, L. Weber, and M. Whitescarver. I consider myself very fortunate to have been able to use the excellent resources of VPI & SU's Computing Center User Services and Statistical Consulting Center.

A number of land management agency units and their employees were very accommodating throughout this research effort including staff at the Mt. Mitchell North Carolina State Park, Mt. Rogers National Recreation Area of the Jefferson National ~~Park~~ Forest, Toecane District of the Pisgah National Forest, Great Smoky Mountains National Park, Blue Ridge Parkway, Asheville Water Authority, and Grayson Highlands Virginia State Park. In particular I wish to thank J. Sharp, T. McCree, K. Lawrence, L. Grimes, R. Carey, J. Abrell, and B. Teague.

I wish to express thanks for parents and brothers who provided endless optimism and reassurance throughout my formal education.

This research was supported by funds provided by the Southeastern Forest Experiment Station, within the joint US Environmental Protection Agency - USDA Forest Service Forest Response Program. The Forest Response Program was part of the National Acid Precipitation Assessment Program. This set of papers has not been subject to EPA or Forest Service policy review and should not be construed to represent the policies of either Agency.

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Introduction and Justification

Several studies in the past seven years have referred to a southern Appalachian red spruce (*Picea rubens* Sarg.) decline citing evidence of high mortality rates, decreased radial growth rates, and deterioration of crown condition (McLaughlin 1985, Adams et al. 1985, Federer and Hornbeck 1987, McLaughlin et al. 1987, Bruck and Robarge 1988, Bruck et al. 1989). Careful examination of the data indicates that any claims of spruce forest decline may be premature if based only on the evidence provided in those studies.

Spruce decline in the southern Appalachians has been reported but has not been well documented in refereed literature. With the exception of a paper on ice damage in the Black Mountains (Nicholas and Zedaker 1989) there has been no published work on mortality rates but instead reference to standing dead stems (Johnson and Siccama 1983, Dull et al. 1988, Bruck and Robarge 1988, Bruck et al. 1989). Dendrological evidence of a southern decline (Adams et al. 1985, McLaughlin et al. 1987, Van Deusen 1988) is still based on an analysis of increment cores from a small number of trees. In fact, analysis of larger data sets suggests far more moderate claims of growth decline than previous studies (Cook et al. 1992, LeBlanc et al. 1992). Unlike mortality and radial growth data, observation of crown deterioration in southern red spruce has been widely reported (Bruck and Robarge 1988, Zedaker et al. 1988, Bruck et al. 1989, Zedaker et al. 1989, Peart et al. 1992). However, sampling of crown condition is qualitative in nature and there is little evidence for the repeatability of the measurement or if appropriate statistical analyses for detecting real change even exist. Furthermore, there has been little investigation to determine what these subjective measurements indicate biologically.

The concept of decline is still poorly understood. Manion (1981) defines decline as a category of disease that is caused by the interaction of a number of interchangeable, specifically ordered abiotic and biotic factors to produce a gradual general deterioration, often ending in the death of trees. He suggests that there are sets of factors involved including predisposing (static factors that put a permanent stress on the plant), incitants (biotic or abiotic factors that produce a drastic injury), and contributing (persistent factors that directly impact the weakened host). Use of the term decline may indicate an incomplete knowledge of the system of interest. Manion suggests that with additional investigation, some declines may be linked to single causal agents.

Red spruce condition can, therefore, only be assessed within the context of its status in the forest. Red spruce and Fraser fir (*Abies fraseri* (Pursh) Poir.) forests have been characterized as highly shade tolerant and old-growth spruce-fir stands are usually uneven-aged. However, many stands were cut-over in the early twentieth century resulting in a patchwork of even-aged stands in some areas. Recent infestation (detected in the late 1950's) of the ecosystem by an exotic insect, the balsam woolly adelgid (*Adelges piceae* Ratz.), is rapidly eliminating mature fir. Consideration of just these two factors alone indicates that assessment of standing dead stems and crown intactness may be a simplistic methodology for detecting forest decline versus forest change.

The purpose of this study was to provide a more detailed assessment and mechanisms for future predictions of forest change by using forest composition, structure, mortality, and ingrowth to quantify both stand structure and recent growth patterns in three spruce-fir sites (Mt. Rogers National Recreation Area, the Black Mountains, and the Great Smoky Mountains). An evaluation of stand conditions at the initiation of this study (1985-1986) was compared to earlier published descriptions to consider if the existing status is ″normal″ (Chapter 1). Baseline levels of biomass levels and distribution and estimates of overstory foliage surface area were established so that future assessment of forest productivity will be readily quantifiable and can be compared to current conditions (Chapter 2). Stem survivorship patterns were scrutinized to determine if mortality predictions were possible from stem and stand characteristics and if past mortality patterns can be gleaned from enumerations of standing dead trees to provide a more complete picture of spruce-fir demographics (Chapter 3). Finally, growth and mortality data collected over a four year period (1985-1989) were then combined to develop a short-term (20 years) stand structure projection of southern Appalachian spruce-fir forests based on current rates of change (Chapter 4).

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Chapter I

A Comparison of Overstory Community Structure in Three Southern Appalachian Spruce-Fir Forests

ABSTRACT

The southern Appalachian spruce-fir ecosystem is described in terms of stand structure and comparisons of current status to descriptions of earlier studies at three sites: Mount Rogers National Recreation Area (NRA) of Virginia, the Black Mountains of North Carolina, and the Great Smoky Mountains of Tennessee and North Carolina. Community classification using two-way indicator species analysis delineated four forest types: SPRUCE, SPRUCE-BIRCH, SPRUCE-FIR, and FIR. Both the Mt. Rogers NRA and Black Mountains sites were patchworks of disturbance histories while the Smokies site was largely uncut. At second-growth plots the age of average dominant and codominant red spruce (*Picea rubens* Sarg.) ranged from 59-100 years while at the Great Smoky Mountains spruce mean age varied from 168-210. Distribution of basal area at the Smokies was skewed towards diameter distributions of greater than 45 cm DBH while

basal area at Mt. Rogers NRA and the Black Mountains was concentrated in trees with diameters of less than 45 cm. Past studies indicated that undisturbed spruce-fir species distribution tended to follow an elevation gradient: spruce dominance changing to Fraser fir (*Abies fraseri* (Pursh) Poiret) dominance as elevation increased. Current stand composition at the Black Mountains and the Great Smoky Mountains also show a shift from spruce to fir; however, Mt. Rogers is an exception to that trend. As fir abundance increases with elevation there are increasing levels of balsam woolly adelgid-caused (*Adelges piceae* Ratz.) mortality at the Black and Smoky Mountains where there is a greater proportion of standing dead fir than live fir. Unlike the other two sites, Fraser fir on Mount Rogers still have escaped major damage from the adelgid. But age structure of fir stands on top of Mount Rogers may result in high mortality rates in the near future.

INTRODUCTION

Three out of the seven southern Appalachian mountain areas with a well developed spruce-fir forest were selected as intensive study sites to evaluate current forest vigor and monitor long-term stand dynamics as part of NAPAP's (National Acid Precipitation Assessment Program) Forest Response Program. Interest in southern Appalachian spruce-fir forest health heightened after recent studies reported wide-scale forest deterioration in Europe (Schutt and Cowling 1985) and the decline of red spruce (*Picea rubens* Sarg.) in the northeastern United States in terms of higher mortality rates, progressive foliage loss, and a decrease in incremental growth rates (Siccama et al. 1982, Johnson 1983, Foster and Reiners 1983, Scott et al. 1984, Vogelmann et al. 1985). Potential causes of decline that have been suggested include gradual climatic change, insect pests, pathogens and diseases, stand dynamics, and/or atmospheric deposition.

In the past seven years, dendroecological evidence has also been presented indicating a decline in the annual growth of spruce in the southern Appalachians (Adams et al. 1985, McLaughlin et al. 1987). Bruck et al. (1989) also suggest that southern red spruce has recently experienced excessive needle loss. None of these studies evaluated characteristics of decline relative to the expected stand and tree behavior as a result of stand dynamics and the history of their development (Hyink and Zedaker 1987). Discerning the cause(s) of southern spruce-fir forest change is difficult due to several important factors including widely varying land use histories, catastrophic natural disturbances, and introduction of the balsam woolly adelgid (*Adelges piceae* Ratz.), a non-native pest of mature Fraser fir (*Abies fraseri* (Pursh) Poir.). Because of the devastating impact of the adelgid, infested fir stands even without a history of logging can no longer be described as undisturbed. Before thoughtful assessment of a change in forest condition can be made, it is essential that baseline conditions be described and an evaluation of current conditions relative to expected stand behavior be made. The specific objectives for this paper are to 1) quantify overstory characteristics and diameter distribution/age structure of southern Appalachian spruce-fir forests, and 2) make comparisons of current forest structure to descriptions published in earlier studies.

BACKGROUND

The three intensive research sites included in this study were: Mt. Rogers National Recreation Area (NRA) in Virginia (36° 40′ N, 81° 32 ′ W), the Black Mountains of North Carolina (35° 35′ N, 82° 15′ W), and the Great Smoky Mountains of Tennessee and North Carolina (35° 33′ N, 83° 32′ W)(Figure 1.1). The Mt. Rogers NRA study area encompasses all the spruce-fir forests in the Virginia Balsam Mountains including Mount Rogers and Pine Mountain, and a stand of red spruce on Whitetop Mountain. Mount Rogers/Pine Mountain contain the northernmost natural distribution of Fraser fir, a southern Appalachian endemic. The Black Mountains study area is confined primarily to the north-south ridge between Celo Knob and Black Mountain Gap. The research area in the Great Smoky Mountains is roughly 20 percent of the Smokies spruce-fir system concentrated between Newfound Gap and Clingman's Dome.

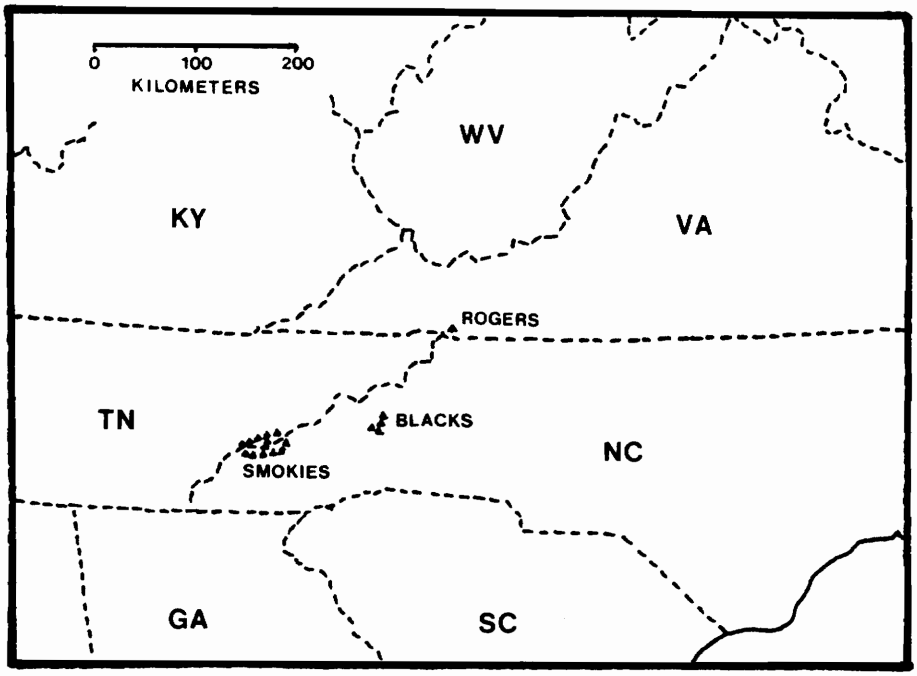

Figure 1.1. Location of the three study areas: Mt. Rogers National Recreation Area, the Black Mountains, and the Great Smoky Mountains.

Commercial logging and associated fires of the early 1900's have reduced the southern Appalachian spruce-fir to a fraction of its former range (Korstain 1937). Presently, the spruce-fir forest (defined as all areas containing dominant and codominant spruce and fir visible from aerial photography) in the southeast occupies 26,577 ha; seventy-four percent of the forest type was found to occur in the Great Smoky Mountains, with 11 percent in the Black Mountains and two percent at Mt. Rogers NRA (Dull et al. 1988). Logging of spruce began in the Mt. Rogers area in 1905 and was essentially finished by 1914-1917 (World War I). In the Black Mountains, spruce logging took place from approximately 1912 to 1927. At the Smokies, most logging took place during World War I, but unlike the other two sites, only a very small percentage of spruce-fir was ever cut (Pyle and Schafale 1988).

After logging was completed at the Black Mountains, a U.S. Forest Service reforestation experiment was initiated using spruce, fir, and eighteen exotic conifer species (Minckler 1940). Remnants of the red spruce, Fraser fir and Norway spruce (*Picea abies* [L.] Karst) plots still remain. Parts of the Cabin Ridge/Cabin Creek at Mt. Rogers NRA were also planted with Fraser fir for the purpose of Christmas tree farming. Tree cutting at Mt. Rogers NRA was halted in 1972 (Pyle and Schafale 1988), but since then the Forest Service has granted permission for individuals to remove Fraser fir seed, seedlings and saplings for commercial Christmas tree farming.

A more recent major disturbance factor is the balsam woolly adelgid (BWA). First detected in the southern Appalachians on Mt. Mitchell (the highest peak in eastern North America at 2037 m) in the Black Mountains in 1957 (Speers 1958), this European native insect pest of *Abies* is suspected to have arrived in the southern mountains in the 1930s via reforestation experiments. Mature Fraser fir is highly susceptible to adelgid attack with death occurring in two to nine years (Amman and Speers 1965, Amman 1970). Total BWA infestation of the Black Mountains occurred a few years after initial detection (Nagel 1959). The Mt. Mitchell infestation then spread to the Fraser fir communities throughout the southern Appalachians. First detection of infestation in the Smokies occurred at Mt. Sterling in 1963 (Ciesla et al. 1963) and infestation of the Mt. Rogers area was projected (using stem analysis) to have occurred by 1962 (Eagar 1984).

It has been suggested that atmospheric deposition may predispose Fraser fir to BWA-caused mortality (Hain and Arthur 1985). However, substantial adelgid-caused fir morality in the pristine Pacific Northwest (Mitchell 1966) and elsewhere offers strong evidence that BWA is a primary pest of fir. In addition, the only indication of possible resistance to adelgid impact has been found on Mt. Rogers where cloud chemistry studies indicate that air quality is comparable or inferior to other mountains sites with fir that does succumb to the BWA (Mohnen, 1992). Furthermore, Tyszko (1991) carried out an ozone fumigation study using fir seedling sources from different southern sites and found that carbon dioxide response curves in the particular seed sources responded differently to ozone exposure: Mt. Mitchell seedlings tended to increase carboxylation efficiency, compensation point, and stomatal limitations, while Mt. Rogers seedlings reduced carboxylation efficiency and stomatal limitations with increasing ozone dose. These initial findings would seem contradictory to the idea of an ozone-adelgid susceptibility interaction since Mt. Rogers fir seedlings seem to have a lower respiration sensitivity to ozone fumigations but trees at Mt. Rogers are the most resistant to the adelgid. It is more likely that fir genetics and site conditions are related to resistance to adelgid impact. Eagar (1984) observed that bark on infested fir at Mt. Rogers was more hardened and had a thicker rhytidome then uninfested trees elsewhere on Mt. Rogers or on infested fir at the Great Smoky Mountains. He suggested that Mt. Rogers fir might have a genetically based ability to rapidly form wound periderm around adelgid feeding sites which prevents diffusion of insect secretions into the tree's xylem. In a more recent study, Hollingsworth (1990) found that adelgid infestation of fir trees at Mt. Rogers induced outer bark formation, leading to tree recovery, a phenomenon not observed at other sites.

The initial wave of BWA-caused mortality of Fraser fir is nearly complete (Eagar 1984). In the Black Mountains, almost all mature Fraser fir have died except for a 120 ha area sprayed with pesticide until 1974. The formerly protected area (which accounts for most of the live fir in the

Black Mountains study area) has been heavily infested and shows signs of increased mortality. Fir growing in a 10 ha area on Clingman's Dome in the Smokies is still sprayed annually; however, the stand is starting to show significant impact by the adelgid. At Mt. Sterling, in the Smokies, understory fir are now approaching a life stage that can support adelgid populations. Eagar (1984) suggested that a cyclic situation will develop: initial infestation followed by limited recovery and then regeneration reinfestation, with a complete cycle on the order of 35-60 years.

METHODS

In 1985 and 1986, a stratified, randomly located, permanent plot system was established in the Black Mountains (40 plots), Mt. Rogers NRA (23 plots), and the Great Smoky Mountains (66 plots). Stratification factors included elevation (four classes: 1525, 1675, 1830, 1980 m, ± 30 m), exposure to prevailing winds (exposed versus protected), and topographic type (ridge/slope/draw) with three replicates per strata combination wherever possible. An *a priori* definition of the southern spruce-fir type required that plots (20 x 20 m^2) had to have at least 25 % spruce and/or fir present (live) or former (dead standing stems) canopy coverage. Overstory strata (defined as woody stems with diameter at breast height [DBH] $\geq$ 5.0 cm) measurements by species included DBH (measured to the nearest mm), inspection for crown condition (live versus dead), and disturbance symptomology (signs of disease or damage to stems) for every tree on each plot. All qualitative observations were made by at least two technicians for each tree, with occasionally a third technician called in as a tie-breaker. Ten, random, intact dominant or codominant spruce or fir stems were cored for age at 15 cm below DBH. Logging history of each plot was determined using maps from Pyle and Schafale (1988) as well as on-site inspection. Site data recorded at each plot included elevation, slope percent, aspect, macro- and micro-topographic features.

Overstory community classification using two-way indicator species analysis (TWINSPAN) (Hill 1979a) of basal area by species was used to delineate forest types. TWINSPAN, a polythetic divisive technique, makes repeated dichotomies by ordinating the data using reciprocal averaging until the sample-units are placed in a hierarchy (i.e. dendrogram) ranging from the total collection to individual sample-units. A dendrogram is produced with integer levels to express relative cluster similarity (Gauch and Whittaker 1981). From this dendrogram forest composition groupings were selected using species with maximum indicator value to define the selected clusters. Indirect ordination analysis was carried out using detrended correspondence analysis (DECORANA) (Hill 1979b). DECORANA summarizes the species composition of samples in various segments of the gradient and develops an arrangement such that equal differences in species composition corresponds to equal differences along the gradient (Hill and Gauch 1980). Site variables including elevation, slope percent, and transformed aspect (Beers et al. 1966), were investigated using regression analysis of the indirect ordinates to determine if site variables explained the distribution.

RESULTS AND DISCUSSION

Forest Types

Historically the high elevation coniferous forests of the southern Appalachians have been referred to as the spruce-fir forest type (Oosting and Billings 1951, Ramseur 1960). Others have described subtypes of the forest but most of those descriptions are based on very restricted in extent and intensity of sampling or limited to just one study area. Davis (1930) referred to the Spruce-Fir Forest Formation of the Black Mountains and divided it into a spruce-fir climax association; a secondary succession community of fire cherry (*Prunus pensylvanica* L.f.), yellow birch (*Betula lutea* Michaux f.), and *Rubus*; and a transition forest of spruce, birch, and red oak (*Quercus rubra*

L.).Cain (1935) described two forest types: the Red Spruce Type and Southern Balsam Fir Type (actually he referred to them as *Piceetum rubentis* and *Abietum fraseri* following the Braun-Blanquet (1932) method of naming plant communities). Similar to Cain, Whittaker (1956) described the southern Appalachian subalpine forest center in the Smokies as including red spruce and Fraser fir forest types, and a heath bald type. Crandall (1958) determined four forest types in the Smokies: fir, spruce-fir, spruce, and spruce-hardwoods. She also divided those four types into ten site types based on understory community composition patterns. The Society of American Foresters (Eyre 1980) recognizes three forest types: red spruce, red spruce-Fraser fir, and red spruce-yellow birch. For the Virginia Balsam Mountains (Mt. Rogers and Whitetop), Rheinhardt and Ware (1984) described three forest types where the overstory included at least 25 percent spruce or fir: spruce-fir, spruce, and yellow birch.

In this study a total of nineteen woody species were recorded in the overstory. The TWINSPAN analysis for the three study sites produced a dendrogram of four forest types: SPRUCE, SPRUCE-BIRCH, SPRUCE-FIR, and FIR. This grouping was most similar to Crandall's (1958) four forest types. The SPRUCE type had an average basal area of 63.7 m^2/ha with red spruce accounting for 83 % of the basal area (Table 1.1). The type was found at the Blacks and the Smokies with the vast majority of plots found at 1525 m elevation. All SPRUCE plots were unlogged except for one pure red spruce plantation.

The SPRUCE-BIRCH type had an average basal area of 48.0 m^2/ha with red spruce and yellow birch combined account for 93 % of the basal area (Table 1.1). The type was predominantly found at the Smokies, but was also represented at the Blacks, and on Whitetop of the Mt. Rogers NRA. Within the SPRUCE-BIRCH type were two subtypes with indicator species of FIRE CHERRY and BASSWOOD (*Tilia heterophylla* Vent.)/BUCKEYE (*Aesculus octandra* Marsh.). All of the BASSWOOD/BUCKEYE subtype was on unlogged stands while most of the FIRE CHERRY subtype was found on previously logged or burned areas.

Table 1.1. Overstory species[1] average basal area in four TWINSPAN community types (N = 129 plots). The order of types follows a decreasing total basal area for spruce-fir types in the southern Appalachian Mountains.

Species		**Spruce**	**Spruce-Birch**	**Spruce-Fir**	**Fir**
	n =	17	62	32	17
		(..................	m²/ha	....	..........)
Picea rubens		52.7	36.1	19.9	3.4
Abies fraseri			.7	16.6	25.0
Betula lutea		5.1	8.5	1.0	1.8
Tsuga canadensis		2.5	*		
Acer rubrum		1.6			
Rhododendron species		.4	.1	*	*
Fagus grandifolia		.4	.1		.2
Acer pensylvanicum		.3	.1		
Amelanchier arborea var. laevis		.3	*		*
Prunus serotina		.2	.2		
Ilex ambigua var. montana		.1	*		*
Kalmia latifolia		*			
Acer saccharum		*	.4		*
Prunus pensylvanica		*	.5	*	.2
Sorbus americana		*	.8	.3	2.5
Magnolia fraseri		*			
Aesculus octandra			.2	*	
Quercus rubra			*		
Tilia heterophylla			*		
Betula papyrifera var cordifolia			*	*	
Vaccinium species					*
Total Mean Basal Area =		63.8	48.0	37.9	33.2

* Present but less than 0.1 m²/ha.

[1] Nomenclature follows Radford et al. (1968).

The SPRUCE-FIR type had an average basal area of 37.9 m^2/ha with red spruce and Fraser fir accounting for 53 % and 44 % of the total basal area, respectively (Table 1.1). Most of the type was found at the Great Smoky Mountains and Mt. Rogers NRA. All Smokies plots were unlogged and all plots at Rogers were unlogged or were former Fraser fir plantations. Plots were primarily at higher elevations, except for the fir plantations and occurred at all three topographic types on both exposed and protected sides of the mountains.

The FIR type had an average basal area of 33.2 m^2/ha with Fraser fir accounting for 75 % of the basal area (Table 1.1). Most of this type was found at the Black Mountains and Mt. Rogers NRA. Plots were primarily at high elevations and on ridgetops except for the Mt. Rogers fir plantations.

The distribution of the four types on the primary DECORANA axis (eigenvalue of .623) was best explained by a linear combination of elevation and slope percent in a regression analysis yielding an r^2 value of .413 ($p < .0001$). No combination of quantifiable environmental characteristics explained the type distribution on the secondary axis (eigenvalue of .224); graphically however, the stands with substantial human-caused disturbance seemed clustered at one end of the secondary gradient.

Diameter and Age Distribution

Overstory stem diameter distributions were determined for each of the three study areas for four elevation classes (1525 m, 1675 m, 1830 m, and 1980 m) and two disturbance classes: unlogged versus logged. Eighteen size classes of 5 cm increments were used from 5 to 95 cm DBH (midpoints: 7.5 cm, 12.5 cm, 17.5 cm, ... 92.5 cm). Stand age distribution was determined in 25 year classes. In general, the Great Smoky Mountains distribution of basal area (with all plots in unlogged sites) was skewed towards stem diameters greater than 45 cm DBH (Figure 1.2), while basal area at the Black Mountains and Mt. Rogers NRA for both logged and unlogged areas was concentrated in trees with diameters of less than 45 cm (Figures 1.3-1.4). Because of a complex historical landownership, cutting patterns varied from tract to tract. Average age of spruce and fir in uncut stands also differed among study sites (Table 1.2). Unlogged stands in the Smokies were significantly older than unlogged stands in the other two sites.

Age distributions were compared for logged versus unlogged sites and showed a skewing of age distribution of logged stands primarily in the 25-75 year old range, while unlogged stands showed a normal distribution (Figure 1.5). In a balanced uneven-aged stand, we initially expect to see a inverted J-shaped distribution (based on density versus DBH) (Smith 1986). Both spruce and fir are shade tolerant and spatially small canopy gaps have been found to dominate the natural disturbance regime of southern Appalachian old growth spruce-fir forests (White et al. 1985). White et al. found that 6-17 % of their study area in the Smokies was classified as 1-10 year old canopy gaps. We might assume that for gap capture, there would have to be a substantive population of smaller size class gap successors. However, for these data, the unlogged sites age distribution in Figure 1.5 is missing younger age classes. One suggestion for the bell-shaped distribution might be that since spruce and fir are highly shade-tolerant, DBH and age are not strongly correlated. However, Nicholas and Zedaker (1992) did find some correspondence between the two variables in that the coefficient of variation for age within 10 cm DBH classes ranged from 35 to 15 % and decreased with increasing stem diameter.

Another reason for the unexpected bell-shaped age distribution might be that old growth spruce-fir stand regeneration is driven by both allogenic (abiotic) and autogenic (biotic) forces. Viable seed production is somewhat sporadic; large fir seed crops occur in 2-4 year intervals and large spruce crops occur every 3-8 years. The majority of seeds for both species are usually empty (USDA Forest Service 1974). Glaze storms damage the tops of spruce and fir (Nicholas and

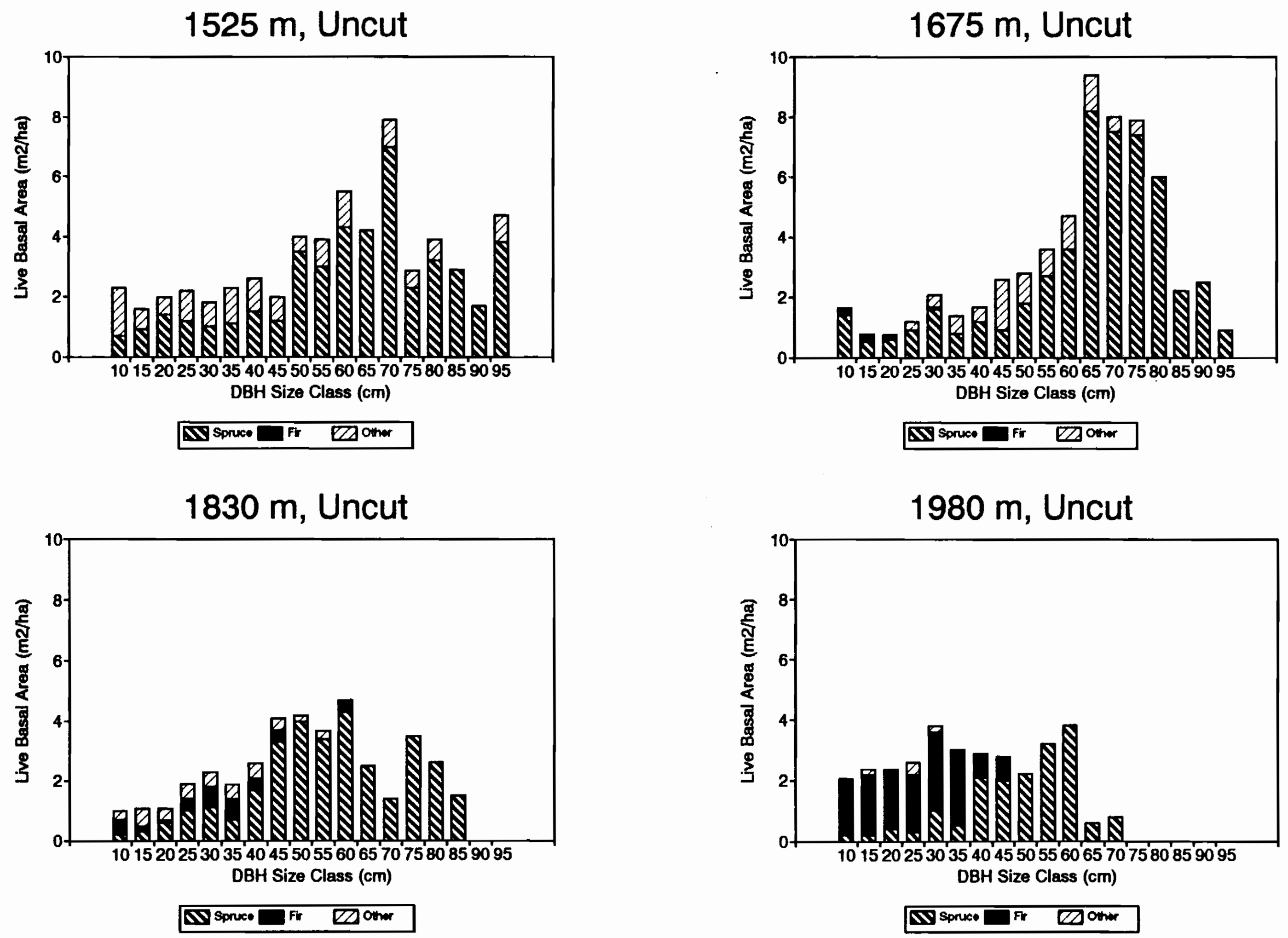

Figure 1.2. Stand diameter distribution for uncut stands at four elevations for the Great Smoky Mountains of Tennessee and North Carolina.

Table 1.2. Average stand age and standard error for four elevation classes and two disturbance classes at three southern spruce-fir sites.

Elevation	LOGGED Spruce	 Fir	UNLOGGED Spruce	 Fir
(m)	(. . . . . years		. . . .)	
	MT. ROGERS NATIONAL RECREATION AREA			
1525	98 ± 15	42 ± 2	105 ± 7	-
1675	59 ± 6	72 ± 6	127 ± 8	83 ± 5
	BLACK MOUNTAINS			
1525	79 ± 7	-	115 ± 3	-
1675	68 ± 3	-	141 ± 8	-
1830	59 ± 3	38 ± 2	-	-
1980	101 ± 44	56 ± 7	135 ± 50	-
	GREAT SMOKY MOUNTAINS			
1525	-	-	199 ± 11	-
1675	-	-	201 ± 33	-
1830	-	-	210 ± 10	-
1980	-	-	168 ± 11	137 ± 36

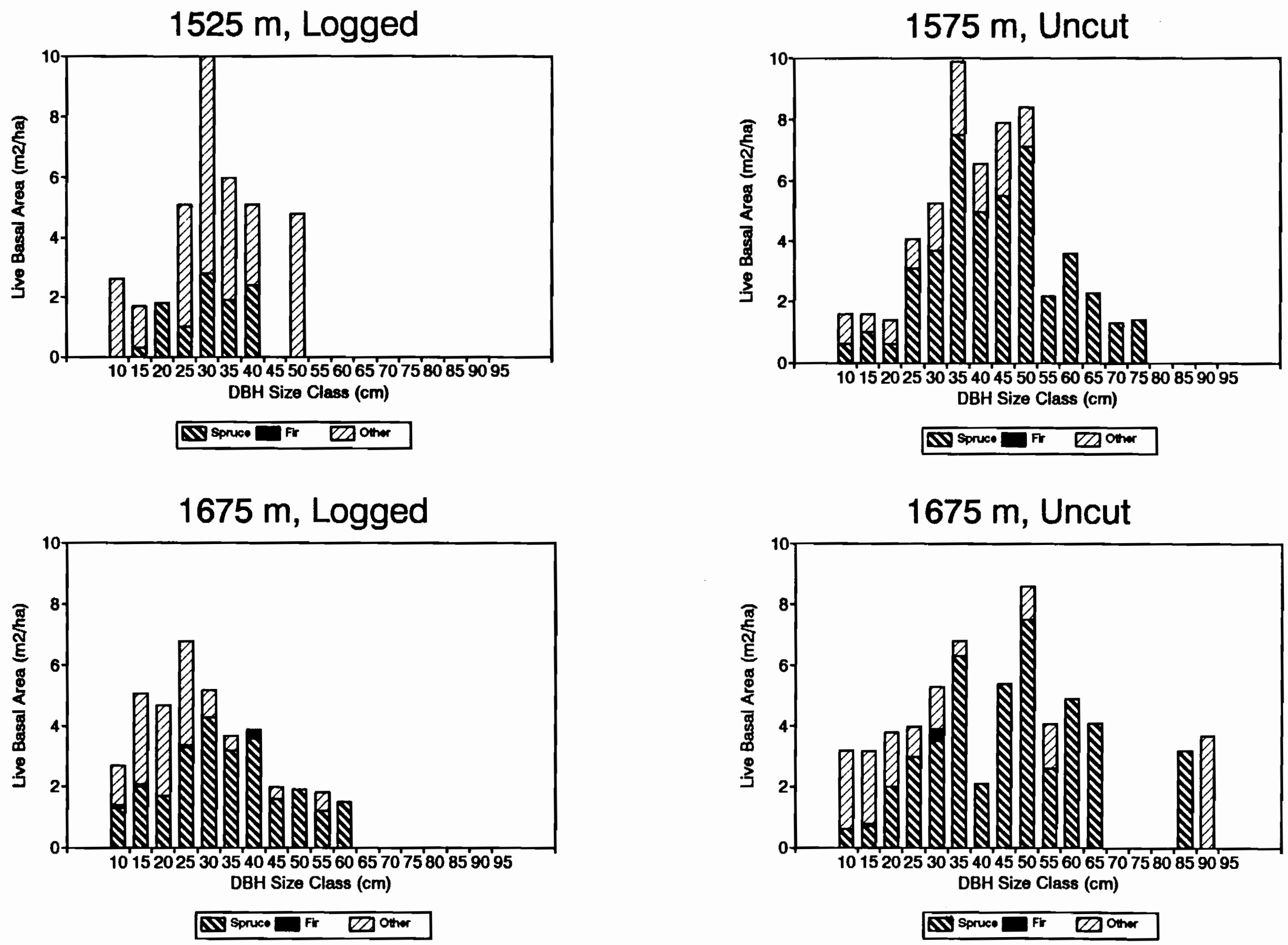

Figure 1.3. Stand diameter distribution for logged stands and uncut stands at four elevations for the Black Mountains of North Carolina.

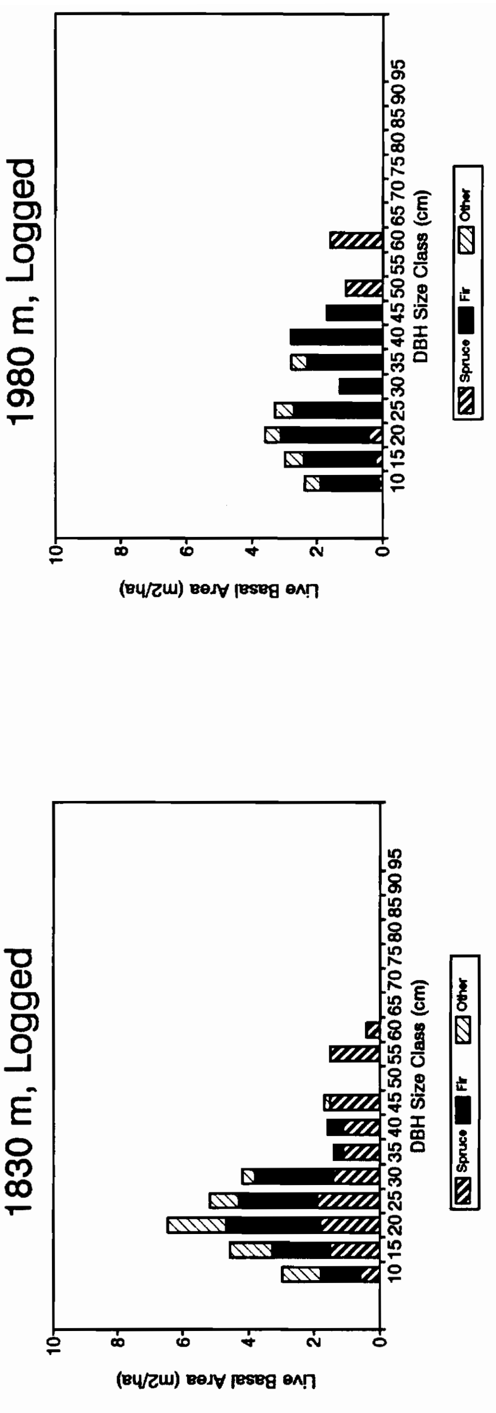

Figure 1.3. cont.

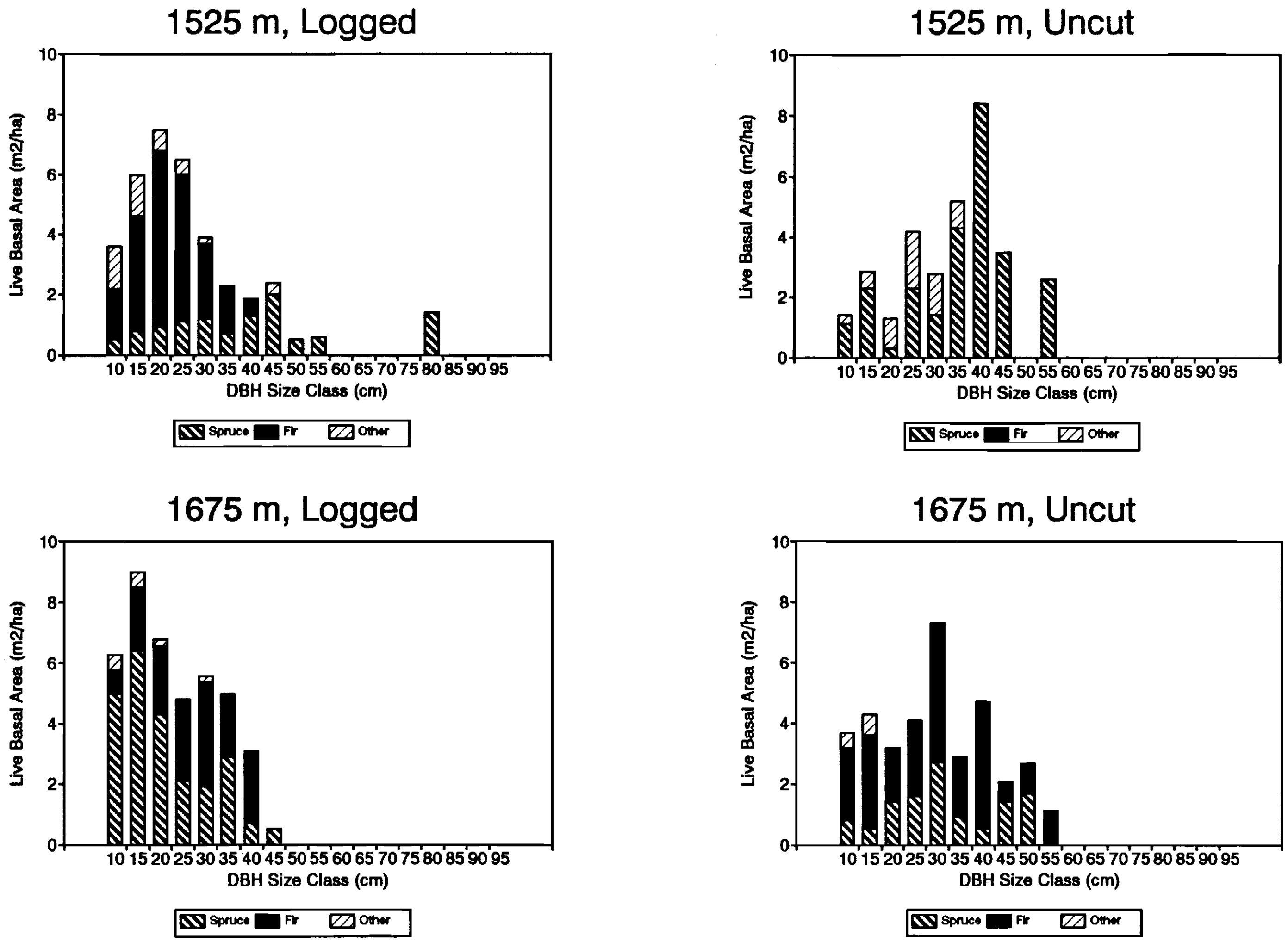

Figure 1.4. Stand diameter distribution for logged stands and uncut stands at two elevations for Mt. Rogers National Recreation Area, Virginia.

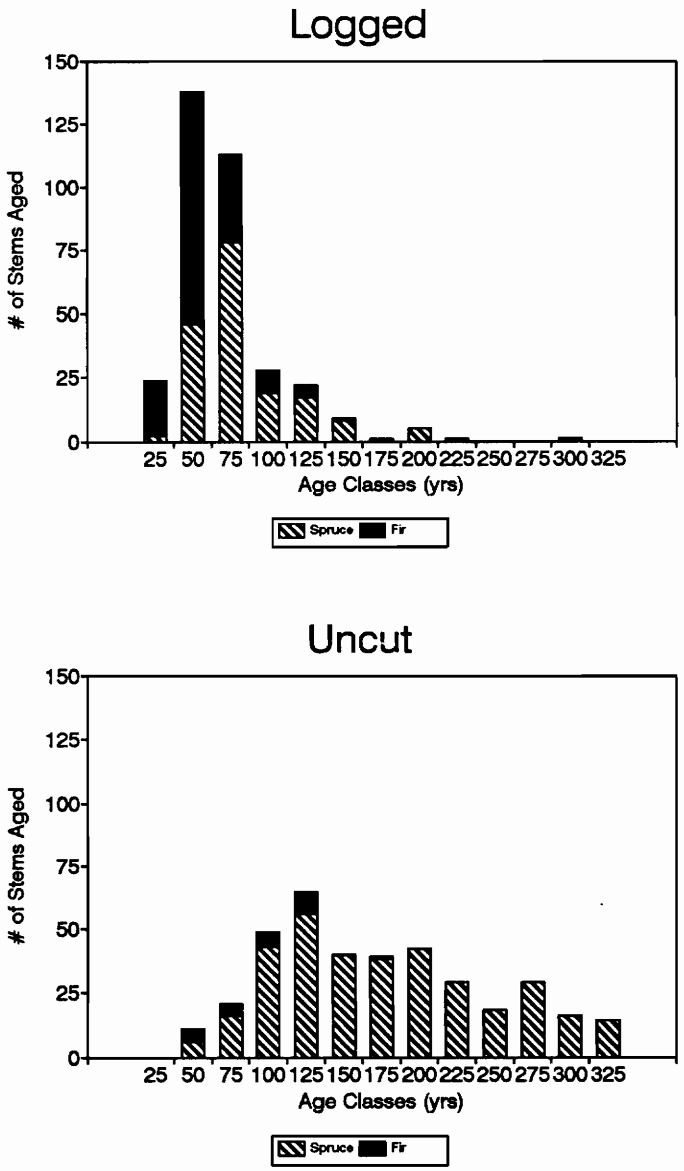

Figure 1.5. Stand age distribution for logged stands and uncut stands at Mt. Rogers National Recreation Area, the Black Mountains, and the Great Smoky Mountains.

Zedaker 1989) where cone production is greatest. Nicholas and Zedaker (1989) suggest that ice storms in high elevation forest dynamics are probably not uncommon. Nicholas et al. (1992) found the germination rate for viable southern red spruce seeds to be 5 to 28 % and only a 3 % germination rate for viable Fraser fir seed. They also found low survivorship success of spruce and fir germinals, suggesting that the unfavorable climatic conditions (summer droughts) during their study may have affected the young seedlings. Therefore, while large seed crops may occur several times during a ten-year period, additional factors such as low seed viability, low germination rates, and variable germinal survivorship rates may result in sporadic and infrequent successful regeneration.

Examination of each study site separately revealed that stem diameter distribution of the unlogged Smokies, at the highest elevation (1980 m), was fairly evenly distributed among classes up to 60 cm DBH (Figure 1.2). The hardwood component of total live basal area decreased with increasing elevation: hardwoods contributed 23 % of total basal area at 1525 m decreasing to 4 percent at 1980+ m. Fir contribution increased with increasing elevation: no fir was found at 1525 m to 44 % fir basal area at or above 1980 m. The adelgid had already killed the normally small fir component at the lower elevations. Most cored dominants and codominants were red spruce due to the tremendous impact of the BWA. Average stand age showed little variation with elevation except at the highest elevation class (1980 m) (Table 1.2).

Size class distributions for logged stands at 1525-1830 m elevations in the Black Mountains were skewed toward smaller stems with most stems less than 35 cm DBH (Figure 1.3). For logged stands at 1525 m, 73 % of the live basal area was represented by hardwoods and those stands had only two-thirds of the live basal area of uncut stands at the same elevation. The hardwood component of logged stands at 1675 m elevation was reduced to a third of the live basal area, and those logged stands had only 63 % of the basal area of unlogged stands at the same elevation. In the Black Mountains, Fraser fir was not a dominant or codominant at or below 1675 m elevation; but, at and above 1830 m, fir made up the majority of intact dominant and codominant stems and most were less than 75 years in age. Few undisturbed sites in the Black Mountains were located at or above 1830 m. The hardwood component of cutover stands at 1830 m was 21 %, with fir contributing 37 % of the live basal area and red spruce contributing 42 percent. At the high peaks (1980+ m) diameter size distribution was more evenly distributed than at lower elevation with Fraser fir comprising three-quarters of stand live basal area.

Like the Black Mountains, size class distributions for logged stands at Mt. Rogers NRA were skewed toward smaller stems (Figure 1.4). Fir at lower elevation (1525 m), logged sites at Mt. Rogers NRA made up 58 % of the live basal area component compared to an absence of fir in the uncut lower elevation plots. Except for parts of the northern slopes of Mt. Rogers proper, most of the lower elevation sites at Mt. Rogers NRA have been cut. Much of the lower elevation fir was suspected to have been planted and are under 50 years of age, and the scattered large spruce (DBH 40-89 cm) may have been left during cutting to provide shade for the fir seedlings. At the higher elevations of Mt. Rogers, there was little evidence of Christmas tree planting and unlike the Black Mountains and Great Smoky Mountains, there is limited evidence of BWA impact although the insect is present in high numbers. At uncut, low elevation sites (1525 m) there was no fir, while at uncut high elevation (1675 m) there were few hardwoods. Average fir age near the top of Mt. Rogers is 72 years with a fir age class maximum of 125 years. Since Fraser fir is a short-lived species and has an average maximum age of 150 years (Oosting and Billings 1951), it is suspected that much of the overstory fir will begin to senesce in the next decade.

Stand Structure Comparisons

Within undisturbed southern spruce-fir forests in the Great Smoky Mountains, species distribution tended to follow an elevation gradient: spruce forest from 1370 to 1675 m, spruce-fir from 1675 to 1890 m, and fir forest from 1890 m and higher (Whittaker 1956). Detailed descriptions of other southern spruce-fir sites prior to logging are nonexistent. Current stand composition at the Black Mountains and the Great Smoky Mountains (Tables 1.3 and 1.4) also show a shift from spruce to fir as elevation increases. The Mt. Rogers NRA site is an exception to the species composition trend (Table 1.5) for several probable reasons. Much of the lower elevation slopes in the study site were planted with Fraser fir for Christmas tree plantations. Fir is absent from Whitetop Mountain, the site of 25 % of the higher elevation plots for this study. Based on a hypothesis of Whittaker (1956), both White et al. (1984) and Rheinhardt (1984) suggest that a slight shifting in ecotonal boundaries upward in the last post-Wisconsin xerothermic period may have led to the elimination of fir on Whitetop (peak: 1672 m) but not on Mt. Rogers (peak: 1746 m). Maximum elevation at Mt. Rogers NRA is several hundred meters lower than in the Blacks or Great Smoky Mountains. And unlike the other study sites, the Mt. Rogers area is not contained within a distinct mountain range. Landscape roughness (Z_o, Satterlund 1972) is probably lower than other sites with well-developed spruce-fir forests. Increased landscape roughness increases the rate of atmospheric convective heat transport which increases the adiabatic cooling rate of air (Satterlund 1972). The Mt. Rogers area with its gentle slopes, limited maximum height, and small active surface, may not have enough of an elevation differential and landscape roughness to provide conditions similar to high mountain peaks where fir dominates.

Data are limited but comparison of this data to the very few earlier quantitative studies is appropriate to determine if and how the forest has changed. Cain (1935) sampled two sites in the Great Smoky Mountains, one at 1555 m representing an old-aged red spruce stand sampled in 50 10 x 20 m plots and another at 1921 m representing a pole fir stand with substantial density-induced mortality sampled in ten 10 x 20 m plots (Table 1.6a). While Cain did not include density or standing dead tree information and was rather vague on stem size lower limits for inclusion in sampling, his data do indicate a predominance of fir at higher elevations as well as a decrease in total basal area as elevation increased.

Table 1.3. Live and dead basal area and density means and standard error, stratified by elevation, of red spruce, Fraser fir, and all overstory species for 40 permanent plots (data collected in 1985 and 1986) at the Black Mountains, North Carolina.

	ELEVATION							
	1525 m		1675 m		1830 m		1980 m	
	BA	Density	BA	Density	BA	Density	BA	Density
	m^2/ha	stems/ha	m^2/ha	stems/ha	m^2/ha	stems/ha	m^2/ha	stems/ha
Live								
Spruce	41.9 ± 9.1	603 ± 100	32.0 ± 5.3	760 ± 99	13.0 ± 3.4	457 ± 114	3.4 ± 1.5	75 ± 10
Fir	- -	15 ± 12	0.4 ± .2	38 ± 19	11.4 ± 3.8	675 ± 235	17.6 ± 5.7	913 ± 251
Total	56.7 ± 6.2	1216 ± 151	46.8 ± 4.0	1717 ± 184	30.6 ± 2.9	1672 ± 236	23.8 ± 6.2	1188 ± 296
Dead								
Spruce	1.6 ± .6	88 ± 25	2.0 ± .6	81 ± 21	3.1 ± 1.4	63 ± 21	5.2 ± 5.2	75 ± 75
Fir	- -	- -	.3 ± .2	6 ± 4	6.1 ± 1.6	267 ± 77	21.7 ± 4.9	1141 ± 625
Total	3.9 ± .8	206 ± 41	9.2 ± 2.2	410 ± 42	15.4 ± 2.4	698 ± 105	29.2 ± 4.7	1388 ± 645

Table 1.4. Live and dead basal area and density means and standard errors, stratified by elevation, of red spruce, Fraser fir, and all overstory species for 66 permanent plots (data collected in 1985 and 1986) at the Great Smoky Mountains, North Carolina and Tennessee.

	ELEVATION							
	1525 m		1675 m		1830 m		1980 m	
	BA	Density	BA	Density	BA	Density	BA	Density
	m^2/ha	stems/ha	m^2/ha	stems/ha	m^2/ha	stems/ha	m^2/ha	stems/ha
Live								
Spruce	46.0 ± 5.1	504 ± 71	50.6 ± 3.2	347 ± 35	32.2 ± 3.7	269 ± 31	17.2 ± 3.5	175 ± 19
Fir	.1 ± .1	10 ± 10	.5 ± .4	65 ± 39	3.8 ± 1.6	196 ± 60	14.3 ± 2.0	821 ± 214
Total	59.7 ± 4.8	829 ± 89	60.3 ± 2.7	533 ± 66	40.0 ± 2.9	638 ± 65	32.7 ± 1.8	1077 ± 244
Dead								
Spruce	4.7 ± 1.8	64 ± 17	4.9 ± 1.4	67 ± 19	3.2 ± 1.6	39 ± 11	1.1 ± .7	13 ± 5
Fir	1.9 ± .7	100 ± 37	12.2 ± 1.0	675 ± 66	14.0 ± 1.6	576 ± 93	21.4 ± 2.2	744 ± 114
Total	8.0 ± 2.1	207 ± 45	19.2 ± 1.8	821 ± 71	19.4 ± 3.1	724 ± 96	25.7 ± 2.4	919 ± 139

Table 1.5. Live and dead basal area and density means and standard error, stratified by elevation, of red spruce, Fraser fir, and all overstory species for 23 permanent plots (data collected in 1985 and 1986) at Mt. Rogers National Recreation Area, Virginia.

	ELEVATION			
	1525 m		1675 m	
	BA (m^2/ha)	Density (stems/ha)	BA (m^2/ha)	Density (stems/ha)
Live				
Spruce	13.7 ± 3.8	391 ± 116	18.8 ± 4.7	1365 ± 645
Fir	17.2 ± 4.8	950 ± 290	20.7 ± 3.9	930 ± 217
Total	38.2 ± 2.5	1887 ± 197	40.4 ± 2.7	2588 ± 585
Dead				
Spruce	1.2 ± .7	41 ± 16	6.3 ± 2.1	410 ± 269
Fir	1.9 ± .8	311 ± 143	8.6 ± 1.6	330 ± 114
Total	6.0 ± 6.4	518 ± 134	17.2 ± 2.8	985 ± 238

Table 1.6. Live basal area and density means, stratified by elevation, of red spruce, Fraser fir and all overstory stems at the Great Smoky Mountains of Tennessee and North Carolina reported by a) Cain 1935 (basal area data only) and b) Oosting and Billings 1951.

	ELEVATION							
	1525 m		1675 m		1830 m		1980 m	
	BA	Density	BA	Density	BA	Density	BA	Density
	m^2/ha	stems/ha	m^2/ha	stems/ha	m^2/ha	stems/ha	m^2/ha	stems/ha
a) Basal area data reported in Cain (1935) for the Great Smoky Mountains.								
Live **Spruce**	67.6						3.7	
Fir	5.6						58.7	
Total	76.0						66.3	
b) Data reported in Oosting and Billings (1951) for seven stands in the Great Smoky Mountains for all stems with DBH > 5.0 cm.								
Live **Spruce**			28.6	487	39.7	237	13.4	200
Fir			15.8	787	18.9	897	32.5	1310
Total			55.6	1594	69.0	1380	46.5	1533

Oosting and Billings (1951) sampled virgin stands in the Great Smoky Mountains in 1946, before adelgid impact or suspected atmospheric deposition problems. They sampled seven stands intensively (ten 10 x 10 m plots per stand) between 1662 and 1921 m, and included basal area and density by diameter class for live stems (Table 1.6b). Again there was a predominance of fir and a decrease in total basal area at the highest elevations. The percentage of hardwood composition was greater at lower elevations as found in this data (Table 1.4). However, comparison of Fraser fir basal area and density values for the 1946 study and this project underscores the significant impact of the BWA on forest structure. Current live fir densities are only 8-62 percent of the values recorded in 1946 (Oosting and Billings 1956). Total live basal areas for Oosting and Billings and this study do not differ markedly if recently killed fir are added to the live basal area. Comparison of spruce basal area indicates higher values at 1675 m and 1980 m found in this study than found by Oosting and Billings. Basal areas from Cain (1935) are quite high compared to Oosting and Billings (1951) as well as the present data. It should be pointed out that random sampling was not used in Cain's study, instead he sought stands specifically for their high spruce or fir component.

There was almost no quantitative work done in the Black Mountains prior to the BWA infestation except for studies documenting the efforts of the Forest Service to reclaim eroded cutover lands (Minckler 1940, Minckler 1945). Davis (1930) describes the Black Mountains area prior to cutting: "Fraser fir is most abundant at high altitudes and the red spruce at low altitudes. In places either may be found in pure stands as consociations. In constancy they both occur in over 80 % of the quadrats, in exclusiveness the fir is more confined to this association than the spruce. *Betula lutea*, *Sorbus americana*, and an occasional *Prunus pensylvania* occur as codominant in the upper stratum." Harshberger (1903) describes a similar species composition but refers to the spruce as *Picea mariana*.

The cutover and repeatedly burned areas regenerated little spruce-fir but supported successional shrubs and hardwoods including fire cherry, yellow birch, mountain laurel (*Kalmia latifolia* L.), serviceberry (*Amelanchier arborea* var. laevis (Wiegand) Ahles), *Rhododendron* species, striped maple (*Acer pensylvanicum* L.), mountain maple (*A. spicatum* Lam.), and *Rubus* species (Korstain 1937, Minckler 1945). Consequently, the areal extent of spruce-fir forests in the Black Mountains has been greatly reduced at the middle and lower elevations. In a recent study at the Black Mountains, Bruck and Robarge (1988) reported a rapid deterioration of the spruce-fir forest based on high levels of crown thinning and standing dead stems, but did not specifically address potential roles of site degradation after a variable logging history or the complex impact of adelgid infestation. The total basal areas for the Blacks are not substantially different from those in the Great Smoky Mountains considering diminished site quality probably occurred after logging (Zedaker et al. 1988). Extensive logging and associated fires in the Blacks probably accounts for the greater dominance of spruce in the virgin Great Smoky Mountains stands.

As in the Black Mountains, there has been little early quantitative work at Mt. Rogers NRA. Shields (1962) sampled stands along compass lines using 0.1 acre (0.04 ha) plots, not distinguishing between disturbed versus virgin stands. Table 1.7a shows Shields averaged data stratified by elevation (using data from applicable elevations). A comparison of Shields' high elevation data to the paper by Stephenson and Adams (1984) indicates that fir density has more than doubled in the twenty years between the two studies (Table 1.7). Shields found a much higher hardwood basal area component at 1525 m than found in the present study (Table 1.5). While total stand densities for the present study appear to be much higher than those measured for either Shield (1962) or Stephenson and Adams (1984), our study measured stems > 5 cm DBH while the earlier studies only included stems > 10 cm DBH. A re-analysis of these data to exclude stems that were 5-10 cm in diameter, reduced the total live stem densities by 32 percent at 1525 m and 48 percent at 1675 m elevation. This recalculation of the data brings our live stem densities more in line with those found by Shield (1962) and Stephenson and Adams (1984) for the higher elevation stands. Unfortunately, the most extensive published study of the Mt. Rogers Area (Rheinhardt and Ware 1984) included only relative basal area and density data, so comparisons with other studies are not possible.

Table 1.7. Live basal area and density means, stratified by elevation, of red spruce, Fraser fir, and all overstory (all stems with DBH ≥ 10.0 cm) species for Mt. Rogers National Recreation Area, Virginia as reported by a) Shields 1962 and b) Stephenson and Adams 1984.

	ELEVATION 1525 m		ELEVATION 1675 m	
	BA	Density	BA	Density
	m^2/ha	stems/ha	m^2/ha	stems/ha
a) Basal area and density data reported in Shields (1962) for Mt. Rogers National Recreation Area.				
Live **Spruce**	12.1	242	8.4	232
Fir	5.7	126	36.3	311
Total	40.8	682	47.5	1341
b) Basal area and density data reported in Stephenson and Adams (1984) for five stands on the summit of Mt. Rogers.				
Live **Spruce**			9.3	222
Fir			32.2	742
Total			43.0	1066

Few previous studies in the southern Appalachian spruce-fir have quantified standing dead stems. In a 1983 study at the Great Smoky Mountains that concentrated on sites where the BWA had impacted fir stands, Nicholas and White (1985) found that total standing dead basal area ranged from 7-27 m^2/ha depending on elevation and length of time since infestation. In comparison they found that dead basal area ranged from 5-8 m^2/ha in fir stands not yet impacted by the adelgid. In a 1987 examination of elevational trends at Mt. Mitchell (in the Black Mountains), Bruck and Robarge (1988) found 10-20 m^2/ha of dead standing fir and 5-15 m^2/ha of dead standing spruce. The present analysis of the entire Black Mountains found 6-22 m^2/ha of dead standing fir and 2-5 m^2/ha of dead standing spruce (Table 1.3). Dull et al. (1988) carried out the most comprehensive inventory of standing dead stems in the southern Appalachian spruce-fir using a combination of aerial photography and ground truthing for the Great Smoky Mountains, the Blacks, and Mt. Rogers NRA (as well as Roan Mountain, Grandfather Mountain, and the Balsam Mountains). However, Dull et al.'s report only includes volume estimates which are not comparable to most other studies which report basal area and density data. Furthermore, resolution of their aerial photos did not allow differentiation of spruce from fir.

Because fir abundance increases with elevation, there has been a corresponding increase of BWA-caused mortality at higher elevations. At both the Great Smoky Mountains and the high elevation Black Mountains, there was a greater proportion of standing dead fir basal area than live fir (Tables 1.3-1.4). At the Great Smoky Mountains, high elevations 48 % of standing fir were dead and an even higher percent of fir density was dead (56 %) at the Black Mountains. The populations of Fraser fir on Mount Rogers have escaped major damage from the adelgid, while most mature fir populations at the other two sites have been eliminated. Dead fir density averaged 25 % and dead fir basal area averaged 22 % for the Mt. Rogers NRA (Table 1.5).

While areas impacted by the adelgid show a visibly large number of dead fir stems, the amount of dead spruce is relatively small. A comparison was made of our red spruce standing dead data to that reported for the Northeastern spruce-fir. Johnson (1983) reported values of 15-45 percent of dead standing spruce out of both live and dead spruce for the northern montane forest. Our study at the southern sites found that 8-17 % of standing red spruce stems were dead, while Dull et al. (1988) found that 9-14 % of the standing spruce volume was dead for the Great Smoky Mountains and the Black Mountains. In the Black Mountains mean standing dead spruce densities range between 63-88 stems/ha (Table 1.3) and in the Great Smoky Mountains the mean densities range between 13-67 stems/ha (Table 1.4). At the highest elevations of Mt. Rogers NRA standing dead spruce densities averaged 410 stems/ha (Table 1.5). Partial explanation for the substantially higher levels of standing dead compared to the lower elevations at Mt. Rogers NRA may be that 35 percent of those plots are second-growth pure spruce stands (aged at approximately 60 years) that are densely crowded. Zedaker et al. (1988) also suggest that red spruce in fir dominated BWA-infested areas may have increased mortality rates due to shock of sudden exposure with the rapid removal of the fir canopy. The exposure effect may be exacerbated in even-aged second growth stands like those found in the Black Mountains. Furthermore, at the Black Mountains both spruce and fir may have higher mortality trends for several years in the future partly due to severe glaze storms that occurred in the winter of 1986-1987 which damaged many crowns (Nicholas and Zedaker 1989).

CONCLUSIONS

The southern Appalachian forest has been dramatically changed in the last century. Logging, repeated burning, and replanting have eliminated old-growth stands in many areas, changed species composition, and probably altered site quality. The fir populations at Mt. Rogers NRA have escaped major damage from the adelgid, while those at the Great Smoky Mountains and the Black Mountains have been decimated. Second growth red spruce in fir dominated BWA-infested areas may be particularly susceptible to shock of sudden exposure. When adelgid-caused mortality is included, stand basal areas are consistent with stand descriptions in historical studies. Because fir is a short-lived species, older fir stands at the top of Mt. Rogers may also experience high mortality levels in the near future. Furthermore many of the stands sampled in the Great Smoky Mountains are dominated by old red spruce. It is expected that some of these stands will be dramatically changed in the near future with the death of these old trees.

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Chapter II

Leaf area and above-ground biomass prediction equations for southern Appalachian red spruce, Fraser fir, and yellow birch

ABSTRACT

Biomass distribution, biomass prediction equations, and leaf area estimations were determined for overstory and understory southern Appalachian red spruce (*Picea rubens* Sarg.), Fraser fir (*Abies fraseri* (Pursh) Poir.), and yellow birch (*Betula lutea* Michaux f.). Distribution of foliage biomass allocation decreased between understory and overstory stems by one half for all three species. Above ground biomass estimation equations were developed for several components (foliage, live branches, dead branches, bole bark, and bole wood) of overstory stems using diameter at breast height (DBH) as the independent variable. Coefficients of determination ranged from .717 to .981

with the lowest values found for foliage components and highest values found for total above-ground biomass. Biomass equations were developed for understory stem components (foliage and woody material) and, for all but fir foliage, basal diameter alone was the best estimator of dry weight. Leaf area (projected area) equations were developed for spruce, fir and birch using predicted foliage weight from the overstory biomass equations. Calculation of projected leaf area index (m^2/m^2) for all permanent plots found that spruce-fir stands at the Great Smoky Mountains (Tennessee and North Carolina) had an average LAI (11.9) significantly greater than stands at Mt. Rogers National Recreation Area of Virginia (9.1) or the Black Mountains of North Carolina (8.3). LAI was also higher at lower elevations (1525-1675 m) and on sites with no logging history.

INTRODUCTION

There has been considerable speculation on the health of southern Appalachian spruce-fir forests in recent years. Like northeastern red spruce (*Picea rubens* Sarg.), southern Appalachian red spruce has been observed to have significant crown deterioration (Bruck and Robarge 1988, Bruck et al. 1989, Peart et al. 1992) at some sites. However, evidence of southern spruce radial incremental growth reduction is currently in dispute (McLaughlin et al. 1987, Cook 1992, LeBlanc et al. 1992). Furthermore, the infestation of the balsam woolly adelgid (*Adelges piceae* Ratz.) on the southern endemic Fraser fir (*Abies fraseri* (Pursh) Poiret), a major associate of southern Appalachian red spruce, has complicated efforts to assess changing stand structure.

In order to better evaluate hypotheses of forest decline in this ecosystem, it has become evident that quantifying nutrient status, estimating system biomass levels, and modeling effects of light interception on tree and stand growth, are necessary. As atmospheric deposition models become more detailed, information on foliage mass, distribution, and surface area will be necessary for the prediction of deposition interception loads from throughfall. It is also essential that biomass and related foliage area equations be available so that growth functions and nutrient distributions can be estimated at the stand level. Without the ability to link stemwood production to foliar parameters such as leaf area and dry weight, attempts to quantify the effects of various possible foliage impacts (ie. insect defoliations, atmospheric deposition) will be limited (Geron and Ruark 1988). While some analysis of biomass distribution, biomass prediction equations, and leaf area estimations have been carried out in some northeastern spruce-fir stands (Baskerville 1965, Baskerville 1966, Whittaker et al. 1974, Ker and van Raalte 1981, Marchand 1984, Sprugel 1984), there has been little work of this kind done in the southern Appalachians. Currently no clear model of expectation exists for total above-ground biomass of the southern spruce-fir. In order to determine if change in forest productivity has occurred and then quantify any variation, base-line information is needed for comparison. This paper provides biomass and projected foliage surface area equations for overstory and understory red spruce, Fraser fir, and their codominant yellow birch (*Betula lutea* Michaux f.), and compares overstory foliage area (LAI) estimates at different sites and elevations of the southern Appalachian spruce-fir forest type.

METHODS

FIELD SAMPLING

Biomass

A permanent plot system was established in 1985 to allow long term monitoring of changes in the composition, vigor, and growth of southern Appalachian spruce-fir stands (Nicholas and Zedaker 1989, Gregoire et al. 1990, Nicholas et al. 1991, Chapter 1). Plots were randomly located within stratification factors of elevation (four classes: 1525 m, 1675 m, 1830 m, 1980 m), topography type (three classes: ridge, slope, draw), and exposure to prevailing winds (two classes: exposed versus protected). A total of 142 (20 m x 20 m) plots were located at Mt. Rogers National Recreation Area in Virginia, the Black Mountains of North Carolina, and the Great Smoky Mountains of Tennessee and North Carolina and trees were remeasured in 1987 and 1989. Between 1986 and 1988 a destructive sampling plot (10 x 10 m) was located near each of eighteen permanent plots on National Forest lands including eight plots at Mt. Rogers National Recreation Area (Jefferson National Forest) and ten plots at the Black Mountains (Pisgah National Forest). Every effort was made to distribute the destructively sampled plots equally among the different elevation classes; however only one destructive plot could be located at 1980 m due to limited National Forest lands at the highest elevations.

All overstory (≥ 5.0 cm diameter at breast height, 1.37 m [DBH]) stems on each destructive plot were mapped with an x,y coordinate, identified by species, measured at DBH, classified for crown position, and assessed for disturbance symptomology. Dimension analysis was conducted on a maximum of six live trees per plot. No more than three trees per species were measured per plot and none of the dimension analysis stems could have visible sign of top breakage. A two tier selection process was used to determine sample trees. All live dominant or codominant spruce, fir, or birch stems greater than 5 m tall without visible sign of forks, crooks, severe insect or pathogen infestation on the destructive plot were considered possible sample trees. If more than three trees per species were selected then qualifying stems were randomly selected using the x,y mapping coordinate system. If less than six stems were chosen in this manner then random mapping coordinates were used to select any remaining overstory trees that had an intact top.

Dimension analysis trees were felled at or below a 30 cm stump height and measured for length. Then all branches were removed from the main stem up to a bole diameter of 5.0 cm where the entire top portion was cut and treated as a separate branch. For each individual sample tree all live branches were divided into five arbitrary size classes so that there was a relatively equal number of branches among the classes. All dead branches for a tree were combined into one branch class. Fresh branch class weights (to the nearest 1.0 kg) were obtained in the field and then one branch from each class was randomly chosen, weighed (to the nearest 0.1 kg) separately, and returned to the laboratory to cold storage (Madgwick 1981, Crow 1983, Czapowskyj et al. 1985). The main stem was then sectioned at DBH and thereafter in 2 m intervals to the top. All sections were weighed (to the nearest 1.0 kg) and then three sections were selected using importance sampling (Valentine et al. 1984). From the selected three sections a 5 cm thick disc was cut from the top of the section, weighed (to the nearest 0.1 kg), and returned to the laboratory to cold storage. Rings were counted for all spruce and fir DBH sections for age determination.

Understory ($<$ 5.0 cm DBH and height $\geq$ 1.37 m high) live stems were sampled at two randomly selected 4 x 4 m sub-plots. Stems were measured for height and diameter at 15 cm and then severed at ground level and returned to the laboratory to cold storage.

Samples were kiln-dried to retard decay and then branch and understory samples were sorted to separate foliage from wood. Disc samples were separated into bark and wood. Samples were oven-dried at 65° C to a constant weight.

Leaf Area

Foliage samples were collected from spruce, fir, and yellow birch trees near permanent plots at the Black Mountains study site (Pisgah National Forest, Mt. Mitchell State Park, and the Blue Ridge Parkway, North Carolina). Morgan et al. (1983) detailed the need for a sampling intensity that includes the full range of variability. Therefore a branch sample was collected from the upper and lower canopy of two to three dominant or codominant spruce, fir, or birch per plot location. An attempt was made to sample three plots at each elevation class for each species, however dominant or codominant stems could not be found near plots for fir at 1525 m or 1675 m, or for birch at 1980 m. Branches were sampled using pole pruners or a shotgun (on National Forest lands only) and samples were all at least 1 m in length. Spruce and fir samples were collected in late summer of 1988 and 1989 while birch samples were collected in July of 1989.

Samples were returned to the laboratory in cold storage. While several techniques have been suggested that avoid direct measurement (Drew and Running 1975, Johnson 1984) of needles, it was decided that accuracy might be better assured with direct measurement. Green needle dimensions (length and width) measurements were made on ten randomly chosen needles for each of five age classes (current year, second year, third year, fourth year, and fifth year) for each branch using a digital caliper to the closest 0.01 mm. Birch leaf areas were determined to the nearest 0.01 cm^2, for 10 randomly chosen leaves among those determined to have little insect or buckshot damage per branch using an area meter. Foliage was then oven-dried at 65°C to a constant weight. Needle weights (to the nearest 0.0001 g) were recorded for each group of ten needles per age class per branch while birch leaves were weighed (to the nearest 0.01 g) individually.

ANALYSIS

Distribution of above-ground biomass components for overstory and understory stems was calculated. Biomass equations were developed separately for overstory and understory spruce, fir, and birch. Overstory biomass equations were fitted to estimate bole bark, bole stemwood, live branches, dead branches, and foliage dry weights as a function of DBH, age at DBH (spruce and fir only), total height, and DBH^2 *total height. Dry weights for entire stems were extrapolated from fresh weights using moisture content percentages calculated for samples returned to the laboratory. Understory biomass equations had basal diameter and height as the independent variables and foliage and wood dry weights as the dependent variables. Three data points were eliminated from analysis as extreme outliers that suggested an error in data collection. All three data eliminated were Fraser fir overstory foliage weights all collected on the same plot on the same day. Ratio of foliage to total stem dry weights for those three points averaged 27 percent while the rest averaged 10 percent with a maximum value of 17 percent.

Projected surface leaf areas for spruce, fir, and birch were developed using the final biomass equations discussed above. Since the cross-section of a fir needle is flat and the cross-section of a spruce needle is diamond-shaped, projected area for fir needles was estimated by calculating length*width while spruce needle projected area was calculated as length*(width* $\sqrt{2}$). Separate equations were considered for different elevations. Leaf area indices (m^2/m^2), a ratio of totaled projected leaf areas to horizontal plot area, were calculated for all three study sites at different elevations and disturbance histories using DBH data collected in 1989 for 142 permanent plots. Leaf area index (LAI) was also compared to stand live basal area. Leaf area index (LAI) was a three-part calculation. Individual stem diameters were used to to predict foliage dry weights for all live spruce, fir, and birch and then the estimated foliar weights were used to predict projected leaf area. Individual stem projected leaf areas were summed for each plot and then divided by the plot area (4,000,000 cm^2).

RESULTS

Biomass Distribution

Foliage made up a small proportion of above-ground biomass for overstory red spruce, Fraser fir, and yellow birch. Fraser fir and red spruce needles had similar values (10 and 11 %), while yellow birch leaves made up only 2 % of the total above-ground stem dry weight (Table 2.1). One factor that must be considered with respect to yellow birch foliage weights is the widespread insect damage observed. All biomass sampling was carried out in the late summer and autumn. While deciduous tree foliage data points collected after September 15 were eliminated from the data base, nothing was done to correct for insect damage. In contrast, for all three species, contribution of the foliage component to total above-ground dry weight for understory stems was noticeably larger than for overstory stems (Table 2.2). Understory spruce and fir foliage components were 19 and 21 percent, respectively, and birch foliage made up 5 % of total understory above-ground dry weights.

Overstory biomass components, other than foliage, varied little (Table 2.1). Bole bark ranged from 7-9 percent and bole wood made up the bulk of above-ground weight ranging from 52-69

Table 2.1. Dry weight distribution of above-ground stem components for overstory southern Appalachian red spruce (n = 45), Fraser fir (n = 10), and yellow birch (n = 14).

	Spruce		Fir		Birch	
Variable	Mean	Std Error	Mean	Std Error	Mean	Std Error
	(.		%		. . . .)	
Bole Bark	6.9a	0.2	7.3ab	0.6	8.7b	0.7
Bole Wood	53.3a	1.7	51.7a	3.4	59.3a	3.8
Foliage	11.4a	0.8	9.7a	1.2	1.9b	0.2
Live Branches	24.3a	1.4	26.2a	2.9	27.9a	3.6
Dead Branches	4.1a	0.5	5.2a	1.3	2.1a	1.1

Note: Mean percentages within rows followed by different letters differ significantly at $p = 0.05$ based on the Scheffe procedure for multiple contrasts among means using angular transformations.

Table 2.2. Dry weight distribution of above-ground stem components for understory southern Appalachian red spruce (n = 14), Fraser fir (n = 7), and yellow birch (n = 3).

	Spruce		Fir		Birch	
Variable	Mean	Std Error	Mean	Std Error	Mean	Std Error
	(............................		%		............................)	
Foliage	19.2a	2.0	21.0a	5.6	4.7a	1.2
Woody Tissue	80.8a	2.0	79.0a	5.6	95.3b	1.2

Note: Mean percentages within rows followed by different letters differ significantly at $p = 0.05$ based on the Scheffe procedure for multiple contrasts among means using angular transformations.

percent. Live branches (those with foliage attached) made up 24-28 percent of the above-ground biomass and dead branch dry weight ranged from 2-5 percent.

Biomass Equations

In most cases the relationship between natural logarithms of DBH and the dependent variable dry weights furnished precise predictions for overstory stems (Tables 2.3-2.5). While multiple regression equations were developed using DBH and total height as the independent variables, little improvement of fit was noted using the adjusted coefficient of determination, mean square error, and the Mallows C_p statistic (Mallows 1973) as measures. Most regression equations that were developed using DBH^2*total height instead of DBH were inferior (in terms of the coefficient of determination and patterns of residual values versus the independent variable) and, like the multiple regression equations using total height, were abandoned. Coefficients of determination ranged from .717 to .981 (when excluding equations for dead branch biomass prediction), with more precise predictions for bole (bark and wood) than for crown components (foliage and live branches). The proportion of variation accounted for by DBH was better for whole stem biomass ($R^2 = .922$ to .981) than for individual components.

The relationship between the natural logarithm of DBH and the dependent variable dry weights furnished moderately good predictions for understory spruce (Table 2.6) and birch (Table 2.7) but not for fir (Table 2.8a). Multiple regression equations were developed using DBH and total height as independent variables, and significant improvement of fit was noted for the fir foliage component (Table 2.8b). Coefficients of determination for final equations ranged from .494 to .989 with all efforts failing to significantly improve goodness of fit for predicting understory spruce foliage.

Table 2.3. Regression components for estimating foliage, branch, stem, and total aboveground weights (grams) of overstory ($\geq$ 5.0 cm DBH) southern Appalachian red spruce with DBH (cm) as the predictor (X) variable using the linear equation: $\ln Y = a + b \ln X$.

Y	N	Parameter Estimates a	Parameter Estimates b	p > F	R^2	MSE	Range of X	*CF*[a]
							. .(cm). .	
Foliage	46	3.279	2.053	.0001	.837	.178	5.5 - 42.5	1.09
Live Branches	46	4.108	2.031	.0001	.850	.158	5.5 - 42.5	1.08
Dead Branches	46	.470	2.547	.0001	.544	1.182	5.5 - 42.5	1.79
Total Branches + Foliage	46	4.524	2.069	.0001	.907	.096	5.5 - 42.5	1.05
Bole Bark	45	1.407	2.530	.0001	.950	.075	5.5 - 42.5	1.04
Bole Wood	45	2.857	2.722	.0001	.952	.084	5.5 - 42.5	1.04
Total Bole	45	3.050	2.700	.0001	.954	.078	5.5 - 42.5	1.04
Bole + Branches + Foliage	45	4.498	2.399	.0001	.970	.039	5.5 - 42.5	1.02

[a] Correction for logarithmic bias (from Sprugel 1983) (R^2 reported on a logarithmic scale, non-weighted).

Table 2.4. Regression components for estimating foliage, branch, stem, and total aboveground weights (grams) of overstory ($\geq$ 5.0 cm DBH) southern Appalachian Fraser fir with DBH (cm) as the predictor (X) variable using the linear equation: $\ln Y = a + b \ln X$.

Y	N	Parameter Estimates a	Parameter Estimates b	p > F	R^2	MSE	Range of X	*CF*[a]
							. .(cm). .	
Foliage	10	1.153	2.637	.0002	.832	.340	6.7 - 25.0	1.94
Live Branches	13	4.279	1.941	.0003	.717	.310	6.7 - 25.0	1.62
Dead Branches	13	-3.416	3.863	.0044	.536	2.689	6.7 - 25.0	63.26
Total Branches + Foliage	10	3.108	2.469	.0001	.926	.119	6.7 - 25.0	1.26
Bole Bark	13	2.250	2.185	.0001	.894	.120	6.7 - 25.0	1.20
Bole Wood	13	3.637	2.383	.0001	.906	.125	6.7 - 25.0	1.21
Total Bole	13	3.848	2.356	.0001	.908	.119	6.7 - 25.0	1.20
Bole + Branches + Foliage	10	4.179	2.440	.0001	.981	.027	6.7 - 25.0	1.05

[a] Correction for logarithmic bias (from Sprugel 1983) (R^2 reported on a logarithmic scale, non-weighted).

Table 2.5. Regression components for estimating foliage, branch, stem, and total aboveground weights (grams) of overstory ($\geq$ 5.0 cm DBH) southern Appalachian yellow birch with DBH (cm) as the predictor (X) variable using the linear equation: $\ln Y = a + b \ln X$.

Y	N	Parameter Estimates a	b	p > F	R^2	MSE	Range of X	*CF*[a]
							. .(cm). .	
Foliage	14	2.433	1.755	.0001	.760	.222	7.4 - 38.2	1.33
Live Branches	20	4.979	1.825	.0001	.816	.199	5.9 - 38.2	1.13
Dead Branches	18	1.574	1.721	.0665	.195	3.631	5.9 - 38.2	9.46
Total Branches + Foliage	14	4.432	2.066	.0001	.859	.157	7.4 - 38.2	1.22
Bole Bark	20	1.620	2.639	.0001	.869	.278	5.5 - 38.2	1.19
Bole Wood	20	3.928	2.490	.0001	.859	.269	5.5 - 38.2	1.18
Total Bole	20	4.020	2.513	.0001	.863	.266	5.5 - 38.2	1.18
Bole + Branches + Foliage	14	5.480	2.142	.0001	.922	.087	7.4 - 38.2	1.12

[a] Correction for logarithmic bias (from Sprugel 1983) (R^2 reported on a logarithmic scale, non-weighted).

Table 2.6. Regression components for estimating foliage, woody material, and total aboveground weights (grams) of understory (< 5.0 cm DBH) southern Appalachian red spruce with basal diameter (cm) measured 15 cm above-ground as the predictor (X) variable using the linear equation: $\ln Y = a + b \ln X$.

Y	N	Parameter Estimates a	Parameter Estimates b	$p > F$	R^2	MSE	Range of X	*CF*[a]
							. .(cm). .	
Foliage	14	.645	1.244	.0050	.494	.150	2.0 - 5.1	2.20
Woody Tissue	14	-1.817	2.395	.0001	.923	.045	2.0 - 5.1	1.27
Woody Tissue + Foliage	14	-.844	2.177	.0001	.917	.041	2.0 - 5.1	1.24

[a] Correction for logarithmic bias (from Sprugel 1983) (R^2 reported on a logarithmic scale, non-weighted).

Table 2.7. Regression components for estimating foliage, woody material, and total aboveground weights (grams) of understory (< 5.0 cm DBH) southern Appalachian yellow birch with basal diameter (cm) measured 15 cm above-ground as the predictor (X) variable using the linear equation: $\ln Y = a + b \ln X$.

Y	N	Parameter Estimates a	b	$p > F$	R^2	MSE	Range of X	CF^a
							. .(cm). .	
Foliage	3	-5.830	2.839	.0670	.989	.074	1.1 - 3.5	1.57
Woody Tissue	7	-1.111	2.367	.0001	.968	.064	1.1 - 5.6	1.26
Woody Tissue + Foliage	3	-.197	2.043	.0789	.993	.054	1.1 - 3.5	1.06

[a] Correction for logarithmic bias (from Sprugel 1983) (R^2 reported on a logarithmic scale, non-weighted).

Table 2.8a. Regression components for estimating foliage, woody material, and total aboveground weights (grams) of understory (< 5.0 cm DBH) southern Appalachian Fraser fir with basal diameter (cm) measured 15 cm above-ground as the predictor (X) variable using the linear equation: $\ln Y = a + b \ln X$.

Y	N	Parameter Estimates a	b	p > F	R^2	MSE	Range of X	*CF*[a]
							. .(cm). .	
Foliage	7	4.148	.292	.7197	.028	.724	1.9 - 6.4	49.01
Woody Tissue	7	.106	1.849	.0051	.818	.186	1.9 - 6.4	2.70
Woody Tissue + Foliage	7	1.490	1.535	.0123	.746	.197	1.9 - 6.4	2.90

[a] Correction for logarithmic bias (from Sprugel 1983) (R^2 reported on a logarithmic scale, non-weighted).

Table 2.8b. Regression components for estimating foliage, woody material, and total aboveground weights (grams) of understory (< 5.0 cm DBH) southern Appalachian Fraser fir with basal diameter (cm) measured 15 cm above-ground and total height (dm) as the predictor variables (X_1, X_2) using the linear equation: $\ln Y = a + b \ln X_1 + c \ln X_2$.

Y	N	Parameter Estimates a	b	c	p > F	R^2	MSE	Range of X_1 and X_2	*CF*[a]
Foliage	7	-3.895	-1.669	4.958	.0444	.789	.196		26.49
Woody Tissue	7	-1.642	1.422	1.078	.0242	.844	.200	X_1:1.9-6.4 X_2: 16-28	28.62
Woody Tissue + Foliage	7	-1.449	.818	1.812	.0245	.843	.152		12.86

[a] Correction for logarithmic bias (from Sprugel 1983) (R^2 reported on a logarithmic scale, non-weighted).

Table 2.9. Average needle length (mm) among year of production (1985-1990) for southern Appalachian red spruce (n = 2480) and Fraser fir (n = 1450).

	Year of Needle Production					
Species	1985	1986	1987	1988	1989	1990
Spruce	11.57a	11.61a	11.58a	11.31a	10.63b	11.07ab
Fir	13.87a	12.03c	12.71bc	13.19ab	12.87ab	12.78bc

Note: Mean values within rows followed by different letters differ significantly at $p = .05$ based on the Scheffe procedure for multiple contrasts among means.

Variation of Needle and Leaf Size

Analysis of foliage collected for the determination of surface area-weight relationship indicated significant variation for spruce and fir needle length among samples collected for different age classes and at different canopy positions and elevations. Spruce needles that were produced in 1989 and 1990 were shortest while the shortest fir needles were produced in 1986 (Table 2.9). For both species needles located in the lower half of the tree canopy were shorter than those found in the upper canopy (Table 2.10). Needle length of both species decreased with increasing elevation (Table 2.11). Tests of variation of needle length were significant for all combinations of needle age, canopy position, and elevation.

Significant variation was also noted of birch surface area among samples collected at different canopy positions and elevations. Leaf size was larger in the lower canopy (Table 2.10) and at lower elevations (Table 2.11). A test of variation of leaf size was significant for a combination of canopy position and elevation.

Leaf Area Index

Leaf area (projected area) equations were developed for spruce, fir, and birch using foliage weight as a predictor variable (Table 2.12). Separate equations developed for different elevations, canopy positions, needle age classes did not result in overall better fitting models for fir. Separate equations for sun (upper canopy) and shade (lower canopy) birch leaves resulted in improved equations; however, calculation of LAI used the combined birch leaf area equation since it was impossible to determine the percentage of sun versus shade leaves on an individual tree for this study. Separate equations for different elevations improved spruce leaf area models only for the lower elevations samples. While logarithmic transformations resulted in slightly better fitting

Table 2.10. Average leaf size in lower and upper canopy position for southern Appalachian red spruce (n = 2480), Fraser fir (n = 1450) and yellow birch (n = 600).

Species	Unit of Measure	Canopy Position Lower	Upper
Spruce	Length (mm)	11.24a	11.39b
Fir	Length (mm)	12.56a	13.00b
Birch	Surface Area (cm^2)	23.34a	19.65b

Note: Mean values within rows followed by different letters differ significantly at $p = 0.05$ based on the Scheffe procedure for multiple contrasts among means.

Table 2.11. Average leaf size among four elevation classes for southern Appalachian red spruce (n = 2480), Fraser fir (n = 1450) and yellow birch (n = 600).

		Elevation (m)			
Species	Unit of Measure	1525	1675	1830	1980
Spruce	Length (mm)	12.02a	11.50b	11.48b	11.02c
Fir	Length (mm)			13.72a	12.02b
Birch	Surface Area (cm^2)	24.88a	18.63c	21.10b	

Note: Mean values within rows followed by different letters differ significantly at **p** = 0.05 based on the Scheffe procedure for multiple contrasts among means.

models, the resulting equations resulted in large underestimations of leaf area when converted back to the antilogarithmic form.

Spruce-fir stands at the Smokies had a LAI (11.9) significantly greater than the other two study areas (Table 2.13a). LAI was higher for sites with no logging history compared to logged stands (Table 2.13b), and at lower elevations (Table 2.13c). Trends in stand total live basal area were quite similar to trends in LAI, with two exceptions. Numerically LAI increased between 1525 m and 1675 m, although not significantly, for stands at Mt. Rogers NRA and the Great Smoky Mountains while live basal area remained unchanged (Table 2.13c). Both these situations had a substantially greater amount of conifer contribution to live basal area for the 1675 m elevation plots than for the 1525 m elevation plots. Stand total live basal area provided a good prediction ($R^2 = .84$ to .89) of stand LAI for all three study sites (Table 2.14).

DISCUSSION

The trend of increasing concentration of biomass in the stem with increasing size (understory versus overstory) was also noted by Whittaker et al. (1963) and Grier et al. (1981). Proportion of foliage to total above-ground biomass decreases as bole diameter increases. While few studies have carried out biomass studies on sapling size individuals of tree species, distribution of overstory stem biomass has been examined in a number of North American species. Table 2.15 includes above-ground biomass distribution values for twelve species. With the exception of *Acer spicatum* Lam. (Whittaker et al. 1974), the proportion of hardwood foliage was equal to or less than 2.2 percent.

The Whittaker study also has biomass percentage distributions for red spruce and yellow birch from research carried out at Hubbard Brook, New Hampshire (Table 2.15). Comparison of the

Table 2.12. Regression components for estimating projected leaf area for overstory ($\geq$ 5.0 cm DBH) southern Appalachian red spruce, Fraser fir, and yellow birch using the linear equation: Leaf Area (cm^2) = a + b Foliage weight (g).

		Parameter Estimates				
Y	N	a	b	p > F	R^2	MSE
Red spruce	253	0.042	22.442	.0001	.594	.0003
Fraser fir	146	0.098	39.592	.0001	.393	.0033
Yellow birch	60	8.499	109.458	.0001	.460	26.2981
Yellow birch (Lower canopy only)	30	9.332	127.083	.0001	.566	17.4396
Yellow birch (Upper canopy only)	30	4.298	120.666	.0001	.629	19.8046

Table 2.13a. Average projected LAI (m^2/m^2) among three spruce-fir study sites. Average stand live basal area (m^2/ha) are in parentheses.

	Mt. Rogers NRA	Black Mountains	Great Smoky Mountains
LAI	9.14a (39.6ab)	8.30a (38.5a)	11.91b (48.0a)

Table 2.13b. Average projected LAI (m^2/m^2) for uncut versus logged stands among three spruce-fir study sites. Average stand live basal area (m^2/ha) are in parentheses.

	Disturbance History	
Study Site	Uncut	Logged
Mt. Rogers NRA	9.75a (40.5a)	8.79a (39.1a)
Black Mountains	11.63a (51.8a)	6.91b (33.0b)
Great Smoky Mountains	11.91 (48.0)	

Table 2.13c. Average projected LAI (m^2/m^2) for four elevation classes among three spruce-fir study sites. Average stand live basal area (m^2/ha) are in parentheses.

	Elevation (m)			
Study Site	1525	1675	1830	1980
Mt. Rogers NRA	8.54a (40.0a)	9.69a (39.2a)		
Black Mountains	10.98a (52.4a)	9.88a (43.5a)	5.57b (27.2b)	4.45b (20.1b)
Great Smoky Mtns.	13.66ab (60.2a)	15.16a (58.6a)	10.12bc (38.4b)	7.08bc (28.4b)

Note: Mean values within rows followed by different letters differ significantly at $p = 0.05$ based on the Scheffe procedure for multiple contrasts among means.

Table 2.14. Linear regression components for estimating LAI (m^2/m^2) for overstory ($\geq$ 5.0 cm DBH) southern Appalachian spruce-fir stands with live stand basal area (m^2/ha) the predictor (X) variable for three sites.

Study Site	N	Parameter Estimates a	b	$p > F$	R^2	MSE	Range of X (m^2/ha)
Mt. Rogers NRA	25	-1.346	0.265	.0001	.837	1.889	3.7 - 58.4
Black Mountains	51	-1.745	0.261	.0001	.861	3.141	7.6 - 83.7
Great Smoky Mountains	66	-0.370	0.256	.0001	.893	2.870	15.9 -119.9
All Sites	142	-1.329	0.265	.0001	.880	2.984	3.7 -119.9

Table 2.15. Dry weight distribution of above-ground stem components for twelve species.

Species	(N)	$\overline{\text{Age}}$	Bole Bark	Bole Wood	Foliage	Live Branches	Dead Branches	Source
		Yrs	(.	. . . .	%	. . . .	. . . .)	
Abies amabilis	-	23	5.4	51.0	27.8	15.8	-	1
Abies amabilis	-	180	14.0	66.0	4.9	15.2	-	1
Abies balsamea (medium stand density)	16	42	9.0	63.0	14.9	13.1	-	2
Abies fraseri	10	25	7.3	51.7	9.7	26.2	5.2	Table 1
Acer saccharum	14	79	7.5	59.6	1.5[a]	30.6	0.8	3
Acer saccharum	9	50	9.4	65.9	2.2	20.1	2.5	4
Acer spicatum	15	24	8.0	54.1	5.3[a]	29.7	5.3	3
Betula lutea	14	66	5.0	43.1	1.6[a]	48.1	2.2	3
Betula lutea	14	-	8.7	69.4	1.9	27.9	2.1	Table 1
Fagus grandifolia	14	106	3.7	56.5	1.1[a]	34.2	4.5	3
Liriodendron tulipifera	10	75	9.2	76.4	2.2[a]	12.2[b]	-	5
Picea rubens	14	87	8.0	57.0	7.1	19.6	8.2	3
Picea rubens	45	60	6.9	53.4	11.4	24.4	4.1	Table 1
Pinus echinata	10	72	8.9	80.1	3.5[a]	7.5[b]	-	5
Populus tremuloides	9	63	15.6	71.4	1.0	10.3	1.9	4
Quercus alba	10	96	12.5	58.5	2.1[a]	26.9[b]	-	5

[a] Includes twigs.
[b] Includes dead branches.

1 - Grier et al. (1981) which used equations from Gholz et al. (1979)
2 - Baskerville (1965)
3 - Whittaker et al. (1974)
4 - Pastor and Bockheim (1981)
5 - Whittaker et al. (1963)

present study to the one at Hubbard Brook does not indicate large differences. All five biomass components (bole bark, bole wood, foliage, live and dead branches) are all within five percent for red spruce. Both studies sampled a comparable average age for spruce trees (60 versus 87 years), while the present study had a sample size three times larger than the Hubbard Brook study. Both studies have similar values for yellow birch for bark, foliage, and dead branches, while the Hubbard Brook project had noticeably lower proportion of bole wood (43.1 %) than this study (69.4 %). Since the Hubbard Brook birch trees were larger (mean DBH-24.6 cm, mean height-16.2 m, n = 14) than the trees for this study (mean DBH-12.4 cm, mean height-11.2 m, n = 14), perhaps the difference is due to the geographic difference between the two study sites. Unfortunately stem age comparison between the two studies was impossible because yellow birch biomass trees were not measured for age in this study.

While no other biomass distribution values for Fraser fir were found, Baskerville's (1965) comprehensive study of the closely related balsam fir (*Abies balsamea* (L.) Mill.) provides a means for comparison. Some differences between balsam fir and Fraser fir biomass distribution are evident (Table 2.15); balsam fir had 11 % more biomass associated with bole wood and 13 % less biomass in live branches. However, the balsam fir samples were part of a carefully manipulated study with an average release age of 42 years, compared to an average age at DBH of 25 for the Fraser fir sample trees which were found in naturally seeded, unmanaged stands.

While the addition of height as an independent variable only very slightly improved overstory biomass equations for the samples collected for this study, it is quite likely that total height would not explain additional variation for biomass if applied for a more randomized sample. All three species for this study are found at high elevations, on steep slopes, in areas with high winds and heavy snow and ice loads, and top breakage is common (Nicholas and Zedaker 1989), but only intact stems were used as biomass sample trees. Furthermore height data is often not available for more than a few trees in a stand. Geron and Ruark (1988) suggest diameter at the base of the live crown as another variable for precise estimation of biomass. Since above-ground primary production tends to be greater in younger stands (Jarvis and Leverenz 1983), stem age might be considered as an independent variable for prediction of overstory biomass. However, both red spruce and Fraser fir are very shade tolerant (Burns and Honkala 1990) and DBH was found to explain a greater proportion of biomass variation for samples collected in this study. A number of studies have also found that foliage biomass in particular is strongly related to sapwood conducting tissue (Grier and Waring 1974, Snell and Brown 1978, Kaufmann and Troendle 1981, Marchand 1984). Marchand's study examined the utility of sapwood area as an estimator to predict northeastern red spruce and balsam fir foliage biomass and found that sapwood predicted a larger proportion of variation for spruce ($R^2 = .97$) and fir ($R^2 = .94$) than the present study found for DBH ($R^2 = .84$ and .83 for spruce and fir respectively). However, sapwood area, like age and diameter at the base of live crown, is a variable that is time-consuming to collect and would make whole stand biomass estimates difficult to obtain.

There are few other species-specific biomass estimate equations to directly compare to this study. Weaver (1972) developed equations for overstory spruce, fir, and birch from data collected in 1959 during the building of a Blue Ridge Parkway right-of-way in the Balsam Mountains of North Carolina. The data was collected years prior to Weaver's involvement in the project and his dissertation offers little insight into how data collection was carried out or any description of the sample trees other than the stand was young second-growth. Comparison of the equations developed for this study to those developed by Weaver suggests that, for red spruce, bole and foliage estimates were similar, but Weaver's branch biomass estimates were half of those found during this study. Fir foliage estimates were similar for the two studies, but Weaver's fir branch estimates were half of those found during this study, and Weaver's fir bole estimates were 35 % more than those found during this study. Little differences were found for birch biomass estimates between the two southern Appalachian studies. In contrast to Johnson (1991), this study indicates that Weaver's foliage regression equations are not inaccurate. In contradiction to suggestions of Johnson et al. (1991), any application of foliage equations from second-growth stands to old-growth forests of larger trees will probably overestimate foliage biomass, since there is a trend of an increasing proportion of biomass in a tree's stem as it increases in size.

Red spruce and yellow birch allometric ratios were also developed for the Hubbard Brook study. Whittaker et al. (1974) described their methods of sampling and there appeared to be one significant difference: the New Hampshire study did not obtain fresh weight for all branches and instead only weighed a subsample. Range and average size of trees were similar to this present study. Comparison of the ratios developed for this present study and Hubbard Brook (Table 2.15) indicated that Hubbard Brook biomass estimates were similar (±15 %) for most components with the exception of birch branches; branch ratios from Hubbard Brook were allocated 45 percent more biomass branch ratios found for this study.

Like overstory stems, diameter alone can be used to predict understory above ground biomass with respectable precision ($R^2 = .746$-$.993$). While in a few cases the addition of stem height substantially improves the fit, many studies estimating small tree biomass use basal diameter alone as a predicting variable (Brown 1976, Grigal and Ohmann 1977, Roussopoulos and Loomis 1980, Grier and Milne 1981, Smith and Brand 1983) probably because it is easier to more accurately measure in the field.

It is unfortunate that few biomass studies include equations for small trees (DBH $<$ 5.0 cm) since the ratio of photosynthetic tissue to woody material probably changes as a tree grows. Only one other study (Weaver 1972) includes equations for small red spruce, Fraser fir, and yellow birch stems; however, he used diameter at 46 cm as the dependent variable, a measure usually not included in most standard sampling. Small tree equations would be invaluable for stands recently harvested or that had significant blowdown. However, the minimum stand age for the plots sampled for this study was 23 years, and the maximum understory strata contribution to the pool of woody biomass was only 1 percent.

Once allometric relationships are known, prediction of foliage area can be used for the estimation for measures of stand productivity. Determination of leaf size to weight ratios allows the calculation of LAI. One problem encountered with determined LAI was the disappointing model fit for the prediction of Fraser fir foliage area ($R^2 = .393$). All areas in the Black Mountains where the foliage samples were collected have been infested with the balsam woolly adelgid and since mortality of mature fir takes from two to nine years after stem infestation, it is likely that the fir trees sampled were in varying stages of adelgid infestation. Adelgid infestation of a fir causes the formation of premature heartwood which results in greatly reduced translocation of water and minerals to the crown, resulting in water stress, causing the tree to dramatically reduce the capability for photosynthesis (Puritch 1973). With varying levels of crown water stress among the fir samples and probable leaf organelle deterioration, it is likely that the relationship between needle area and weight is no longer a constant.

Range of LAI in temperate forests has been recorded from 1-21 m^2/m^2 depending on stand type, developmental stage, and climate (Jarvis and Leverenz 1983). Leaf areas of coniferous forests are generally large while decidous forests of the eastern United States typically have average maximum projected leaf areas of 6 m^2/m^2 (Whittaker 1966). Broadleaf decidous stand LAI values are probably lower due to the annual cost of entire foliage renewal (Jarvis and Leverenz 1983). Comparison of LAI values found for this study to other North American conifer forests (Table 2.16) suggests that maximum average LAI values for southern Appalachian lower elevation spruce found in this study are 65-75 % of average values found Pacific Northwest coastal forests (Westman and Whittaker 1975, Gholz et al. 1976, Grier and Running 1977, Waring et al. 1978). Interestingly, low elevation old-growth spruce-fir stands measured in 1989 had similar values to those recorded by Whittaker (1966) for spruce-fir stands in the Smokies. While there has been some evidence of red spruce crown thinning in the Great Smoky Mountains (Peart et al. 1992), deterioration of projected leaf area does not seem to be obvious yet. In contrast, high elevation stands in the Black and Great Smoky Mountains, where more than 50 % of the trees are recently dead probably due to the balsam woolly adelgid (Chapter 1), have LAI values substantially lower than values found by Whittaker in the 1960's (before substantial balsam woolly adelgid mortality) for high elevation fir in the Smokies. Weaver's (1972) LAI values were much higher than the values determined by this study for young second-growth spruce-fir (Table 2.13b), but were based on a very small sampling of foliage, and therefore some caution might be used with his equations.

Leaf area increases as a forest stand develops and then stabilizes at climax. Jaevis and Leverenz suggest that maximum leaf area in some forest types may be re-established after disturbance within a relatively small fraction of a stand generation time, noting that data from Marks and Bormann (1972) and Marks (1974) indicated that maximum leaf area in northern hardwoods may be reestablished five years after disturbance. However, stands in the Black Mountains were last logged in the 1930's (Pyle and Schafale 1988), and LAI in those formerly cut stands is significantly lower than on old-growth (Table 13b). Second growth stands at lower elevations (1525-1675 m) have probably been partially converted to increased hardwoods (mostly yellow birch) (Chapter 1) with a resulting lower leaf area capability. Future monitoring of the study sites will determine if maximum leaf area is still increasing and therefore stand productivity is contining to slowly increase, or rather if LAI values have stabilized suggesting long-term site quality deterioration with past logging practices. At higher elevation (1830-1980 m) stands, whether virgin or logged, LAI will probably continue to decrease as the remaining fir die due to the ongoing balsam woolly adelgid infestation. However, at lower elevation sites where Fraser fir is not a large component of the system, a decrease of LAI with time may suggest an ongoing deterioration of site productivity.

Table 2.16. Average projected LAI values for several different coniferous forests.

Forest Type	Location	LAI (m^2/m^2)	Source
Spruce, 1525 m	Great Smoky Mtns.	13.7	Table 2.13c
Spruce, 1675 m	Great Smoky Mtns.	15.2	Table 2.13c
Spruce-Fir, 1830 m	Great Smoky Mtns.	10.1	Table 2.13c
Spruce-Fir	Great Smoky Mtns.	14.8	1
Fir-Spruce, 1980 m	Great Smoky Mtns.	7.1	Table 2.13c
Fir	Great Smoky Mtns.	12.3	1
Spruce-Fir	Balsam Mtns, NC	12.0[a]	2
Hemlock	Great Smoky Mtns.	13.1	1
Pine	Great Smoky Mtns.	4.7	1
Sitka spruce	Western Oregon	19.0	3
Redwood	Northern California	20.0	4
Douglas-fir-Mt. Hemlock-Silver fir	Western Oregon Cascades	18.6	5

[a] Only a range of all-sided leaf area was given so a mean of the range was selected and then divided by 2.

1 - Whittaker (1966)
2 - Weaver (1972)
3 - Grier and Running (1977)
4 - Westman and Whittaker (1975)
5 - Gholz et al. (1976)

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Chapter III

Short-term mortality patterns in spruce-fir forests at the Balsam Mountains of Virginia, the Black Mountains of North Carolina, and the Great Smoky Mountains of Tennessee and North Carolina

ABSTRACT

Three southern Appalachian spruce-fir forests were monitored for overstory (DBH $\geq$ 5.0 cm) mortality between 1985 and 1989 for the four predominant tree species: red spruce (*Picea rubens* Sarg.), Fraser fir (*Abies fraseri* (Pursh) Poiret), yellow birch (*Betula lutea* Michaux f.), and mountain-ash (*Sorbus americana* Marshall). All trees were tagged and revisited each year. Overstory annual mortality varied with species; mountain-ash had the highest rate (6.4 %), followed by

fir (5.8 %), birch (2.7 %), and spruce had the lowest (2.1 %). A substantial proportion (20-30 %) of all trees that died, fell to the ground in same year, and were never part of the pool of standing dead stems. Comparisons of fir diameter distribution indicated that at sites where the balsam woolly adelgid (*Adelges piceae* Ratz.) was causing significant fir mortality (Black Mountains and Great Smoky Mountains), stand structure was shifting because of the elimination of larger (> 35 cm DBH) live fir stems. While fir mortality due to the adelgid has been observed for over thirty years, the pool of standing dead fir continues to increase. Prediction of individual tree mortality using logistic regression was unsuccessful for birch and mountain-ash, while equations to predict spruce and fir mortality depended on crown condition (amount of intact needles), as a predictor variable.

INTRODUCTION

Plant population trends can be entirely described with mortality and natality information. However complete mortality information on forest tree populations is rarely available for most species. Instead, most data that have been used to assess overstory mortality are based on standing dead stem densities (or basal area or volume) from ground surveys or aerial photography. Standing dead stems provide an inadequate substitute for an actual mortality rate unless information is included on decay and ingrowth rates (Peart et al. 1992), and the proportion of trees that die and immediately fall to the ground is known.

Mortality rates may be influenced by a number of characteristics. Harcombe (1987) reviewed a number of studies indicating a decline in mortality with increasing size. Goff and West (1975) and Lorimer and Frelich (1984) suggest that mortality rates increase with very large trees in uneven-aged stands. A concave curve of death rate may actually be U-shaped for tree populations with large individuals (Harcombe 1987). Furthermore, several studies (Goff and West 1975, Buchman et al. 1983, Lucier et al. 1989) indicate that there is a link between mortality and growth rate where a strong relationship has been found for mortality and trees with low growth rates. Stand-level as well as individual stem characteristics influence mortality. Stand population structure changes over time, most smaller stems die as a consequence of failing to successfully compete for resources such as light, water, or soil nutrients. Mortality is therefore related to size as a function of ability to compete or capture resources as well as stand successional stage (Peet and Christensen 1987).

Recently there has been some debate on whether the southern Appalachian spruce-fir is currently experiencing a form of forest decline. There has been documentation of red spruce (*Picea rubens* Sarg.) canopy crown deterioration (Bruck and Robarge 1988, Bruck et al. 1989, Peart et al. 1992), high levels of standing dead biomass (Bruck and Robarge 1988, Dull et al. 1988), as well as possible radial incremental growth reduction (McLaughlin et al. 1987, Cook 1992, LeBlanc et al. 1992). However, there is limited mortality rate information available for this forest type and that is based on small, short-term, localized studies (Nicholas and Zedaker 1989, Bruck et al. 1989, Busing and Wu 1990). Without complete mortality information, an accurate assessment of stand dynamics and forest health will be impossible.

Since mortality is an on-going natural ecological process, interest in tree death data for the southern Appalachian spruce-fir is centered around the question of whether tree mortality is higher than expected while considering documented past disturbances including degradative logging practices and the infestation of the balsam woolly adelgid (*Adelges piceae* Ratz.). Since little historical quantitative information is available (see Chapter 1), determination of what is "expected" is difficult without system-specific baseline information. Assessment of tree mortality in the spruce-fir may be possible with some reliance on information from other forest types. Research in other ecosystems suggests that mortality rates are influenced by a number of factors including tree size, growth rate, canopy competition, drought, nutrient deficiencies, mechanical abrasion, and insects and diseases (Goff and West 1975, Buchman et al. 1983, Franklin et al. 1987, Harcombe 1987, Waring 1987).

The objective of this paper is to describe recent mortality patterns for the predominant tree species of southern Appalachian spruce-fir forest type including red spruce, Fraser fir (*Abies fraseri* (Pursh) Poiret), yellow birch (*Betula lutea* Michaux f.), and mountain-ash (*Sorbus americana* Marshall) at different geographic locations, varying elevations, and different past land use histories, and therefore provide a baseline level for future demographic information. Prediction of the probability of tree mortality using logistic regression models was also examined using stem size, competition index, and stand characteristics.

METHODS

Field Sampling

In 1985, a stratified, randomly located, permanent plot system was established in the Balsam Mountains of Virginia (Mt. Rogers National Recreation Area), the Black Mountains of North Carolina, and the Great Smoky Mountains of Tennessee and North Carolina. Stratification factors included elevation (four classes: 1525, 1675, 1830, 1980 m, ± 30 m), exposure to prevailing winds (exposed versus protected), and topographic type (ridge/slope/draw) with three replicates per strata combination where ever possible. An *a priori* definition of the southern spruce-fir type required that plots (20 x 20 m^2) had to have at least 25 % spruce and/or fir live or former (dead standing stems) canopy coverage. Overstory strata (defined as woody stems with diameter at breast height [DBH] $\geq$ 5.0 cm) measurements by species included DBH (measured to the nearest mm), inspection for stem survivorship (live versus dead), crown condition (only for live spruce and fir; class 1: 100-90 % needles intact, class 2: 90-50 % needles intact, and class 3: 49- 1 % needles intact), and disturbance symptomology (signs of disease or damage to stems) for every tree on each plot. Ten, randomly selected, terminal intact, dominant, or codominant spruce or fir stems were cored for age at 15 cm below DBH. Past disturbance history of each plot was determined using maps from Pyle and Schafale (1988), consideration of average stand age calculated from the tree cores, as well as on-site inspection. Site data recorded at each plot included elevation, slope percent, aspect, macro- and micro-topographic features.

One hundred eight plots were sampled for the first time in 1985 (Table 3.1). Twenty-one additional plots were established in 1986, seven plots were added in 1987, and six in 1988. The overstory strata of each plot was inspected for stem survivorship, disturbance symptomology, and crown condition for each tree each year up to and including 1989.

Analysis

Tree species considered for analysis of mortality patterns had to make up at least one percent of all live standing overstory stems at each of the three study sites, and so included Fraser fir, red spruce, yellow birch, mountain ash, and Rhododendron species (*R. maximum* L. and *R. catawbiense* Michaux). Rhododendron was excluded from analysis because its prolific basal sprouting and layering (Plocher and Carvell 1987) made determination of mortality within a particular sampling period inexact. Overstory species that did not make up one percent of live density at all three sites and therefore were not part of the mortality analysis included striped maple (*Acer pensylvanicum* L.), red maple (*A. rubrum* L.), sugar maple (*A. saccharum* Marshall), mountain maple (*A. spicatum* Lam.), serviceberry (*Amelanchier arborea* var. *laevis* (Wiegand) Ahles), yellow buckeye (*Aesculus octandra* Marshall), paper birch (*Betula papyrifera* var. *cordifolia* (Regel)

Table 3.1. Chronology of spruce-fir plot establishment at three southern Appalachian study sites.

Study Area	Year of Plot Establishment					Total
	1985	1986	1987	1988	1989	
Mt. Rogers NRA	20	3	2			25
Black Mountains	32	8	5	6		51
Great Smoky Mountains	56	10				66
(Total)	108	21	7	6		142

Fernald), alternate-leaved dogwood (*Cornus alternifolia* L. f.), hawthorne (*Crataegus* spp.), American beech (*Fagus grandifolia* Ehrhart), witch-hazel (*Hamamelis virginiana* L.), mountain holly (*Ilex montana* T. & G.), mountain laurel (*Kalmia latifolia* L.), Fraser magnolia (*Magnolia fraseri* Walter), Norway spruce (*Picea abies* (L.) Karst.), fire cherry (*Prunus pensylvanica* L. f.), black cherry (*P. serotina* Ehrhart), and basswood (*Tilia heterophylla* Vent).

Species specific annual mortality rates were calculated on a by-plot basis and average rates were determined for all study site-elevation class combinations. Logistic multiple regression was used to develop models to predict probability of mortality of individual trees. Each fir, birch, spruce, and mountain-ash tree live at plot establishment formed a separate binary data point; each stem was designated as 0 if no event (alive in 1989) or 1 if the tree died during the study prior to 1989 field sampling. Maximum likelihood was used to estimate the parameters. Only independent variables significant at the 95 percent level were included. Independent variables considered for entry in the logistic model included live stand density (stems/ha), stand age, elevation (m), stem DBH (cm), crown condition, and a stem-specific competition index. Other variables sometimes included in mortality modeling such as stem age, height, and diameter growth prior to mortality (Hamilton and Edwards 1976) were not available for all stems. Crown position class was avoided due to the lack of repeatability (and therefore reliability) in reclassification for multi-aged, multi-storied stands (Nicholas et al. 1991).

Stand density was considered as an independent variable because it combines information on light availability, site productivity, and stage of stand development. Stand age gives some information on stand history; younger stands had most likely been logged or experienced a relatively recent catastrophic event. Elevation has been demonstrated to be correlated to spruce-fir species composition and abundance (Chapter 1). Stem DBH and crown condition give some indication of stem vigor, and DBH also provides information on stem height (Nicholas and Zedaker 1992).

A competition index was used as a more precise replacement for crown class. While crown position of a stem gives an indication of light availability for the tree, competition index is a function of stand density and stem size which may give a better indication of the tree's potential uptake of radiation, especially in shade tolerant system. Competition indices were derived from initial DBH measurements of live trees within a sample plot. Hegyi's (1974) diameter-distance index was tried but plot size was usually much too small to calculate an index for the larger trees. Lorimer (1983) suggested that competition indices are most effective when inclusion of size of the subject tree in relation to its competitors is factored into the index. Based on the assumption that DBH (measured for every tree) and height (which was not measured on every tree) are related, a competition index was computed by totaling basal area of all live stems on a plot with DBH greater than or equal to the sample tree.

RESULTS

Overall mortality rates varied with species; mountain-ash had the highest with an overall annual rate of 6.4 % and ranged from 3.3 % to 9.7 % among the three study sites (Tables 3.2a-c). No significant elevational trends were found. Fraser fir had an overall mortality rate of 5.8 % with the highest mortality found at the Great Smoky Mountains with 7.4 % (Table 3.2c) and the lowest found at the Black Mountains with 4.7 % (Table 3.2b). Fraser fir was the only species to have significant differences detected among elevation classes with mortality rates significantly higher at 1980 m at the Black Mountains (Table 3.2b). Yellow birch had a average mortality rate of 2.7 % between 1985 and 1989 for the three study sites. Birch was concentrated at or below 1830 m elevation and the highest mortality rate was found at the Black Mountains (3.9 %). Red spruce had the lowest annual mortality rate averaging 2.1 % among the three study sites. Higher spruce mortality at higher elevations (p = 0.20) did not heavily impact overall mortality rates since there was a decreasing density of spruce at increasing elevations.

Comparisons of mortality rates were made at the Black Mountains and Mt. Rogers area between old-growth and second growth stands within elevation classes. While second growth stands tended to have slightly higher mortality rates, there were no significant ($p > .05$) differences between land use histories for fir, birch, spruce, or mountain-ash.

A large proportion of trees that died, fell to the ground within the same year (Table 3.3). Many of these trees probably died as a result of being blown over. A full third (32.9 %) of all red spruce that died in a year, did not remain standing. More than a quarter of all mountain-ash (28.2 %) and yellow birch (26.9 %) that died, were never recorded as standing dead. Fraser fir had the lowest incidence (17.4 %) of stems that fell over during the same year that they died, with only 4.4 % of high elevation fir that died at the Great Smoky Mountains, fell down in the same sampling year.

A comparison of the number of standing live and dead stems at plot establishment and the number of standing dead stems in 1989 among diameter size classes (10 cm increments) for fir, birch, spruce, and mountain-ash at the three study sites allows consideration 1) if the size distribution of dead stems was comparable to live stems, 2) if the pool of standing dead stems was increasing, decreasing, or stable, and 3) if mortality was consistent among diameter size classes (Tables 3.4-3.15). (Note: percent of stems that died during 1985-1989 was included in Tables 3.4-3.15 in parentheses to provide a transfer rate from live to dead stems, however multiplication of the number of live trees by the percent of trees that died will underestimate mortality rates since not all plots were sampled in 1985 (see Table 3.1)).

The majority of live stems at the Mt. Rogers area (Tables 3.4-3.7) and the Black Mountains (Tables 3.8-3.11) were concentrated in the 5-15 cm DBH size class while live birch, spruce, and

Table 3.2a. Average annual mortality rates for Fraser fir, yellow birch, red spruce, and mountain-ash at two elevations at Mt. Rogers National Recreation Area.[1,2]

Elevation	Fraser fir	Yellow birch	Red spruce	Mountain-ash
m	(.	. . . . %	. . . .	. . . .)
1525	4.5 n = 428	1.7 n = 192	1.4 n = 193	4.8 n = 11
1675	6.4 n = 416	1.6 n = 94	2.4 n = 682	3.1 n = 85
Average	5.4 n = 844	1.7 n = 286	2.2 n = 875	3.3 n = 96

[1] No significant differences were found between elevations within a species based on the Scheffe procedure for multiple constrasts among means using angular transformations.

[2] n refers to the number of live trees encountered during the study (1985-1989).

Table 3.2b. Average annual mortality rates for Fraser fir, yellow birch, red spruce, and mountain-ash at four elevations at the Black Mountains.[2,3, 4]

Elevation	Fraser fir	Yellow birch	Red spruce	Mountain-ash
m	(......................	....	%	......................)
1525	. **n = 6**	2.1 **n = 68**	2.4 **n = 440**	7.7 **n = 21**
1675	5.7 **n = 33**	3.6 **n = 277**	2.4 **n = 501**	12.0 **n = 27**
1830	3.6 **n = 414**	5.4 **n = 97**	3.6 **n = 279**	6.0 **n = 128**
1980	7.6 **n = 161**	. **n = 4**	5.5 **n = 19**	1.0 **n = 26**
Average	4.7 **n = 614**	3.9 **n = 446**	2.7 **n = 1239**	6.4 **n = 202**

[2] **n** refers to the number of live trees encountered during the study (1985-1989).

[3] Mortality rates were not calculated when $n < 10$.

[4] Mean percentages between elevations within species differed significantly at $p = 0.1$ only for Fraser fir based on the Scheffe procedure for multiple contrasts among means using angular transformations.

Table 3.2c. Average annual mortality rates for Fraser fir, yellow birch, red spruce, and mountain-ash at four elevations at the Great Smoky Mountains.[1,2]

Elevation	Fraser fir	Yellow birch	Red spruce	Mountain-ash
m	(.	. . . . %	. . . .	. . . .)
1525	. n = 9	1.1 n = 96	1.1 n = 352	. n = 5
1675	11.7 n = 47	2.3 n = 57	0.8 n = 222	4.6 n = 11
1830	9.5 n = 140	1.9 n = 73	1.2 n = 154	13.9 n = 24
1980	6.1 n = 398	. n = 1	4.2 n = 75	10.3 n = 38
Average	7.4 n = 594	1.8 n = 227	1.3 n = 803	9.7 n = 78

[1] No significant differences were found between elevations within a species based on the Scheffe procedure for multiple constrasts among means using angular transformations.

[2] **n** refers to the number of live trees encountered during the study (1985-1989).

[3] Mortality rates were not calculated when **n** < 10.

Table 3.3. Percent of trees that fell to the ground during the same year of death (number of trees that died and fell/(trees that died and fell plus trees that died and remained standing) between 1985 and 1989 at three spruce-fir study sites.[1]

Study Site	Fraser fir	Yellow birch	Red spruce	Mountain-ash
	(.	. . . . %	. . . .	. . . .)
Mt. Rogers NRA	23.3 a n = 163	21.3 a n = 17	25.4 a n = 71	25.0 a n = 12
Black Mountains	28.6 a n = 98	17.6 a n = 61	38.3 a n = 107	39.0 a n = 41
Great Smoky Mountains	4.4 b n = 159	66.7 a n = 15	31.7 a n = 41	12.0 a n = 25
Average	17.4 n = 420	26.9 n = 93	32.9 n = 219	25.2 n = 78

Note: Mean percentages within columns followed by different letters differ significantly at $p = 0.1$ based on the Scheffe procedure for multiple contrasts among means using angular transformations.

[1] n refers to the number of trees that died during the study (1985-1989).

Table 3.4. Number of live Fraser fir at plot establishment, percent of fir that died between plot establishment and 1989, number of dead standing fir at plot establishment, and number of dead standing fir in 1989, stratified by diameter and elevation class at Mt. Rogers National Recreation Area.

DBH Sizeclass (cm)	1525 m (N = 12 plots)				1675 m (N = 13 plots)			
	Live Trees	% Died	*Dead*$_o$	*Dead*$_{89}$	Live Trees	% Died	*Dead*$_o$	*Dead*$_{89}$
5-15	265	(23)	139	165	293	(16)	157	126
15-25	137	(4)	8	10	76	(26)	49	59
25-35	24	(4)	6	6	51	(41)	21	27
35-45	3	(33)	2	3	15	(7)	1	2
45-55	0	(0)	0	0	2	(0)	1	1
Total	430	(16)	155	184	437	(21)	229	215

Table 3.5. Number of live yellow birch at plot establishment, percent of birch that died between plot establishment and 1989, number of dead standing birch at plot establishment, and number of dead standing birch in 1989, stratified by diameter and elevation class at Mt. Rogers National Recreation Area.

DBH Sizeclass (cm)	1525 m (N= 12 plots)				1675 m (N= 13 plots)			
	Live Trees	% Died	$Dead_o$	$Dead_{89}$	Live Trees	% Died	$Dead_o$	$Dead_{89}$
5-15	157	(6)	43	40	79	(6)	32	19
15-25	32	(0)	8	6	2	(0)	3	1
25-35	7	(0)	0	1	1	(0)	0	0
35-45	1	(0)	1	0	0	.	1	1
45-55	0	.	1	1				
Total	197	(5)	52	48	82	(6)	36	21

Table 3.6. Number of live red spruce at plot establishment, percent of spruce that died between plot establishment and 1989, number of dead standing spruce at plot establishment, and number of dead standing spruce in 1989, stratified by diameter and elevation class at Mt. Rogers National Recreation Area.

	1525 m (N = 12 plots)				1675 m (N = 13 plots)			
DBH Sizeclass (cm)	Live Trees	% Died	Dead_o	Dead_{89}	Live Trees	% Died	Dead_o	Dead_{89}
5-15	110	(5)	16	19	549	(7)	171	167
15-25	39	(5)	3	3	115	(11)	39	22
25-35	20	(5)	0	0	46	(11)	13	10
35-45	17	(0)	1	0	9	(11)	3	1
45-55	6	(0)	0	0	2	(0)	1	0
55-65	0	.	1	0				
65-75	0	.	0	0				
75-85	1	(100)	0	0				
Total	193	(4)	21	22	721	(8)	227	200

Table 3.7. Number of live mountain-ash at plot establishment, percent of mountain-ash that died between plot establishment and 1989, number of dead standing mountain-ash at plot establishment, and number of dead standing mountain-ash in 1989, stratified by diameter and elevation class at Mt. Rogers National Recreation Area.

DBH Sizeclass (cm)	1525 m (N = 12 plots)				1675 m (N = 13 plots)			
	Live Trees	% Died	*Dead$_o$*	*Dead$_{89}$*	Live Trees	% Died	*Dead$_o$*	*Dead$_{89}$*
5-15	6	(33)	5	4	87	(9)	22	29
15-25	5	(0)	1	1	2	(0)	1	1
25-35	0	.	1	0				
Total	11	(18)	7	5	89	(9)	23	30

mountain-ash at the Great Smoky Mountains (Table 3.13-3.15) were distributed among small and larger diameter classes. With a few exceptions, dead standing stems made up a small proportion of all stems within diameter classes. Dead standing Fraser fir at the Black Mountains (Table 3.8) and the Great Smoky Mountains (Table 3.12) and high elevation spruce at the Black Mountains (Table 3.10) had a higher proportion of standing dead than live stems in the larger DBH classes.

The pool of standing dead stems appeared to be stable or decreasing between 1985 and 1989 for yellow birch at all three study sites (Tables 3.5, 3.9, 3.13) while increasing for Fraser fir (Tables 3.4, 3.8, 3.12). There were increasing numbers of standing dead mountain-ash at the Great Smoky Mountains (Table 3.15) where annual mortality rates were the highest for mountain-ash (Table 3.2c), and for red spruce at the Black Mountains (Table 3.10) where annual mortality rates were also the highest for spruce (Table 3.2b).

Partly because of the large variability of sampling units (individual plots), tests for differences among mortality percentages among diameter classes did not reveal significant differences within elevation classes. Mortality percentages tended to be consistent among diameter classes except for Fraser fir at all three sites (Tables 3.4, 3.8, 3.12) and red spruce at the Black Mountains (Table 3.12) where greater proportions of larger diameter trees died.

Efforts to build logistic regression models for the prediction of individual birch and mountain-ash mortality were unsuccessful for each species as a whole or for each species at the different study sites. Logistic regression models were developed to predict the probability of individual tree mortality for Fraser fir and red spruce (Table 3.16). Separate models for each species among the three locations were compared and were determined to differ significantly and therefore separate equations were developed for each study site. The models selected as most appropriate for predic-

Table 3.8. Number of live Fraser fir at plot establishment, percent of fir that died between plot establishment and 1989, number of dead standing fir at plot establishment, and number of dead standing fir in 1989, stratified by diameter and elevation class at the Black Mountains.

DBH Sizeclass (cm)	1525 m (N = 14 plots)				1675 m (N = 16 plots)				1830 m (N = 16 plots)				1980 m (N = 5 plots)			
	Live Trees	% Died	$Dead_o$	$Dead_{89}$	Live Trees	% Died	$Dead_o$	$Dead_{89}$	Live Trees	% Died	$Dead_o$	$Dead_{89}$	Live Trees	% Died	$Dead_o$	$Dead_{89}$
5-15	8	(0)	2	2	34	(15)	2	2	283	(9)	93	93	120	(19)	140	121
15-25	0	(0)	1	1	1	(0)	2	2	113	(17)	66	80	36	(33)	60	59
25-35					0	(0)	1	1	28	(18)	18	22	9	(33)	15	11
35-45					1	(0)	1	1	3	(33)	6	5	7	(0)	3	3
45-55									0	.	2	2	0	.	2	2
Total	8	(0)	3	3	36	(14)	6	6	427	(12)	185	202	172	(22)	219	196

Table 3.9. Number of live yellow birch at plot establishment, percent of birch that died between plot establishment and 1989, number of dead standing birch at plot establishment, and number of dead standing birch in 1989, stratified by diameter and elevation class at the Black Mountains.

	1525 m (N = 14 plots)				1675 m (N = 16 plots)				1830 m (N = 16 plots)				1980 m (N = 5 plots)			
DBH Sizeclass (cm)	Live Trees	% Died	*Dead*$_o$	*Dead*$_{89}$	Live Trees	% Died	*Dead*$_o$	*Dead*$_{89}$	Live Trees	% Died	*Dead*$_o$	*Dead*$_{89}$	Live Trees	% Died	*Dead*$_o$	*Dead*$_{89}$
5-15	32	(16)	13	4	205	(13)	51	46	57	(16)	60	31	4	(50)	4	2
15-25	19	(5)	2	2	59	(10)	14	14	38	(16)	6	6	0	.	1	0
25-35	14	(0)	0	0	9	(11)	5	2	3	(33)	0	0				
35-45	5	(0)	1	1	1	(0)	1	0	1	(0)	0	0				
45-55	2	(0)	0	0	3	(0)	0	0	0	.	1	1				
55-65	1	(0)	0	0	2	(100)	0	2	0	.	0	0				
65-75	0	(0)	0	0	1	(100)	0	0	0	.	1	0				
75-85	1	(0)	0	0	0	.	0	0								
85-95					1	(0)	0	0								
Total	74	(8)	16	7	281	(13)	71	64	99	(16)	68	38	4	(50)	5	2

Table 3.10. Number of live red spruce at plot establishment, percent of spruce that died between plot establishment and 1989, number of dead standing spruce at plot establishment, and number of dead standing spruce in 1989, stratified by diameter and elevation class at the Black Mountains.

DBH	1525 m (N = 14 plots)				1675 m (N = 16 plots)				1830 m (N = 16 plots)				1980 m (N = 5 plots)			
Sizeclass (cm)	Live Trees	% Died	*Dead*$_o$	*Dead*$_{89}$	Live Trees	% Died	*Dead*$_o$	*Dead*$_{89}$	Live Trees	% Died	*Dead*$_o$	*Dead*$_{89}$	Live Trees	% Died	*Dead*$_o$	*Dead*$_{89}$
5-15	190	(6)	96	100	261	(6)	36	34	166	(13)	18	14	7	(0)	0	0
15-25	92	(10)	17	22	119	(10)	13	17	76	(5)	10	6	5	(40)	2	3
25-35	65	(2)	3	3	72	(8)	3	8	23	(13)	4	2	5	(0)	10	7
35-45	39	(0)	0	0	34	(3)	2	2	13	(23)	4	1	1	(0)	2	2
45-55	17	(6)	1	1	18	(11)	2	4	4	(0)	2	0	1	(100)	0	1
55-65	9	(11)	0	0	8	(13)	0	0	1	(100)	1	1	1	(0)	0	0
65-75	4	(25)	1	1	2	(0)	0	0								
75-85	1	(0)	0	0	1	(0)	1	1								
Total	417	(6)	118	127	515	(7)	57	66	283	(11)	39	24	20	(15)	14	13

Table 3.11. Number of live mountain-ash at plot establishment, percent of mountain-ash that died between plot establishment and 1989, number of dead standing mountain-ash at plot establishment, and number of dead standing mountain-ash in 1989, stratified by diameter and elevation class at the Black Mountains.

DBH Sizeclass (cm)	1525 m (N = 14 plots) Live Trees	% Died	$Dead_o$	$Dead_{89}$	1675 m (N = 16 plots) Live Trees	% Died	$Dead_o$	$Dead_{89}$	1830 m (N = 16 plots) Live Trees	% Died	$Dead_o$	$Dead_{89}$	1980 m (N = 5 plots) Live Trees	% Died	$Dead_o$	$Dead_{89}$
5-15	14	(14)	8	9	14	(50)	8	12	102	(20)	63	67	21	(5)	17	10
15-25	7	(0)	1	0	12	(50)	4	2	24	(41)	15	24	5	(0)	2	0
25-35	0	.	2	2	1	(0)	1	1	2	(100)	1	0	1	(0)	1	0
Total	21	(20)	11	11	27	(48)	13	15	102	(25)	79	91	27	(4)	20	10

Table 3.12. Number of live Fraser fir at plot establishment, percent of fir that died between plot establishment and 1989, number of dead standing fir at plot establishment, and number of dead standing fir in 1989, stratified by diameter and elevation class at the Great Smoky Mountains.

	1525 m (N = 18 plots)				1675 m (N = 18 plots)				1830 m (N = 18 plots)				1980 m (N = 12 plots)			
DBH Sizeclass (cm)	Live Trees	% Died	$Dead_o$	$Dead_{89}$	Live Trees	% Died	$Dead_o$	$Dead_{89}$	Live Trees	% Died	$Dead_o$	$Dead_{89}$	Live Trees	% Died	$Dead_o$	$Dead_{89}$
5-15	10	(30)	52	51	51	(27)	348	310	128	(25)	274	268	332	(22)	182	201
15-25	0	.	16	10	3	(100)	107	93	9	(56)	87	84	68	(22)	107	109
25-35	0	.	0	0	1	(100)	20	18	15	(47)	31	38	36	(28)	61	69
35-45	0	.	3	3	0	.	7	6	5	(60)	21	20	6	(17)	12	11
45-55	0	.	1	1	0	.	3	2	0	(0)	4	4	0	.	0	0
55-65					0	.	1	0	1	(100)	0	1	0	.	0	0
65-75									0	(0)	1	1	0	.	1	0
Total	10	(30)	72	65	55	(34)	486	429	158	(30)	418	416	442	(22)	363	391

Table 3.13. Number of live yellow birch at plot establishment, percent of birch that died between plot establishment and 1989, number of dead standing birch at plot establishment, and number of dead standing birch in 1989, stratified by diameter and elevation class at the Great Smoky Mountains.

DBH Sizeclass (cm)	1525 m (N = 18 plots)				1675 m (N = 18 plots)				1830 m (N = 18 plots)				1980 m (N = 12 plots)			
	Live Trees	% Died	*Dead$_o$*	*Dead$_{89}$*	Live Trees	% Died	*Dead$_o$*	*Dead$_{89}$*	Live Trees	% Died	*Dead$_o$*	*Dead$_{89}$*	Live Trees	% Died	*Dead$_o$*	*Dead$_{89}$*
5-15	50	(6)	8	8	15	(7)	8	7	55	(11)	16	12	0	(0)	1	1
15-25	22	(0)	1	1	6	(0)	3	2	17	(0)	9	9	1	(0)	1	1
25-35	9	(0)	1	1	11	(9)	0	1	8	(0)	1	0				
35-45	7	(0)	1	1	10	(20)	1	3	5	(0)	1	1				
45-55	3	(0)	0	0	8	(13)	0	1	2	(0)	0	0				
55-65	2	(0)	0	0	6	(0)	0	0								
65-75	2	(0)	0	0	2	(0)	0	0								
75-85	2	(50)	0	0												
Total	97	(4)	11	11	58	(9)	12	14	87	(7)	26	22	1	(0)	2	2

Table 3.14. Number of live red spruce at plot establishment, percent of spruce that died between plot establishment and 1989, number of dead standing spruce at plot establishment, and number of dead standing spruce in 1989, stratified by diameter and elevation class at the Great Smoky Mountains.

DBH Sizeclass (cm)	1525 m (N = 18 plots)				1675 m (N = 18 plots)				1830 m (N = 18 plots)				1980 m (N = 12 plots)			
	Live Trees	% Died	$Dead_o$	$Dead_{89}$	Live Trees	% Died	$Dead_o$	$Dead_{89}$	Live Trees	% Died	$Dead_o$	$Dead_{89}$	Live Trees	% Died	$Dead_o$	$Dead_{89}$
5-15	194	(4)	30	26	98	(5)	31	34	51	(8)	11	11	25	(24)	1	6
15-25	61	(2)	5	4	35	(0)	2	1	36	(6)	7	5	11	(18)	3	1
25-35	23	(0)	2	0	25	(0)	6	4	20	(5)	3	3	11	(18)	0	2
35-45	16	(0)	2	2	14	(0)	2	2	29	(0)	0	0	16	(6)	1	2
45-55	24	(0)	2	2	16	(6)	0	1	27	(0)	3	3	13	(38)	0	0
55-65	22	(9)	2	2	28	(0)	3	3	18	(0)	5	3	8	(13)	0	1
65-75	18	(6)	3	4	28	(4)	3	4	9	(0)	0	0	1	(0)	1	1
75-85	9	(11)	1	2	13	(8)	1	1	6	(0)	0	0				
85-95	6	(0)	0	0	4	(0)										
95+	1	(0)	1	0	1	(0)										
Total	374	(3)	48	42	196	(4)	48	50	196	(4)	29	25	85	(15)	6	13

Table 3.15. Number of live mountain-ash at plot establishment, percent of mountain-ash that died between plot establishment and 1989, number of dead standing mountain-ash at plot establishment, and number of dead standing mountain-ash in 1989, stratified by diameter and elevation class at the Great Smoky Mountains.

DBH Sizeclass (cm)	1525 m (N = 18 plots) Live Trees	% Died	Dead_o	Dead_{89}	1675 m (N = 18 plots) Live Trees	% Died	Dead_o	Dead_{89}	1830 m (N = 18 plots) Live Trees	% Died	Dead_o	Dead_{89}	1980 m (N = 12 plots) Live Trees	% Died	Dead_o	Dead_{89}
5-15	1	(0)	0	0	10	(20)	2	4	19	(63)	5	6	31	(29)	8	16
15-25	3	(0)	0	0	1	(0)	1	0	5	(20)	0	1	6	(17)	5	5
25-35									2	(20)	0	1	3	(33)	0	1
Total	4	(0)	0	0	11	(18)	3	4	26	(54)	5	8	40	(28)	13	22

tion of fir and spruce mortality all included crown condition as an independent variable. If a tree had lost a noticeable amount of needles then probability of survivorship during the five year sampling period decreased. Elevation was important for prediction of spruce mortality; as elevation increased, survivorship decreased. Factors such stand age, diameter, and competition index were of limited or no use for model building.

Statistics for the assessment of model predictive ability (e.g. the c and R statistics) indicate that the logistic regression models for fir and spruce have limited predictive ability. The R statistic for fir ranged from .377 to .447. The R statistic for the model predicting spruce mortality at the Black Mountains (where significant mortality occurred due to ice storms (Nicholas and Zedaker 1989)) was only .178. The R statistic for spruce at the other two sites ranged from .388 and .426. The highest c statistic value for any of the equations was .807.

DISCUSSION

As different tree species have different typical life spans, they may also have different expected mortality rates. Some species do not have short life spans but have a higher mortality rate compared to their associates (Oliver and Larson 1990). Generally though, with the exclusion of catastrophic events, annual mortality of overstory trees in temperate systems ranges from .5 to 7 % (Harcombe and Marks 1983, Buchman et al. 1983). While this rather short-term study found that red spruce had an overall average mortality rate of 2.1 %, mortality specific to the Great Smoky Mountains (1.3 %, Table 3.2c) was quite similar to findings of Busing and Wu (1990) for a twenty year long study of spruce mortality also set in the Great Smoky Mountains. The overall five year average spruce mortality rate of 2.1 % in no way approached 8.1 % found by Nicholas and Zedaker (1989) or 34 % found by Bruck et al. (1989) both in 1987 for Black Mountains. Substantial ice

Table 3.16. Logistic regression models for prediction of the probability of tree mortality at three southern Appalachian spruce-fir forests. Model follows form: $P(\text{mortality}) = [1 + \exp(-(b_0 + b_1X_1 + \ldots + b_kX_k))]^{-1}$

where:

b_k = parameter coefficients
X_k = independent variables.

Study Site	Species	n	Parameter Estimates: Intercept	Crown Condition	Stand Density	Elevation	Competition Index	DBH	Criteria to Estimate Fit: $p > x^{2a}$	c^b	R^c
					(stem/ha)	(m)		(cm)			
MRNRA	Fir	855	3.1342	-1.5151	.000600				.0001	.758	.377
	Spruce	908	28.2412	-2.4547		-0.0137			.0001	.768	.426
BM	Fir	639	2.7142	-1.2689	.000493		-0.0319		.0001	.768	.378
	Spruce	1232	6.5768	-0.7869	.000329	-0.0022			.0001	.646	.178
GSM	Fir	658	5.8492	-1.6085				-0.0685	.0001	.799	.447
	Spruce	917	14.0387	-1.6158	-.000550	-0.0046			.0001	.807	.388

[a] Significance value of the log likelihood chi-square that tests model goodness of fit.

[b] The c statistic is the proportion of concordant pairs plus one-half the proportion of tied pairs and is a measure of the predictive value of the model. The values range from 0 to 1; values closer to 1 indicate better predictive ability.

[c] The R statistic measures the model likelihood ratio chi-square with a correction for the number of independent variables and is similar to the coefficient to coefficient of determination (R^2) in Least Squares Regression. The values range from 0 to 1; values closer to 1 indicate a better model fit (Harrell 1986).

storms occurred during the winter of 1986-1987 in the Black Mountains and were the only major catastrophic events to occur during my study. In contrast to red spruce, average fir mortality rates ranged from 4.7 to 7.4 percent. Higher mortality rates might be attributed to the ongoing balsam woolly adelgid infestation. However, stands at the Mt. Rogers area, where fir is not as susceptible to the adelgid (Eagar 1984), have average fir mortality of 5.4 percent, with mortality at the higher elevations at 6.4 percent a year. Stand age information in Chapter 1 has led to a hypothesis that fir stands on the top of Mt. Rogers may experience high mortality in the near future due to advanced age. Data from this study indicates that higher fir mortality rates on Mt. Rogers may have already commenced.

A study tracking mortality of permanently marked red spruce and balsam fir (*Abies balsamea* (L.) Mill.) was carried out in Vermont, New Hampshire, and New York also during 1985-1989 (Peart et al. 1992). Overall, the annual mortality for red spruce was 0.85 %, but it must be recognized that the demographic data was collected well after significant spruce basal area and density reductions were reported in the northern Appalachians from the mid-1960's to the early 1980's (Siccama et al. 1982, Foster and Reiners 1983, Vogelmann et al. 1985, Friedland 1989). Annual balsam fir mortality averaged 1.2 % for the northern Appalachian study, somewhat lower than the 5.8 % found for southern Appalachian fir. It should be also noted that no coincident significant balsam woolly adelgid or other insect infestation was found during the northern Appalachian study. Sprugel (1984) tracked mortality rates in wave-regenerated balsam fir forests and found that as stand density decreases after canopy closure, fir mortality was as high as 20-25 % (between ages 20-30), and decreased down to 4 % by age 55. Average age of second growth fir in my study was predominantly under age 50 (Table 1.5, Chapter 1), which suggests that some competition-related mortality may be occurring at second growth stands at Mt. Rogers National Recreation Area and the Black Mountains.

Since little mortality information exists for southern Appalachian yellow birch or mountain-ash, it is difficult to assess if rates found in this study are normal. An average mortality rate of 2.7 % for yellow birch does not seem alarmingly high, however Erdmann (1990) points out that birch commonly live to more than 300 years of age. Widespread mortality of yellow birch occurred between the 1930's and 1950's in Canada and the northeastern United States due to birch dieback, however the disease symptomology was not frequently observed throughout this study. Yellow birch is susceptible to root, stem, and crown injury and is more severely affected than its associates (Erdmann 1990). During the present study yellow birch was frequently observed to have signs of stem disease (23 % of all stems), severe insect-related defoliation (20 % of all stems), and bole damage (18 % of all stems). It may be since high elevation yellow birch exist in a harsh environment, damaged stems are more susceptible to mortality.

Little information is available on life expectancy of southern mountain ash, but an average mortality rate of 6.7 % seems high for a tree that can live at least half a century. The mountain-ash sawfly (*Pristiphora geniculata* Hartig), an insect pest of the *Sorbus* genus, has been identified as a major defoliator of high elevation mountain-ash in the southern Appalachians (P. Durr, personal communication). More than a quarter of all mountain-ash were observed to have significant insect-related defoliation during this study. While the sawfly has not been considered to cause lasting harm to the tree since it is an mid-season defoliator (Johnson and Lyon 1988), perhaps mountain-ash located in the high elevation spruce-fir forest may not store enough food reserves to withstand additional stress.

Prediction of mortality in old-growth forests or stands with long-lived or shade-tolerant species may not be easily done. Instead of the classic Type III survivorship curve (an inverse J-shaped curve) (Deevey 1947), Goff and West (1975) suggest that in all-aged stands understory trees should experience high mortality, vigorous overstory trees should experience low mortality and bigger trees should experience high mortality because they are more vulnerable to allogenic stresses. A survivorship curve of red spruce in Great Smoky Mountains old-growth stands follows the pattern outlined by Goff and West (Figure 3.1). There are high densities for overstory trees from 5 to 25 cm DBH, stable densities for trees with 25 to 65 cm DBH, and larger trees steadily decrease in numbers. While logistic regression have thus far provided the best function to model mortality (Monserud 1976, Press and Wilson 1978, Guan and Gertner 1991), most successful prediction models have been built for managed stands or those with few large or slow-growing trees (Hamilton and Edwards 1976, Buchman et al. 1983, Hamilton 1986, Avila 1990), or for stands that have sustained a single encompassing catastrophic event such as fire (Greene and Shilling 1987, Regelbrugge 1988). Instead, montane spruce-fir forests exist in harsh environments, where stand dynamics are dominated by relatively small-scale wind-caused tree throws (Foster and Reiners 1983, White et al. 1985) for old-growth or at least older stands. Storm events that cause heightened mortality levels are stocastic events but cannot be considered rare (Nicholas and Zedaker 1989). Mortality rates in spruce-fir stands may more variable than in other temperate forests, where compensating factors exist such as extreme shade tolerance of the dominant species and the longevity of red spruce.

Most stands for this study were more than 40 years of age (except for high elevation fir stands) and it is likely that competition-based mortality had long since occurred. Most of the spruce trees in this study probably fall in the portion of a death rate curve where mortality is consistent among diameter classes. Mortality of Fraser fir is predominantly driven by the balsam woolly adelgid. However, since fir death is not immediate (Amman and Speers 1965, Amman 1970), infestation of different study areas was not simultaneous (Chapter 1), and adelgid-caused mortality is partly related to climatic conditions (Hay et al. 1978, Eagar 1984), fir survivorship may not be accurately predicted based on the available variables. The only variable that did consistently aid in the description of spruce and fir mortality was crown condition or the amount of foliage retained. It is not surprising that a tree that has lost more than half of its needles has a higher probability of death. In the northern Appalachians, MacLean and Ostaff (1989) also found that balsam fir mortality was correlated with visual estimates of cumulative defoliation.

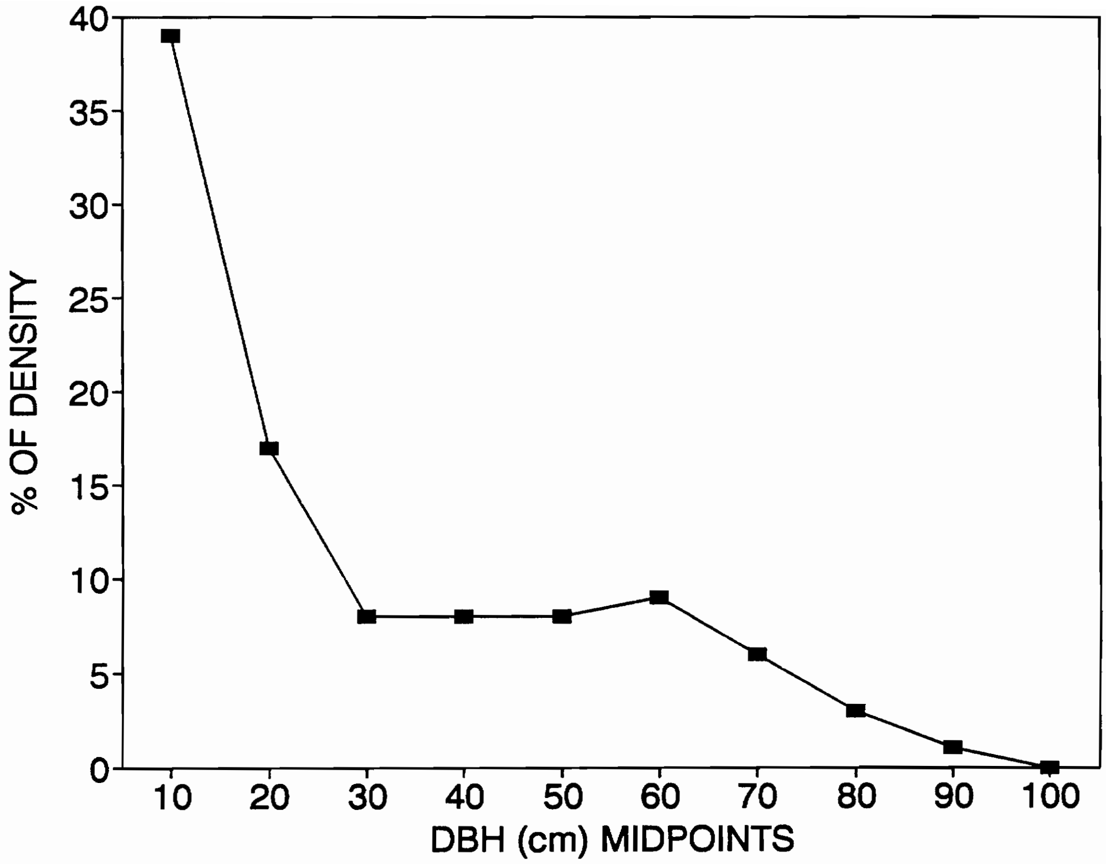

Figure 3.1. Diameter distribution of percentage of live red spruce stems in old-growth stands in the Great Smoky Mountains.

The results from this study suggest that enumerations of standing dead trees should not be used to assess tree mortality patterns. The large and variable proportion of overstory trees that fell down immediately and are never counted as standing dead suggest that the use of standing dead to reconstruct past stand structure provides an incomplete picture. Recent studies that concentrated on reporting amount of dead red spruce stems (Dull et al. 1988, Tritton and Siccama 1990, Silver et al. 1991, Craig and Friedland 1991) with no consideration of stem size, offer little insight into previous stand development. Furthermore, assessments of standing dead stems using aerial photography are still unable to detect the difference between dead spruce or dead fir (Dull et al. 1988). Such data provide little information on spruce mortality trends in areas previously infested with the balsam woolly adelgid. Harcombe (1987) points out that the relationship between percent dead basal area and percent dead standing density allows some reflection of stand age structure and dynamics. Clearly more complex analysis will need to be carried out, including research on decay rates and consideration of site effects (e.g. elevation, topography), before use of standing dead tree densities will provide meaningful information on changes in forest structure.

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Chapter IV

Short-term projection (20 years) of forest growth and structure of the southern Appalachian spruce-fir

ABSTRACT

A short term (twenty year) projection of forest structure was developed for southern Appalachian spruce-fir stands at Mt. Rogers National Recreation Area in Virginia, the Black Mountains of North Carolina, and the Great Smoky Mountains of Tennessee and North Carolina using data from permanent plots collected from 1985 to 1989. Individual tree basal area increment predictions for red spruce *Picea rubens* Sargent), Fraser fir (*Abies fraseri* (Pursh) Poiret) and yellow birch (*Betula lutea* Michaux f.), along with ingrowth and mortality information were combined to provide predictions starting from the year 1989 and ending in 2009. Mt. Rogers NRA, a primarily second-growth forest, was projected to have increases in spruce basal area, decreases in fir, and little change in birch. Lower elevations for the Black Mountains, another forest with a substantial logging history, were projected to have little change in basal area with some decreases in live densities.

At higher elevations fir basal area contribution increased and at the highest elevations spruce and birch disappeared. Little change was predicted for the old-growth spruce-fir forest found at the Great Smoky Mountains at or below 1830 m; however, at higher elevations both spruce and fir contributions were reduced by half.

INTRODUCTION

While lightning fire and debris avalanches occur, spatially small canopy gaps ($\geq 200\ m^2$) dominant the natural disturbance regime of old-growth southern Appalachian spruce-fir forests (White et al. 1985a). Previous efforts to simulate future southern Appalachian spruce-fir forest structure have been based on gap models which primarily estimate the direction of forest succession. White et al. (1985b) used transition probability analysis to examine overstory/understory comparisons in an old-growth stand for the prediction of future composition. They found that predictions of future composition depended on type of input variable including understory size class, type of stand descriptor (frequency versus density), and gap versus shade plot status. Their results suggested that in an undisturbed stand shade-tolerant Fraser fir (*Abies fraseri* (Pursh) Poiret) was predicted to increase in importance while yellow birch (*Betula lutea* Michaux f.) was predicted to become established in gaps. A gap model was developed from the FORET model of Shugart and West (1977) to stimulate stand dynamics of an old-growth, all-aged spruce-fir forest in the Great Smoky Mountains (Busing and Clebsch 1987). In the absence of exogenous disturbance, the model predicted long-term coexistence of red spruce (*Picea rubens* Sargent) and Fraser fir. Unlike the transition analysis, Busing and Clebsch were able to validate their model for stands that were 35, 50, and 70 years old. Both models provided for long-term predictions but were built from very limited data sets that each included only one year of data from a small sampling area.

Dramatic changes have been recently documented for this forest type including significant crown deterioration for red spruce (Bruck and Robarge 1988, Bruck et al. 1989, Peart et al. 1992), high mortality rates for Fraser fir (Chapter 3) most likely due to regional infestation of the balsam woolly adelgid (*Adelges piceae* Ratzeburg), and some conflicting evidence of a reduction in spruce radial incremental growth (McLaughlin et al. 1987, Cook 1992, LeBlanc et al. 1992). Most previous research done on stand dynamics of southern spruce-fir has been carried out on old-growth spruce-fir or stands not yet impacted by the balsam woolly adelgid. However, at this point much of the ecosystem now includes second growth forest or stands severely impacted by the balsam woolly adelgid, and stand dynamics may not be still dominated by small canopy gaps (Nicholas and Zedaker 1989).

This study is aimed at providing a short-term projection (20 year) of forest structure since accelerated rate of change is expected to occur with increased mortality and reduced growth. Unlike gap models which estimate the direction of forest succession based on hypothesized mechanics of forest dynamics, this distance-independent tree-level model estimates forest growth and changes given current conditions. The model developed here predicts individual tree basal area and is calibrated for the predominant overstory tree species of the southern Appalachian spruce-fir including red spruce, Fraser fir, and yellow birch. Equations are based on individual tree data collected from a series of permanent plots located over an extensive portion of the spruce-fir forest with considerable variation in site, species composition, age structure, and past management. Basal area increment predictions along with understory and mortality information are combined to provide short-term predictions of stand structure that are compared to current stand conditions. The permanent plot data (that formed the basis of the model) are also compared to a second data set collected from a systematic sampling of the southern Appalachian high elevations in order to determine the pervasiveness of the forest type.

METHODS

Field Methods

Beginning in 1985 a stratified, randomly located, permanent plot system was established in the Mt. Rogers National Recreation Area of Virginia (located in the Jefferson National Forest), the Black Mountains of North Carolina (including the Mt. Mitchell State Park, and parts of the Pisgah National Forest, Blue Ridge Parkway, and City of Asheville Watershed), and the Great Smoky Mountains of Tennessee and North Carolina (located in the Great Smoky Mountains National Park) as part of the National Acid Precipitation Assessment Program's Forest Response Program to monitor current spruce-fir forest vigor and long-term dynamics. Stratification factors included elevation (four classes from 1525 to greater than 1980 m), exposure to prevailing winds (exposed versus protected aspects), and topography type (ridge, slope, or draw) with three replicates per strata combination wherever possible (Table 4.1). An *a priori* definition of the southern spruce-fir type required that plots (20 x 20 m^2) had to have at least 25 % spruce and/or fir live or former (dead standing stems) canopy coverage. One hundred and eight plots were sampled for the first time in 1985. Twenty-one additional plots were established in 1986, seven were added in 1987 and six in 1988 (see Table 3.1).

Tree (defined as stems with diameter at breast height (DBH) ≥ 5.0 cm) measurements included DBH (measured to the nearest mm), inspection for stem survivorship (live versus dead), crown condition (only for live spruce and fir (class 1, 100-90 % needles intact; class 2, 89-50 % needles intact; class 3, 49-1 % needles intact; class 4, recently dead; class 5, dead), and disturbance symptoms (signs of disease or damage to stem) on every tree on each plot. All qualitative observations were made by at least two technicians for each tree. At each plot ten, randomly selected, terminal intact, dominant, or codominant spruce or fir stems were measured for height and cored for age at

Table 4.1. Distribution of permanent plots among elevation, topography, and exposure classes at three southern Appalachian spruce-fir sites.

	Topographic Position					
	Draw		Slope		Ridge	
Elevation	Exposed	Protected	Exposed	Protected	Exposed	Protected
(m)	(.	. . . .	. . . # of plots . . .	. . . .	. . . .	. . . .)
A. Mt. Rogers National Recreation Area						
1525	2	2	2	3	3	
1675		1	3	3	3	3
B. Black Mountains						
1525	2	3	3	3		3
1675	2	2	3	3	3	3
1830	2	3	2	3	3	3
1980			1		1	3
C. Great Smoky Mountains						
1525	3	3	3	3	3	3
1675	3	3	3	3	3	3
1830	3	3	3	3	3	3
1980			3	3	3	3

15 cm below DBH. Past disturbance history of each plot was determined using maps from Pyle and Schafale (1988), consideration of average stand age calculated from the tree cores, as well as on-site inspection. Site data recorded at each plot included elevation, slope percent, aspect, macro- and micro-topographic features. The overstory strata of each plot was inspected for stem survivorship, disturbance symptomology, and crown condition for each tree each year up to and including 1989. Diameter measurements were made at plot establishment and then again in 1987 and 1989.

Understory (defined as woody stems with DBH < 5.0 cm and height greater than 1.37 m) measurements included basal diameter (15 cm above ground for uphill side of the stem) to the nearest mm for all live and dead stems at three permanently marked, randomly selected 16 m^2 subplots at each plot. Understory strata was sampled at plot establishment and then again in 1987 and 1989. Ingrowth trees (stems that grew from understory into tree size strata) throughout each plot were tabulated in 1987 and 1989.

In 1986 and 1987 a systematic sampling of the overstory using line transects was carried out for the high elevation portions of Mt. Rogers National Recreation Area (8 transects), the Black Mountains (20 transects), and the Great Smoky Mountains (26 transects). Transect starting points were along each site's main ridgeline and proceeded downslope following a randomly chosen azimuth (Table 4.2). Azimuth directions were equally distributed among four categories (Northeast: 1-90°, Southeast: 91-180°, Southwest: 181-270°, Northwest: 271-360°). Variable plot sampling was started at 1980, 1905, 1830, 1755, or 1675 m elevation (whichever was closest to the elevation of the starting point) and continued every 76 m decrease in elevation, with three plots per point. Transects were continued until an elevation of 1370 m was reached (transects in the Smokies were only continued until 1525 m) or until private lands were encountered. Overstory data collected included live and dead stand basal area and density, individual stem DBH, crown condition, and disturbance symptomology.

Table 4.2. Origin, maximum elevation, azimuths of transects sampled at three southern Appalachian spruce-fir sites.

Transect Origin	Maximum Elevation	Azimuths
	(m)	(°)
A. Mt. Rogers National Recreation Area		
Whitetop	1683	18, 72, 135, 249
Mt. Rogers	1747	49, 166, 237, 313
B. Black Mountains		
Celo Knob	1944	265, 301
Horse Rock	1878	89, 116
Deep Gap	1744	90, 115, 264, 310
Balsam Cone	2012	253, 310
Mount Craig	2027	80, 109
Mt. Mitchell	2038	82, 163, 255, 340
Gap below Mt. Mitchell State Park Restaurant	1881	250, 314
Clingman's Peak	1991	88, 116
C. Great Smoky Mountains		
Mt. Buckley	2003	344
Clingman's Dome	2027	16, 103, 134
Mt. Love	1954	118, 354
Mt. Love, intersection of TN & NC state lines and Swain county line	1902	120
Mt. Collins	1870	8, 75, 132
Mingus Lead	1726	270
Cliff Top, Mt. LeConte	1998	305
High Top, Mt. LeConte	2010	4, 162
Mt. Kephart	1895	251, 264
Laurel Top	1801	41, 284
Mt. Sequoyah	1813	264, 171
Mt. Chapman	1956	269, 337
Mt. Guyot	2019	244, 258
Old Black	1942	251, 256

Analysis

Tree species groups considered for model analysis included Fraser fir, red spruce, yellow birch, and all other woody species measured as ingrowth or trees with the exception of Rhododendron species (*R. maximum* L. and *R. catawbiense* Michaux). Rhododendron was excluded from any analysis because it was inconsistently sampled in the Great Smoky Mountains. Species that occurred too infrequently for adequate prediction of ingrowth, mortality, and stem growth were lumped into the "other species" category included striped maple (*Acer pensylvanicum* L.), red maple (*A. rubrum* L.), sugar maple (*A. saccharum* Marshall), mountain maple (*A. spicatum* Lam.), serviceberry (*Amelanchier arborea* var. *laevis* (Wiegand) Ahles), yellow buckeye (*Aesculus octandra* Marshall), paper birch (*Betula papyrifera* var. *cordifolia* (Regel) Fernald), alternate-leaved dogwood (*Cornus alternifolia* L. f.), hawthorne (*Crataegus* spp.), American beech (*Fagus grandifolia* Ehrhart), witch-hazel (*Hamamelis virginiana* L.), mountain holly (*Ilex montana* T. & G.), mountain laurel (*Kalmia latifolia* L.), Fraser magnolia (*Magnolia fraseri* Walter), Norway spruce (*Picea abies* (L.) Karst.), fir cherry (*Prunus pensylvanica* L. f.), black cherry (*P. serotina* Ehrhart), mountain ash (*Sorbus americana* Marshall), basswood (*Tilia heterophylla* Vent), eastern hemlock (*Tsuga canadensis* (L.) Carr), and blueberry (*Vaccinium constablaei* Gray and *V. erythrocarpum* Michaux). The "other species" group accounted for only 4, 5, and 12 % of total live basal area at permanent plots sampled at the Great Smoky Mountains, Mt. Rogers NRA, and the Black Mountains, respectively.

Poisson regression (using the GLIM package (Royal Statistical Society 1985)), discriminant analysis, and stepwise regression were used to examine relationships between overstory/understory/site variables for rate of ingrowth and mortality on a plot basis. Ingrowth and mortality represented relatively rare events for many of the plots sampled. Therefore Poisson regression considered number of ingrowth or mortality, by species, on a plot basis as a function of stand characteristics (basal area, elevation, understory and overstory densities, stand age, relative importance of overstory spruce, relative importance of overstory fir, etc.) as regressor variables based on the Poisson distribution. Canonical discriminant analysis was used to determine if different levels (high, low, none) of ingrowth or mortality could be predicted on plot basis using stand characteristics as canonical variables. Stepwise regression considered number of ingrowth or mortality, by species, on a plot basis as a function of stand characteristics as the regressor variables. While some studies have relied on applications of the Leslie Matrix (Usher 1966) or Markov chains (Valentine and Furnival 1989) for predicting ingrowth it was decided that understory strata had been inadequately sampled to use those methods, given the wide range of stand age structure. Efforts to build models for the prediction of individual stem mortality were unsuccessful for birch (Chapter 3). Logistic models that were built for spruce and fir were of questionable utility since all equations (R^2 values ranged from .178 to .447) were dependent on the crown condition variable, a variable that would probably change dramatically during a twenty year growth projection period. Therefore logistic equations were not considered for use in this analysis.

A five season diameter growth increment (**dd59**) was calculated for each tree that survived to 1989. Trees from plots that were established in 1986 and 1987 had a growth increment adjusted for four and three years, respectively, of growth. Trees from plots established in 1988 were not used in the development of a basal area increment equation. All trees that had measurements that indicated negative growth or growth greater than 2.5 cm in a two year period were eliminated from the data set used to build an increment equation, on the assumption that a measurement error likely existed. Stepwise regression analysis was used to examine relationships between overstory/site variables and overstory stem growth rates. Regressor variables that measure stem size, site quality, and competition were considered (Wykoff 1990), including DBH, elevation, aspect, slope, site index, basal area, density, stand age, and competition index. Crown ratio has also been suggested to be useful in predicting growth increment (Hahn and Leary 1979, Amateis et al. 1989). However crown ratio was unavailable for most stems and efforts to accurately model it using DBH were unsuccessful (based on coefficient of determination).

Ingrowth, mortality, and growth components were calculated for a four year basis and were combined for a four year stand projection for red spruce, Fraser fir, and yellow birch using the 1989 permanent plot data as the starting point. The number of stems that died and stems that entered the plot as ingrowth were calculated for each species for each plot. Survivorship within a species was randomly assigned to individual stems. Growth increment was then calculated for surviving stems. After survivorship and growth routines were run, understory ingrowth stems were added to the bottom of each plot listing (so that for the next iteration mortality of past ingrowth was possible but not necessarily likely) to complete a four year iteration. Stand level variables (e.g. basal area and density) were recalculated and the model was sent through another iteration. A total of five iterations (for the years: 1993, 1997, 2001, 2005, 2009) were carried out for a final twenty year projection of stand structure. All analysis other than Poisson regression were carried out using the SAS packages (SAS Institute Inc. 1985).

RESULTS

TRANSECTS

Spruce was not found at Mt. Rogers NRA below an elevation of 1525 m (Table 4.3). Transect data indicated that at 1525 m red spruce made up 5 % of the live basal area, increasing to 41 % at 1600 m, and 67 % at 1675 m. Fir was not found until an elevation of 1600 m where it made up 11 % of the basal area and increased to 25 % at the highest elevation sampling station. Yellow birch increased from 14 % of live basal area at 1370 m up to 38 % by 1600 m and decreased to 8 % at 1675 m elevation. Comparison of transect to permanent plot data indicates that plots located at 1525 m elevation are atypical of points systematically distributed along random transects. Permanent plots had a greater amount of spruce, fir, and total basal area and density than the transects at that elevation. In contrast, permanent plots at 1675 m were comparable to transect data with the exception of having a greater total live and dead fir basal area.

Transect data indicated that red spruce appeared as low as 1370 m elevation in the Black Mountains (Table 4.4) and increased to make up 38 % of total live basal area by 1600 m. After that point spruce contribution to stand composition fluctuated, and decreased to 9 % of the basal area at 1980 m elevation. Fraser fir was not found below an elevation of 1600 m, and then steadily increased to make up 87 % of the total live basal area and 91 % of the total live stem density. Substantial amounts of dead fir was not encountered until an elevation of 1905 m. Birch made up a third of stand basal area at 1370 m and contribution stabilized from 1450 to 1755 m elevation with birch averaging 46 % of live basal area. Presence of birch then diminished with increasing elevation with no birch found at 1980 m. Comparison of transect to plot data indicated that plot samples at 1525 and 1675 m had a greater spruce and total live basal area and density and lower birch contribution than the transects.

Great Smoky Mountains transect data indicated that red spruce made up 50 % of live basal area at 1525 m, increased to 70 % by 1830 m, and then decreased to 17 % for the highest elevation sample (Table 4.5). Fir contributed between 1-4 % of the live basal area from 1525 to 1830 m, but large amounts of dead fir were recorded starting at 1675 m elevation and increased with increasing elevation. Live fir increased to 43 % of stand basal area at 1980 m. Yellow birch contribution was greatest (38 % of live basal area) at the lowest sampling point and steadily decreased until it was not found at the highest elevation sample. A comparison of transect to plot data indicated that plot samples at all elevations had higher spruce and total live basal area and a much lower birch contribution than the transects while live and dead fir contributions were quite similar.

Since transect point location was entirely systematic (based on elevation) there was no species composition requirement. In contrast all permanent plots had to have at least 25 % spruce and/or fir live or former (dead standing stems) canopy coverage. Examination of plot data indicated that

Table 4.3. Basal area and density for live and dead spruce, fir, birch, and all overstory species, stratified by elevation, for transects and permanent plots at the Mt. Rogers National Recreation Area, Virginia.

	Elevation = 1370 m			
	Transect Points (n= 6)		Plots (n=)	
	Basal Area	Density	Basal Area	Density
	m^2/ha	stems/ha	m^2/ha	stems/ha
		Live		
Spruce	-	-		
Fir	-	-		
Birch	3.9	8		
Total	27.0	298		
		Dead		
Spruce	-	-		
Fir	-	-		
Birch	-	-		
Total	0.9	16		

	Elevation = 1450 m			
	Transect Points (n= 7)		Plots (n=)	
	Basal Area	Density	Basal Area	Density
	m^2/ha	stems/ha	m^2/ha	stems/ha
		Live		
Spruce	.2	2		
Fir	-	-		
Birch	5.2	30		
Total	27.4	389		
		Dead		
Spruce	-	-		
Fir	-	-		
Birch	0.2	2		
Total	3.6	251		

	Elevation = 1525 m			
	Transect Points (n= 6)		Plots (n= 12)	
	Basal Area	Density	Basal Area	Density
	m²/ha	stems/ha	m²/ha	stems/ha
Live				
Spruce	1.4	48	14.7	403
Fir	-	-	17.0	818
Birch	5.4	47	5.1	390
Total	28.7	475	39.3	1801
Dead				
Spruce	-	-	0.2	34
Fir	-	-	3.6	339
Birch	1.7	15	1.7	113
Total	3.8	64	7.6	580

	Elevation = 1600 m			
	Transect Points (n= 7)		Plots (n=)	
	Basal Area	Density	Basal Area	Density
	m²/ha	stems/ha	m²/ha	stems/ha
Live				
Spruce	14.3	264		
Fir	3.8	80		
Birch	13.0	284		
Total	34.5	743		
Dead				
Spruce	0.7	21		
Fir	0.6	12		
Birch	3.1	159		
Total	6.2	285		

	Elevation = 1675 m			
	Transect Points (n= 8)		Plots (n= 13)	
	Basal Area	Density	Basal Area	Density
	m²/ha	stems/ha	m²/ha	stems/ha
		Live		
Spruce	16.0	568	21.9	1355
Fir	5.9	307	15.8	714
Birch	2.0	52	1.3	145
Total	23.9	927	40.2	2394
		Dead		
Spruce	8.8	375	3.8	370
Fir	2.3	123	7.4	336
Birch	1.7	113	0.5	53
Total	13.3	625	14.3	932

Table 4.4. Basal area and density for live and dead spruce, fir, birch, and all overstory species, stratified by elevation, for transects and permanent plots at the Black Mountains, North Carolina.

	Elevation = 1370 m				
	Transect Points (n= 5)			Plots (n=)	
	Basal Area	Density		Basal Area	Density
	m²/ha	stems/ha		m²/ha	stems/ha
			Live		
Spruce	.3	30			
Fir	-	-			
Birch	8.7	62			
Total	26.0	380			
			Dead		
Spruce	-	-			
Fir	-	-			
Birch	.7	37			
Total	2.0	127			

	Elevation = 1450 m				
	Transect Points (n= 8)			Plots (n=)	
	Basal Area	Density		Basal Area	Density
	m²/ha	stems/ha		m²/ha	stems/ha
			Live		
Spruce	1.9	8			
Fir	-	-			
Birch	13.1	293			
Total	28.2	691			
			Dead		
Spruce	.6	11			
Fir	-	-			
Birch	0.2	31			
Total	2.9	153			

	Elevation = 1525 m			
	Transect Points (n= 12)		Plots (n=)	
	Basal Area	Density	Basal Area	Density
	m^2/ha	stems/ha	m^2/ha	stems/ha
Live				
Spruce	7.8	76	35.5	741
Fir	-	-	-	-
Birch	12.2	251	6.3	165
Total	29.8	603	50.2	1590
Dead				
Spruce	1.9	60	2.2	189
Fir	-	-	0.2	21
Birch	0.6	35	0.7	43
Total	3.3	115	4.7	387

	Elevation = 1600 m			
	Transect Points (n= 12)		Plots (n=)	
	Basal Area	Density	Basal Area	Density
	m^2/ha	stems/ha	m^2/ha	stems/ha
Live				
Spruce	11.0	163		
Fir	1.1	31		
Birch	10.6	196		
Total	28.9	574		
Dead				
Spruce	1.9	78		
Fir	1.1	96		
Birch	1.0	144		
Total	7.4	603		

	Elevation = 1675 m			
	Transect Points (n = 14)		Plots (n = 15)	
	Basal Area	Density	Basal Area	Density
	m^2/ha	stems/ha	m^2/ha	stems/ha
Live				
Spruce	4.5	99	32.1	728
Fir	1.7	43	0.2	54
Birch	16.2	475	9.7	414
Total	27.9	909	46.3	1593
Dead				
Spruce	1.1	19	3.1	76
Fir	1.5	49	0.6	13
Birch	1.9	145	1.5	112
Total	6.8	386	8.5	409

	Elevation = 1755 m			
	Transect Points (n = 12)		Plots (n =)	
	Basal Area	Density	Basal Area	Density
	m^2/ha	stems/ha	m^2/ha	stems/ha
Live				
Spruce	6.3	228		
Fir	0.3	36		
Birch	11.1	550		
Total	22.2	1027		
Dead				
Spruce	1.3	36		
Fir	2.2	110		
Birch	2.3	212		
Total	10.0	567		

	Elevation = 1830 m			
	Transect Points (n= 15)		Plots (n= 15)	
	Basal Area	Density	Basal Area	Density
	m^2/ha	stems/ha	m^2/ha	stems/ha
Live				
Spruce	4.6	104	10.2	392
Fir	5.6	275	11.4	675
Birch	6.4	260	2.5	141
Total	21.9	933	27.8	1588
Dead				
Spruce	1.2	16	1.7	37
Fir	4.2	176	5.8	216
Birch	1.3	83	1.5	97
Total	9.7	544	15.2	667

	Elevation = 1905 m			
	Transect Points (n= 9)		Plots (n=)	
	Basal Area	Density	Basal Area	Density
	m^2/ha	stems/ha	m^2/ha	stems/ha
Live				
Spruce	7.3	123		
Fir	7.8	277		
Birch	1.3	50		
Total	17.2	653		
Dead				
Spruce	0.4	2		
Fir	16.8	656		
Birch	1.3	105		
Total	21.7	988		

	Elevation = 1980 m			
	Transect Points (n= 8)		Plots (n= 5)	
	Basal Area	Density	Basal Area	Density
	m²/ha	stems/ha	m²/ha	stems/ha
		Live		
Spruce	2.7	140	5.0	100
Fir	25.8	2070	14.7	770
Birch	-	-	0.1	15
Total	29.6	2274	22.0	1030
		Dead		
Spruce	0.4	2	2.2	35
Fir	18.5	1087	18.9	930
Birch	0.2	12	0.1	15
Total	20.8	1274	26.7	1250

Table 4.5. Basal area and density for live and dead spruce, fir, birch, and all overstory species, stratified by elevation, for transects and permanent plots at the Great Smoky Mountains, Tennessee and North Carolina.

Elevation = 1525 m	Transect Points (n=23)		Plots (n=18)	
	Basal Area	Density	Basal Area	Density
	m^2/ha	stems/ha	m^2/ha	stems/ha
Live				
Spruce	15.4	238	45.8	502
Fir	0.3	55	0.1	10
Birch	11.6	114	8.3	132
Total	30.6	577	61.5	1323
Dead				
Spruce	1.6	7	4.6	60
Fir	2.1	68	1.8	92
Birch	1.0	28	0.3	12
Total	5.3	118	7.4	191

Elevation = 1600 m	Transect Points (n=11)		Plots (n=)	
	Basal Area	Density	Basal Area	Density
	m^2/ha	stems/ha	m^2/ha	stems/ha
Live				
Spruce	20.5	322		
Fir	0.3	100		
Birch	12.6	98		
Total	37.9	1063		
Dead				
Spruce	1.5	37		
Fir	4.4	186		
Birch	0.9	60		
Total	7.1	300		

Elevation = 1675 m				
	Transect Points (n = 25)		Plots (n = 18)	
	Basal Area	Density	Basal Area	Density
	m^2/ha	stems/ha	m^2/ha	stems/ha
Live				
Spruce	19.7	304	50.8	355
Fir	0.7	177	.4	67
Birch	11.9	268	8.1	75
Total	33.8	890	59.7	604
Dead				
Spruce	2.5	24	4.8	66
Fir	11.2	661	11.7	635
Birch	1.1	8	0.7	20
Total	15.7	725	18.8	789

Elevation = 1755 m				
	Transect Points (n = 11)		Plots (n =)	
	Basal Area	Density	Basal Area	Density
	m^2/ha	stems/ha	m^2/ha	stems/ha
Live				
Spruce	22.9	467		
Fir	1.1	34		
Birch	8.8	218		
Total	34.3	800		
Dead				
Spruce	3.3	14		
Fir	11.5	430		
Birch	1.4	13		
Total	16.8	511		

	Elevation = 1830 m			
	Transect Points (n = 22)		Plots (n = 18)	
	Basal Area	Density	Basal Area	Density
	m²/ha	stems/ha	m²/ha	stems/ha
		Live		
Spruce	18.9	454	32.1	268
Fir	1.1	127	3.3	188
Birch	6.2	156	3.4	116
Total	27.0	796	39.3	633
		Dead		
Spruce	4.0	18	2.8	34
Fir	20.0	690	14.6	590
Birch	0.9	47	0.7	42
Total	26.4	830	20.0	744

	Elevation = 1905 m			
	Transect Points (n = 10)		Plots (n =)	
	Basal Area	Density	Basal Area	Density
	m²/ha	stems/ha	m²/ha	stems/ha
		Live		
Spruce	13.2	243		
Fir	6.1	547		
Birch	0.5	14		
Total	21.3	1005		
		Dead		
Spruce	1.7	55		
Fir	22.4	1156		
Birch	0.3	1		
Total	26.8	1352		

	Elevation = 1980 m		Elevation = 1980 m	
	Transect Points (n = 11)		Plots (n = 12)	
	Basal Area	Density	Basal Area	Density
	m^2/ha	stems/ha	m^2/ha	stems/ha
	Live			
Spruce	5.0	104	16.3	160
Fir	12.6	988	12.9	772
Birch	-	-	-	-
Total	29.6	1224	30.4	1009
	Dead			
Spruce	0.8	10	1.9	26
Fir	24.7	991	23.3	782
Birch	-	-	0.1	4
Total	28.0	1132	29.0	982

no plot had less than 24 % live plus dead standing basal area in spruce and/or fir. When the same criteria were applied to transect data, 41 %, 54 %, and 97 % of all Mt. Rogers NRA, Black Mountains, and Great Smoky Mountains transect points were classified as "spruce-fir" (Table 4.6). (Note that no transect points below 1525 m were sampled at the Great Smoky Mountains). Almost continuous spruce-fir appears to be found at or above 1600 m for Mt. Rogers NRA, 1830 m for the Black Mountains, and 1525 m for the Great Smoky Mountains. A comparison of just the transects points classified as "spruce-fir" to corresponding permanent plots indicated only a few differences. No differences were found at the Mt. Rogers NRA study area since the only "spruce-fir" transect points were found above 1525 m and all points at 1675 were classified as "spruce-fir". Imperceptible differences were found at the Smokies since only one transect point at 1525 m and 1675 m were not classified as "spruce-fir". However at the Black Mountains only 21 of the 41 transect points from 1525-1830 m were classified as "spruce-fir". Comparison of live basal area of spruce and fir between points and plots at the Black Mountains indicated that red spruce was significantly over-represented in the permanent plots at those elevations compared to the actually amount found in the spruce-fir forest as a whole (Table 4.7).

STAND PROJECTION MODEL

Ingrowth

Ingrowth observations by plot were examined using stepwise regression for detection of significant relationships using stand (live basal area, live stand density, stand age, percent of overstory spruce, dead stand basal area, live shrub density) and site (elevation, slope, aspect) regressor variables. Significant, well-fitting (based on tests for R^2, adjusted R^2, C_p, and mean square error) models were built for spruce (Table 4.8) and fir (Table 4.9) ingrowth using stand/site variables. Unlike the other two sites, separate stable equations for spruce ingrowth at the Smokies could not

Table 4.6. Number of transect points, percentage of transect points with 25 % live or dead spruce or fir basal area, and averaged percent of live and dead basal area that was spruce or fir sampled in the transect points for Mt. Rogers National Recreation Area, the Black Mountains, and the Great Smoky Mountains, stratified by elevation class.

	Mt. Rogers NRA			Black Mtns.			Grt. Smoky Mtns.		
Elevation	N	% SF Pts.	Ave. SF BA	N	% SF Pts.	Ave. SF BA	N	% SF Pts.	Ave. SF BA
(m)		(. . . . % . . . .)			(. . . . % . . . .)			(. . . . % . . . .)	
1370	6	0	0.0a	5	0	1.1a			
1450	7	0	0.7a	8	13	7.2a			
1525	6	0	5.2a	12	42	24.8a	23	96	50.2b
1600	7	86	48.6a	12	58	35.5a	11	91	54.9a
1675	8	100	85.4a	14	36	22.5b	25	96	65.2a
1755				12	58	29.4a	11	100	75.6b
1830				15	73	44.2a	22	100	81.4b
1905				9	78	66.1a	10	100	88.0a
1980				8	100	93.0a	11	100	87.5a
Tot./Ave.	34	41	36.4a	95	54	31.2a	113	97	69.6b

Note: Mean values within rows (elevation class) that are followed by different letters differ significantly at p = 0.05 based on the Scheffe procedure for multiple constrasts among means.

Table 4.7. Live basal area for spruce and fir, stratified by four elevations, for transects points classified as "spruce-fir" and permanent plots at the Black Mountains, North Carolina.

	1525 m		1675 m		1830 m		1980 m	
	Trans. (n= 5)	Plots (n= 10)	Trans. (n= 5)	Plots (n= 15)	Trans. (n= 11)	Plots (n= 15)	Trans. (n= 8)	Plots (n= 5)
	(.			. . . . m^2/ha				. . . .)
Spruce	16.7	35.5*	9.3	32.1*	5.8	10.2	2.7	5.0
Fir	0.0	0.0	4.7	0.2*	8.0	11.4	25.8	14.7*

* - ANOVA test indicated a significant difference ($p > .10$) between transect and permanent plot values within an elevation class for a particular species.

be built (by site and/or elevation), possibly because of its very infrequent occurrence. Validation was carried out by a random split of the data set, regression analysis carried on one half the data followed by tests for bias and precision. Validation tests on the other half of the data did not indicate any consistent problems. No reliable relationships were detected for birch or "other species" ingrowth even when data were split into different study site, disturbance history, or elevation classes.

Poisson regression analysis did not detect a reasonable model (based on scaled deviance) between ingrowth (spruce, fir , birch, or "other species") and stand/site variables. Discriminant analysis was unable to predict classes of ingrowth (based on canonical correlations) with much reliability.

Valid stepwise regression equations could only be built relying on understory variables. Since ingrowth predictions would be necessary for a projection of twenty years and it was likely that understory conditions would significantly change, it was determined that average ingrowth values by study site and elevations classes would be used for the growth model (Table 4.10). While a diameter of 5.0 was the requirement for understory to be counted as ingrowth and enter the tree strata, most stems counted as ingrowth had diameters larger than 5.0 at the time of measurement. Spruce, fir, and birch ingrowth DBH averaged 5.3, 5.5, and 5.4 cm respectively and those were the initial diameters of ingrowth in the stand projection model.

Mortality

Mortality observations (number of trees that died between 1985 and 1989) by plot were examined using stepwise regression for detection of significant relationships using stand/site variables as the independent variables. Some reliable relationships (based on tests for R^2, adjusted R^2, C_p, and mean square error) were detected when data was split into different study site or disturbance history classes. Significant, well-fitting models were built for fir at all sites, birch at the Black Mountains,

Table 4.8. Spruce ingrowth regression equations and statistics by spruce-fir study site using the ordinary least squares methods.

Study Site	Equation	R^2	adj.R^2	p
Mt. Rogers NRA	Ingrowth[1] = -67.89 + 1.21 STANDAGE[2] + 0.043 LDEN[3] - 2.09 LBA[4] -40.52 PRBPCT[5]	.656	.588	.0002
Black Mountains	Ingrowth = 104.48 + 0.025 PLSDEN[6] - 0.052 ELEV[7] + 0.012 LDEN - 0.465 LBA	.533	.487	.0001
All Sites Combined	Ingrowth = -94.64 + 0.020 PLSDEN + 13.978 LDEN + 5.920 PRBPCT	.323	.319	.0001

[1] Ingrowth (stems/ha/4 years)
[2] Stand age (years)
[3] Live stand density (stems/ha)
[4] Live basal area (m^2/ha)
[5] Overstory live spruce basal area/Total live basal area
[6] Spruce understory stem density (stems/ha)
[7] Elevation (m)

Table 4.9. Fir ingrowth regression equations and statistics for three spruce-fir sites by elevation class using the ordinary least squares methods.

Elevation (m)	Equation	R^2	adj.R^2	p
1525	Ingrowth[1] = -0.700 + 0.139 ALSDEN[2]	.703	.695	.0001
1675	Ingrowth = 27.62 + 0.033 ALSDEN - 1.62 DBA[3] - 65.18 PRBPCT[4]	.692	.670	.0001
1830	Ingrowth = -166.01 + 0.044 ALSDEN + 0.189 STANDAGE[5] + 24.68 LDEN[6] - 0.0003 LBA[7]	.767	.733	.0001
1980	Ingrowth = -530.35 + .023 ALSDEN + 71.08 LDEN + 202.38 PRBPCT	.341	.189	.0882

[1] Ingrowth (stems/ha/4 years)
[2] Fir understory stem density (stems/ha)
[3] Dead basal area (m^2/ha)
[4] Overstory live spruce basal area/Total live basal area
[5] Stand age (years)
[6] Live stand density (stems/ha)
[7] Live basal area (m^2/ha)

Table 4.10. Average ingrowth and mortality rates for red spruce, Fraser fir, yellow birch, and other woody species (excluding Rhododendron), stratified by elevation, for three southern Appalachian spruce-fir sites.

	Spruce		Fir		Birch		Other	
Elevation	Ing.	Mort.	Ing.	Mort.	Ing.	Mort.	Ing.	Mort.
(m)	(.	stems/ha/yr.	. . . .)					
A. Mt. Rogers National Recreation Area								
1525	1.0a	5.2a	3.6a	37.0a	3.1a	6.3a	6.3a	5.2a
1675	8.7a	30.2b	27.4b	44.7a	1.9a	2.4a	3.8a	4.8a
B. Black Mountains								
1525	5.0a	15.6a	3.8a	0.0a	0.0a	3.1a	0.6a	5.0a
1675	10.8a	17.1a	3.3a	2.5a	2.5a	16.3a	5.4a	22.5a
1830	2.5a	15.0a	18.3a	25.8ab	2.1a	8.8a	5.0a	22.5a
1980	0.0a	7.5a	13.8a	56.3b	0.0a	2.5a	0.0a	2.5a
C. Great Smoky Mountains								
1525	3.5a	5.2a	0.3a	1.0a	0.3a	1.4a	3.5a	3.5a
1675	4.5a	2.4a	4.5a	6.6a	0.3a	1.7a	2.5a	1.0a
1830	0.7a	2.4a	7.3ab	16.3a	1.7a	2.1a	1.4a	5.6a
1980	0.0a	6.3a	24.0b	51.6b	0.0a	0.0a	1.0a	6.8a

Note: Mean values within columns for each study site that are followed by different letters differ significantly at $p = 0.05$ based on the Scheffe procedure for multiple constrasts among means.

spruce at Mt. Rogers NRA, and all remaining woody species at the Black Mountains (Table 4.11). Model validation was carried out by a random split of the data set, regression analysis carried out on one half the data and followed by tests for bias and precision on the other half of the data. Validation tests did not indicate any consistant problems.

Poisson regression analysis did not detect a reasonable model (based on scaled deviance) between mortality (spruce, fir, birch, and ″other species″) and stand/site variables, although the fit of the models for mortality was better than the fit of the ingrowth models. Discriminant analysis did not predict classes of mortality (based on canonical correlation) with much reliability.

Since mortality predictions would be necessary for a projection of twenty years, it was determined that average mortality values by study site and elevations classes (Table 4.10) would be used for the growth routine of the model wherever significant regression models could not be used (Table 4.11). Since stem size was not consistently a significant variable in the logistic modeling of individual stem mortality (Chapter 3), tree mortality was assigned randomly for each four year iteration of the model.

Growth

The relationship of stem size and four year incremental growth was first examined, including transformations of both dependent and independent variables. When **dd59** was plotted against stem size, for both yellow birch and red spruce, the resulting curves have a skewed unimodal form that is typical of increment functions (Figure 4.1). The best behaved model for all four species groups was:

$$\ln(\mathbf{dd59})^2 = b_o + b_1 \ln(DBH) + b_2 DBH^2$$

Table 4.11. Mortality regression equations and statistics for fir, birch, spruce, and other woody species (excluding Rhododendron) using the ordinary least squares methods for three southern spruce-fir sites.

Study Site	Equation	R^2	adj.R^2	p
	Fraser Fir			
Mt. Rogers NRA (Logged Sites)	Mortality[1] = -2069.19 + 0.428 ELE[2] + 4.873 LBA[3] - 10.798 PRBLBA[4]	.535	.419	.0230
Mt. Rogers NRA (Uncut Sites)	Mortality = -951.54 - 1.941 STANDAGE[5] + 0.243 ELE - 2.362 PRBLBA	.832	.731	.0221
Black Mtns. (Logged Sites)	Mortality = -478.48 + 0.062 ELE + 7.507 LBA + 7.525 DBA[6] - 0.044 LDEN[7] -4.895 PRBLBA	.650	.577	.0001
Black Mtns. (Uncut Sites)	Mortality = -142.962 + 0.039 ELE - 1.879 LBA + 1.552 DBA - 0.791 PRBLBA	.794	.711	.0018
Grt. Smoky Mtns. (All Sites)	Mortality = -877.73 + 0.147 ELE + 3.093 LBA + 0.090 LDEN - 3.358 PRBLBA	.536	.504	.0001
	Yellow Birch			
Black Mtns. (Logged Sites)	Mortality = 618.832 - 0.087 ELE - 1.958 LBA	.327	.277	.0047
Black Mtns. (Uncut Sites)	Mortality = 100.857 - 0.035 ELE + 5.412 DBA + 0.046 LDEN	.611	.505	.0129
	Red Spruce			
Mt. Rogers NRA (All Sites)	Mortality = -265.25 - 2.037 STANDAGE + 0.119 ELE - 7.625 LBA + 4.761 DBA + 6.512 PRBLBA	.649	.557	.0007
	Other Species			
Black Mtns. (Logged Sites)	Mortality = 151.65 + 0.824 STANDAGE - 4.789 LBA - 3.781 DBA + 0.042 LDEN + 1.450 PRBLBA	.406	.282	.0215
Black Mtns. (Uncut Sites)	Mortality = -280.43 + 0.043 ELE + 0.088 LDEN - 0.981 PRBLBA	.593	.482	.0162

[1] Mortality (stems/ha/4 years)

[2] Elevation (m)

[3] Live basal area (m^2/ha)

[4] Overstory live spruce basal area (m^2/ha)

[5] Stand age (years)

[6] Dead basal area (m^2/ha)

[7] Live stand density (stems/ha)

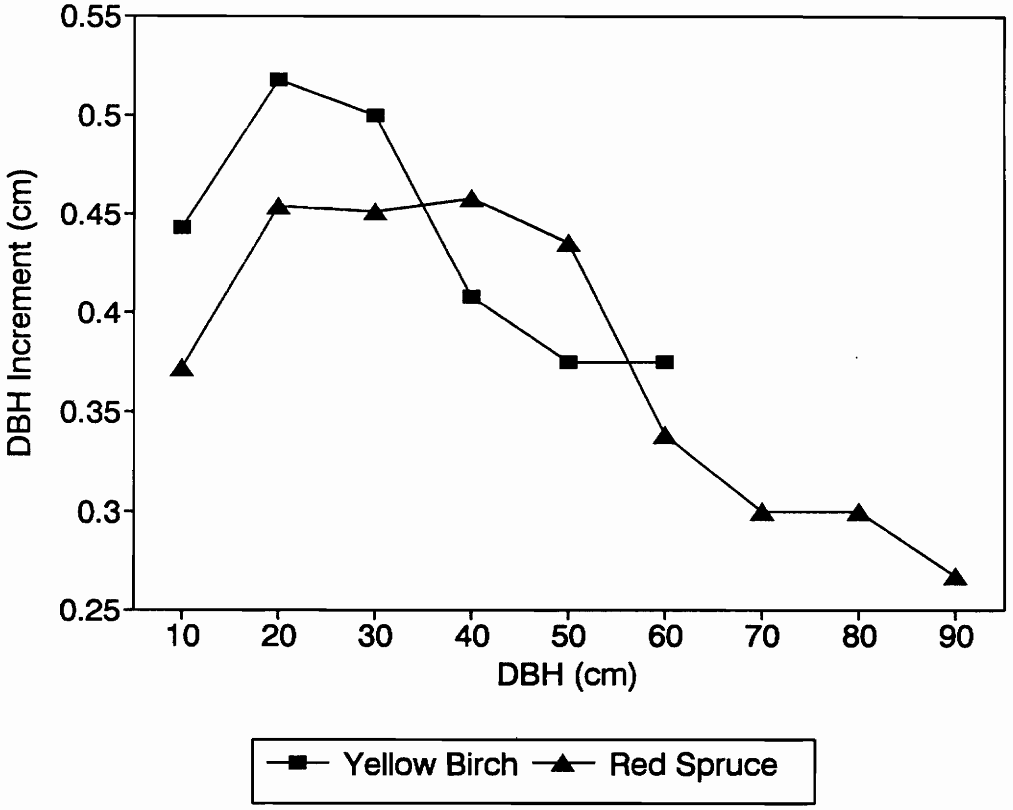

Figure 4.1. Average diameter growth increment plotted against DBH for red spruce and yellow birch.

The models were stable (p values from .0001 to .1100) but were poorly fit (maximum R^2 value of .03).

Better fitting species specific equations were sought by modeling increment growth as a function of stem size, site characteristics (elevation, aspect transformed to a continuous variable (Beers 1966), slope, site index (Nicholas and Zedaker 1992)) and competition (live basal area, dead basal area, live overstory stem density, stand age, and individual stem competition index (Chapter 3)). Dependent variables were plotted against incremental growth to determine appropriate transformations to be considered. A combination of stepwise regression and tests for R^2, adjusted R^2, C_p, and mean square error was used to detect significant relationships between growth and stem/stand/site variables. The single best predictor of birch and spruce increment was the competition index, while live basal area was best for predicting fir and stand age was the best for predicting ″other species″ growth.

Use of multiple regression did not greatly improve the fit of the models. The best fitting equation was for red spruce ($R^2 = .220$) (Table 4.12) while the best fitting equation for the ″other species″ group had an R^2 of less than .1 and a C_p value that indicated a problem with model stability. The ″other species″ group was therefore not included in the stand projection model.

Plots of the differences between the residuals versus observed growth increment indicated that models for both fir and spruce were unable to predict larger growth increments with much accuracy. Plots of the residuals versus the predicted dependent variable indicated a somewhat non-constant variance for the spruce equation. Transformations of the data did not alleviate the problem. Better equations were not detected with the use of dummy variables in order to split the data into different study site, disturbance history, or elevation classes. Model validations were carried out by a random split of the data set, regression analysis carried on one half the data followed by tests for bias and precision. Validation tests on the other half of the data did not indicate any significant problems other than discussed above.

Table 4.12. Growth regression equations and statistics for fir, birch, and spruce using the ordinary least squares methods for three southern spruce-fir sites.

		Parameter Estimates[a]														
Species	Intercept	DBH	DBH^2	LDBH	ELEV	ELEV2	SLP	SITEINDX	LBA	DBA	LDEN	AGE	COMP	R^2	adj. R^2	p[b]
Fir	14.432		-.0007		-.013	.000004	-.013			-.017	-.0002		-.023	.189	.179	.0001
Birch	-18.650	-.029		.425	.022	-.000006		.021	.009			.001	-.018	.127	.105	.0001
Spruce	-3.889		-.0001	.158	.006	-.000002	.002	-.023	.007	.004		-.002	-.010	.220	.213	.0001

[a] Parameter estimators:

DBH = Diameter at breast height (cm)
DBH2 = DBH^2
LDBH = Log(DBH)
ELEV = Elevation (m)
ELEV2 = $ELEV^2$
SLP = Plot slope (%)
SITEINDX = Spruce site index from Nicholas and Zedaker (1992)
LBA = Live basal area (m^2/ha)
DBA = Dead basal area (m^2/ha)
LDEN = Live stand density (stems/ha)
AGE = stand age (years)
COMP = Individual tree competition index.

[b] All individual parameter estimates had $p > .08$ for each growth equation.

Twenty Year Projection

Mt. Rogers National Recreation Area

During the twenty year projection, similar trends were found for all three species at both 1525 m and 1675 m elevations (Figure 4.2). Red spruce steadily increased in basal area (17.1 to 22.7 m^2/ha) as density decreased (798 to 614 stems/ha). Spruce stem size distribution changes were most pronounced for the 15-25 cm diameter class (Table 4.13a). Fraser fir basal area dropped slightly (14.6 to 12.2 m^2/ha) while live density decreases were more substantial (656 to 266 stems/ha). Decreases in live fir diameter distribution were most extreme in the 5-25 cm diameter classes (Table 4.13b). Little change was predicted for yellow birch (Table 4.13c).

Black Mountains

At the end of the fifth iteration of the stand projection model, similar trends were found for the lower (1675 m and below) elevations at the Black Mountains (Figure 4.3). Red spruce slightly decreased in basal area (33.9 to 27.6 m^2/ha) as density (745 to 573 stems/ha) also decreased; decreases seemed to be uniform among diameter classes (Table 4.14a). Fraser fir was rare at lower elevations in 1989 with little change predicted for twenty years later (Table 4.14b). Yellow birch basal area decreased slightly (7.4 to 5.8 m^2/ha) while density decreases were more sizable (269 to 151 stems/ha). Low ingrowth rates for birch at the Black Mountains (Table 4.9) was combined with a 1989 birch density concentrated (63 %) in the 5-15 cm diameter class. Little change in basal area distribution was projected to occur twenty years later (Table 4.14c).

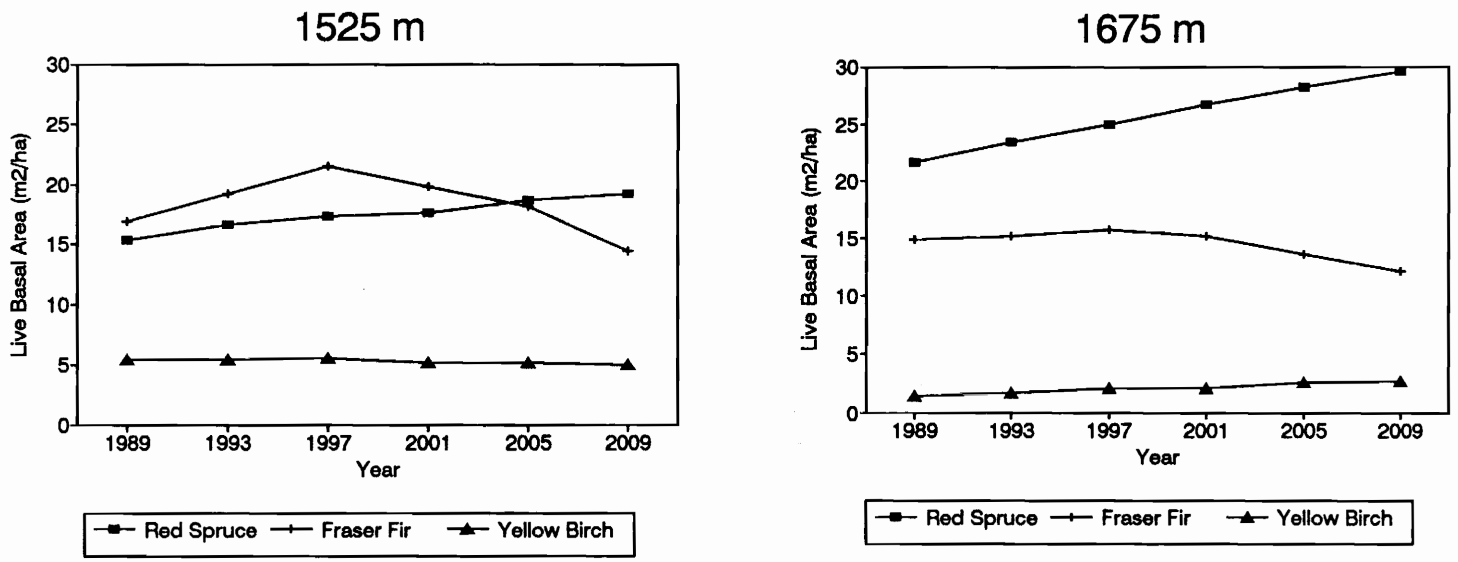

Figure 4.2. Twenty year projection of live basal area for red spruce, Fraser fir, and yellow birch at two elevations for Mt. Rogers National Recreation Area.

Table 4.13a. Red spruce live basal area in 1989 and 2009 (projected) stratified by diameter size class and elevation at Mt. Rogers National Recreation Area.

DBH Sizeclass (cm)	1525 m (N = 12 plots) 1989	1525 m (N = 12 plots) 2009	1675 m (N = 13 plots) 1989	1675 m (N = 13 plots) 2009
	(.	. . . . m^2/ha	. . . .	. . . .)
5-15	1.5	1.2	7.0	4.4
15-25	2.7	2.7	5.9	12.5
25-35	3.2	2.9	6.1	6.3
35-45	3.5	3.5	2.2	4.1
45-55	3.4	6.1	0.4	1.9
55-65	0.0	1.6	0.0	0.5
65-75	0.0	0.0	0.0	0.0
75-85	1.0	0.0	0.0	0.0
85-95	0.0	1.2	0.0	0.0
95+				
Total	15.3	19.2	21.6	29.6

Table 4.13b. Fraser fir live basal area in 1989 and 2009 (projected) stratified by diameter size class and elevation at Mt. Rogers National Recreation Area.

DBH Sizeclass (cm)	1525 m (N = 12 plots)		1675 m (N = 13 plots)	
	1989	2009	1989	2009
	(.	m²/ha	. . . .	.)
5-15	3.3	0.2	3.2	1.0
15-25	8.0	1.4	3.9	3.5
25-35	4.0	6.7	3.4	3.1
35-45	1.1	4.4	3.6	1.9
45-55	0.4	1.2	0.8	2.2
55-65	0.0	0.6	0.0	0.5
65-75				
75-85				
85-95				
95+				
Total	16.9	14.4	14.9	12.2

Table 4.13c. Yellow birch live basal area in 1989 and 2009 (projected) stratified by diameter size class and elevation at Mt. Rogers National Recreation Area.

DBH Sizeclass (cm)	1525 m (N = 12 plots)		1675 m (N = 13 plots)	
	1989	2009	1989	2009
	(.	m²/ha	. . . .	.)
5-15	2.1	1.7	1.0	0.5
15-25	2.0	1.7	0.3	1.8
25-35	0.9	1.5	0.1	0.1
35-45	0.0	0.0	0.0	0.2
45-55	0.3	0.0	0.0	0.0
55-65				
65-75				
75-85				
85-95				
95+				
Total	5.4	5.0	1.4	2.7

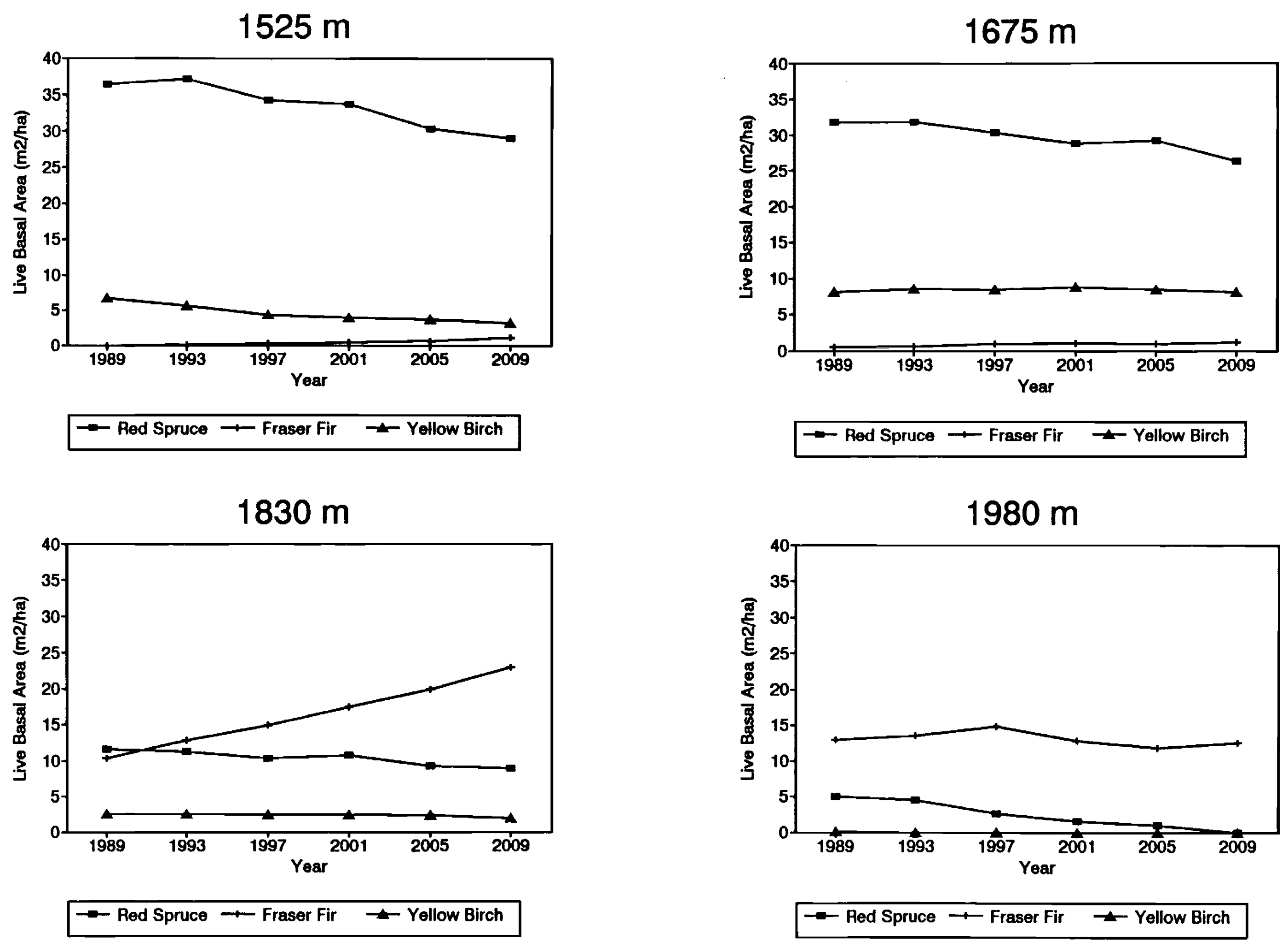

Figure 4.3. Twenty year projection of live basal area for red spruce, Fraser fir, and yellow birch at four elevations for the Black Mountains.

Table 4.14a. Red spruce live basal area in 1989 and 2009 (projected) stratified by diameter size class and elevation at the Black Mountains.

DBH Sizeclass (cm)	1525 m (N = 14 plots)		1675 m (N = 16 plots)		1830 m (N = 16 plots)		1980 m (N = 5 plots)	
	1989	2009	1989	2009	1989	2009	1989	2009
	(................................			m^2/ha			................................)	
5-15	2.2	1.9	2.7	2.6	1.6	0.9	0.2	0.0
15-25	4.8	4.3	5.4	4.0	3.7	2.7	0.6	0.0
25-35	8.1	6.1	7.0	6.0	2.6	3.3	1.9	0.0
35-45	8.3	6.7	7.0	5.6	2.0	1.0	1.1	0.0
45-55	6.2	3.9	4.9	3.0	1.6	0.6	0.0	0.0
55-65	3.9	3.1	3.0	2.8	0.0	0.5	1.3	0.0
65-75	2.0	1.4	1.1	2.3	0.0	0.0	0.0	0.0
75-85	0.9	1.6	0.8	0.0	0.0	0.0	0.0	0.0
85-95								
95+								
Total	36.4	29.0	31.8	26.3	11.6	8.9	5.0	0.0

Table 4.14b. Fraser fir live basal area in 1989 and 2009 (projected) stratified by diameter size class and elevation at the Black Mountains.

DBH Sizeclass (cm)	1525 m (N = 14 plots) 1989	1525 m (N = 14 plots) 2009	1675 m (N = 16 plots) 1989	1675 m (N = 16 plots) 2009	1830 m (N = 16 plots) 1989	1830 m (N = 16 plots) 2009	1980 m (N = 5 plots) 1989	1980 m (N = 5 plots) 2009
	(.	. . . .	. . . .	. . . . m²/ha	. . . .	. . . .	. . . .	. . . .)
5-15	0.0	0.2	0.3	0.2	2.7	1.0	3.1	0.5
15-25	0.0	0.8	0.1	0.9	5.1	6.2	3.9	2.6
25-35	0.0	0.0	0.0	0.0	2.2	7.6	2.7	6.2
35-45	0.0	0.0	0.2	0.0	0.4	6.0	1.5	1.6
45-55	0.0	0.0	0.0	0.0	0.0	2.0	1.6	1.6
55-65								
65-75								
75-85								
85-95								
95+								
Total	0.0	1.1	0.5	1.2	10.4	22.9	12.9	12.5

Table 4.14c. Yellow birch live basal area in 1989 and 2009 (projected) stratified by diameter size class and elevation at the Black Mountains.

DBH Sizeclass (cm)	1525 m (N = 14 plots)		1675 m (N = 16 plots)		1830 m (N = 16 plots)		1980 m (N = 5 plots)	
	1989	2009	1989	2009	1989	2009	1989	2009
	(..................................			m²/ha			..................................)	
5-15	0.5	0.1	2.2	1.0	0.6	0.1	0.1	0.0
15-25	1.0	0.7	2.6	3.1	1.5	0.6	0.0	0.0
25-35	1.7	1.2	0.9	2.3	0.3	1.2	0.0	0.0
35-45	1.4	0.4	0.2	0.0	0.2	0.0	0.0	0.0
45-55	0.7	0.7	1.2	0.0	0.0	0.0	0.0	0.0
55-65	0.6	0.0	0.0	0.8	0.0	0.0	0.0	0.0
65-75	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
75-85	0.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0
85-95	0.0	0.0	0.9	0.9	0.0	0.0	0.0	0.0
95+								
Total	6.7	3.2	8.1	8.1	2.5	1.9	0.1	0.0

At 1830 m elevation both spruce and birch contributions changed little over the twenty year projection (Figure 4.3, Table 4.14a and c). However Fraser fir more than doubled in basal area (10.4 to 22.9 m^2/ha) while slightly decreasing in densities (670 to 527 stems/ha). Substantial basal area increases were projected for larger (25-55 cm DBH) fir stems (Table 4.14b). At the highest elevation (1980 m), both spruce and birch populations disappeared (Figure 4.3) because of very low 1989 densities (90 and 10 stems/ha respectively), nonexistent ingrowth (Table 4.10), and a low but consistent mortality rate. High elevation fir basal area remained stable (12.9 to 12.5 m^2/ha) with a halving of stem numbers (670 to 295 stems/ha). The 1989 fir density was concentrated (71 %) in the 5-15 cm diameter class and randomly assigned mortality combined with large increment growth rates resulted in basal area concentration in the 25-35 cm stem size class (Table 4.14b).

Great Smoky Mountains

During the twenty year projection, similar trends were found for all three species from 1525 m to 1830 m elevations (Figure 4.4). Spruce and birch basal area, density and size distribution (Table 4.15a and c) remained steady. Fraser fir contribution was low to almost nonexistent (Table 4.15b). At the highest elevation, the model predicted little change for yellow birch, however both spruce and fir populations deteriorated (Figure 4.4). Red spruce steadily decreased in basal area (16.7 to 5.2 m^2/ha) and density (158 to 46 stems/ha). Decreases occurred for all diameter size classes (Table 4.15a). Both basal area and density for fir were halved with decreases in basal area distribution occurring for all but the 15-25 cm diameter classes.

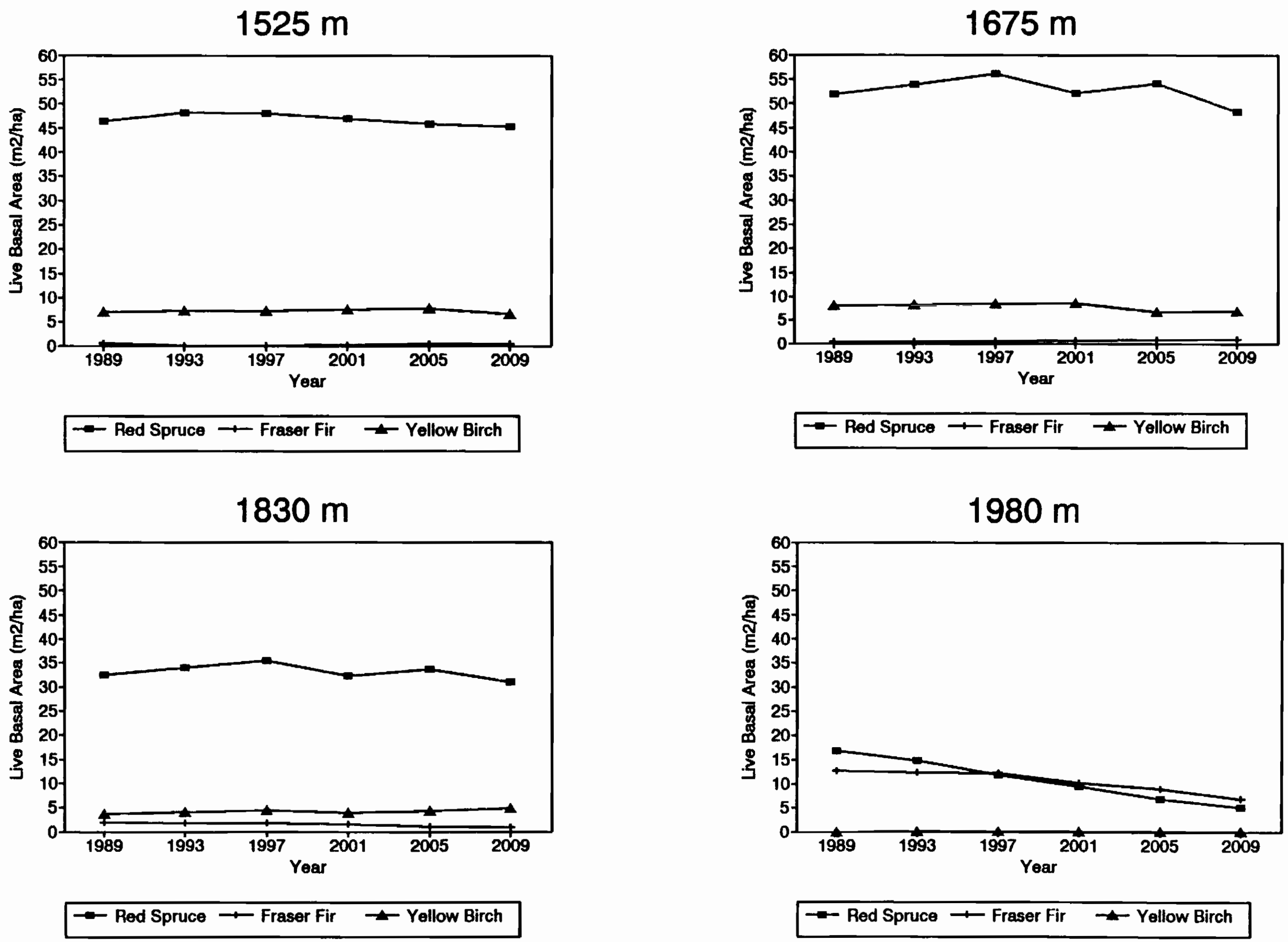

Figure 4.4. Twenty year projection of live basal area for red spruce, Fraser fir, and yellow birch at four elevations for the Great Smoky Mountains.

Table 4.15a. Red spruce live basal area in 1989 and 2009 (projected) stratified by diameter size class and elevation at the Great Smoky Mountains.

DBH Sizeclass (cm)	1525 m (N = 18 plots)		1675 m (N = 18 plots)		1830 m (N = 18 plots)		1980 m (N = 12 plots)	
	1989	2009	1989	2009	1989	2009	1989	2009
	(.		. . . .		m^2/ha		. . . .)	
5-15	1.7	1.7	0.9	1.3	0.5	0.5	0.3	0.1
15-25	2.8	3.4	1.7	1.9	1.5	1.2	0.8	0.2
25-35	2.1	2.9	2.3	3.1	1.8	2.5	1.4	0.6
35-45	2.7	3.1	2.5	2.1	5.3	2.4	3.6	0.9
45-55	6.2	3.2	4.3	3.0	6.4	5.4	5.7	1.0
55-65	9.0	5.1	12.0	6.0	8.4	8.5	3.9	2.3
65-75	9.4	9.4	14.9	13.3	4.5	4.1	0.8	0.0
75-85	5.6	6.6	8.8	12.4	4.1	4.8	0.0	0.0
85-95	5.5	4.4	3.5	4.2	0.0	1.7	0.0	0.0
95+	1.1	5.4	1.0	1.0	0.0	0.0	0.0	0.0
Total	46.5	45.3	51.9	48.3	32.4	31.0	16.7	5.2

Table 4.15b. Fraser fir live basal area in 1989 and 2009 (projected) stratified by diameter size class and elevation at the Great Smoky Mountains.

DBH Sizeclass (cm)	1525 m (N = 18 plots)		1675 m (N = 18 plots)		1830 m (N = 18 plots)		1980 m (N = 12 plots)	
	1989	2009	1989	2009	1989	2009	1989	2009
	(.		. . . .	. . . . m²/ha	. . . .		. . . .	. . . .)
5-15	0.0	0.0	0.3	0.4	0.7	0.3	3.5	0.9
15-25	0.0	0.1	0.0	0.5	0.1	0.4	3.3	3.2
25-35	0.1	0.3	0.0	0.0	0.8	0.0	4.5	2.5
35-45	0.0	0.0	0.0	0.0	0.4	0.2	1.3	0.3
45-55	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
55-65	0.4	0.0	0.0	0.0	0.0	0.0	0.0	0.3
65-75								
75-85								
85-95								
95+								
Total	0.5	0.3	0.3	0.9	1.9	0.9	12.7	5.2

Table 4.15c. Yellow birch live basal area in 1989 and 2009 (projected) stratified by diamcter size class and elevation at the Great Smoky Mountains.

DBH Sizeclass (cm)	1525 m (N = 18 plots)		1675 m (N = 18 plots)		1830 m (N = 18 plots)		1980 m (N = 12 plots)	
	1989	2009	1989	2009	1989	2009	1989	2009
	(................................ m^2/ha ....)							
5-15	0.5	0.4	0.1	0.1	0.5	0.3	0.0	0.0
15-25	1.0	0.9	0.3	0.3	0.8	1.4	0.0	0.1
25-35	1.1	1.0	1.1	0.7	0.9	1.1	0.0	0.0
35-45	1.2	1.5	1.5	0.9	0.9	1.3	0.0	0.0
45-55	0.8	0.2	2.4	2.5	0.5	0.5	0.0	0.0
55-65	1.2	1.2	1.5	1.2	0.0	0.0	0.0	0.0
65-75	0.6	0.6	1.1	1.2	0.0	0.0	0.0	0.0
75-85	0.6	0.6	0.0	0.0	0.0	0.0	0.0	0.0
85-95								
95+								
Total	7.0	6.6	8.0	6.9	3.6	4.7	0.0	0.1

DISCUSSION

The stand projections were only extended for a twenty year period, a relatively short time during the life of an overstory red spruce, and certainly much shorter then the 800 year simulation model of the spruce-fir run by Busing and Clebsch (1987). However, because of the adelgid infestation, past land use history, and possible spruce growth decline, stand structure may be changing more rapidly now than in the last few centuries (with the exception of areas that were clearcut). Chapter 3 suggests that mortality predictions may be more variable than other temperate forests, therefore a longer sampling period for mortality would provide some confidence in extending the model over more iterations. Furthermore, shifting patterns of fir mortality are due to the balsam woolly adelgid are dependent on stand age, elevation, geographic location, stem size, and stand species composition (Hay et al. 1978). While this model attempts to consider these factors in predicting fir mortality, little information was available to consider how substantial fir mortality affects remaining codominant overstory species. Zedaker et al. (1988) suggested that red spruce in fir dominated stands may have increased mortality rates due to the effects of sudden exposure with rapid removal of the fir canopy; however no studies have been carried out to test the idea. Prediction of ingrowth rates is linked to understory densities which would require more extensive data on sapling survivorship and growth rates. Since there has been some suggestion that current spruce sapling densities may be lower than expected (Nicholas et al. 1992), there may corresponding changes in future rate of ingrowth. Finally, this model of stand structure makes no provision for stochastic catastrophic events, which may strongly influence future growth and mortality. Based on the above caveats, a maximum of twenty years for model projection seemed appropriate.

Some change is predicted during the twenty year prediction. The relatively young (Chapter 1) spruce at Mt. Rogers NRA increase in basal area while decreasing in numbers. Large numbers of Fraser fir at Mt. Rogers are predicted to die with a resulting slight decrease in basal area. Overall live basal area of spruce, fir, and birch combined is predicted to increase by 10 %. The most no-table change predicted for the Black Mountains is the maturation and increase in basal area of the very young (Chapter 1) Fraser fir at 1830 m. However, high levels of adelgid populations might result in larger mortality rates than predicted by the model and the fir population might, instead, crash. Large changes are also predicted for the high elevations at the Great Smoky Mountains, where the adelgid has only in recent years completely infested fir in the Clingman's Dome area. Both spruce and fir are predicted to be reduced by more than half, no doubt causing great consternation to National Park visitors that will travel along the Clingman's Dome Road. The stand structure projection fits within several scenarios generated by Busing and Clebsch (1987) with their FORET-application model, including a regime of recurrent adelgid infestation with fir regeneration predicted an increase and then stabilization of stand density (quite close to the initial density) within 100 years. At mid-elevations (1830 m) in the Black Mountains the adelgid has been causing fir mortality for more than 40 years. A 20 year projection of fir density indicated a little change.

The extent that the model stand projections may apply is not limited to the permanent plot data collected for the Forest Response Program. Transect data indicated that the spruce-fir type (as defined for this project) is almost continuous at or above 1600 m for Mt. Rogers NRA, 1830 m for the Black Mountains, and 1525 m for the Great Smoky Mountains. Red spruce extends as low as 1525 m for the Mt. Rogers NRA and 1370 m for the Black Mountains. While this study did not sample below 1525 m for the Great Smoky Mountains, Whittaker (1956) reported red spruce as low as 1370 m. While 74 % of the southern Appalachian spruce-fir is located in the Great Smoky Mountains, the remaining quarter of spruce-fir in the south is found in the Black Mountains (11 %), the Plott Balsams and Balsam Mountains of North Carolina (10 %), Mt. Rogers NRA (2 %), Roan Mountain of Tennessee and North Carolina (2 %), and Grandfather Mountain of North Carolina (1 %) (Dull et al. 1988). More than three-quarters of the spruce-fir in the Smokies has no known logging history, as well as small portions of the Black Mountains and Mt. Rogers area (Pyle and Schafale 1988, Chapter 1) while most of the other spruce-fir sites were logged during the early twentieth century (Brown 1941, Weaver 1972, Groton 1985). The extension of results of this study to the remaining three southern spruce-fir sites (Balsams, Roan, and Grandfather) is possible. One study has substantial ground-level data collected consistently at all six sites (Groton 1985); spruce and fir basal area, densities, age, diameter distributions for the three sites not included in this study fall within the ranges of second-growth stands measured at the Black Mountains and Mt. Rogers NRA.

Confidence in the model must be tempered by several factors. The short-term (four years) nature of the data set is problematic. While Harrison et al. (1986) developed individual trees basal area increment equations of Appalachian mixed hardwoods based on a five year period, stands used in their study were even-aged. Wykoff (1990) developed a basal area increment model for 11 conifer species applicable over much of the northern Rocky Mountains but used a ten year inside bark DBH increment measured from tree cores. Busing and Wu (1990) built a well-fitting ($R^2 = .696$) equation to predict 10 year radial increment of red spruce in the Smokies using a computer-interfaced video camera accurate to 0.01 mm. Sampling of tree diameter by means of calipers or tapes is not a precise measurement (Gregoire et al. 1990). Combined with the possibility of slow growth rates found in the shade tolerant spruce-fir system and some level of repeated measurement error inherent in forest sampling (Zedaker and Nicholas 1990), four years of increment growth may be an inadequate measurement period.

Basal area increment equations developed for this study did not have a high quality of fit. Only two of the three species (spruce and birch) examined showed **dd59** as some kind of function of stem size. It is unlikely that Fraser fir growth in unmanaged stands will ever exhibit a predictable growth-size relationship due to the ongoing balsam woolly adelgid infestation. Infestation causes the formation of abnormal wood which is thought to poorly conduct water (Balch 1952, Mitchell 1967). Stem infestations often include a brief period of increased diameter growth followed by one to several years of reduced growth and then a rapid death (Amman and Talierico 1967). Virtually all remaining stands in the southern Appalachians are now infested (Eagar 1984), and since length of survivorship after individual stem infestation is variable (Amman and Speers 1965, Amman

1970), prediction of fir survivorship and growth is directly linked to the insect and is unlikely to be accurately modeled from only stand variables.

Hopefully with a longer data period, better-fitting southern Appalachian spruce and birch increment equations can be built. However it seems that better basal area increment models might be available with increasing levels of stand management. Hahn and Leary (1979) developed diameter growth functions for 25 Lake States species from forest survey plots with R^2 values ranging from .12 (yellow birch and elm (*Ulmus spp.*)) to .64 (red pine (*Pinus resinosa* Ait.) and balsam fir (*Abies balsamea* (L.) Mill.)) using diameter, crown ratio, and site index as predictor variables. Equations for even-aged, Appalachian mixed hardwoods had R^2 values ranging from .41 (red maple (*Acer rubrum* L.)) to .77 (black cherry (*Prunus serotina* Ehrhart)) (Harrison et al. 1986). Diameter increment equations for loblolly pine (*Pinus taeda* L.) on cut-over, site-prepared plantations had a coefficient of determination ranging from .55 to .68 (Walsh 1986, Amateis et al. 1989).

While the R^2 value for this study's red spruce equation was somewhat lower than that found by Busing and Wu (1990), a replacement of the Busing and Wu's equation in the 20 year stand projection resulted in very little difference for predicted spruce basal area in the Smokies. Busing and Wu developed their equation from a very small sample ($n = 70$) of trees in an old-growth forest while the equation built for this study was based on hundreds ($n = 1395$) of trees, located at different locations, stand ages, etc. Using the Busing and Wu equation for this data set resulted in only a 4 percent decrease in spruce basal area estimates in the old-growth Smokies, but a slightly larger difference for the younger Black Mountains (7 %) and Mt. Rogers NRA (12 %) stands. While a validation of the Busing and Wu equation was not provided in their 1990 paper, an application of their equation to this study's growth increment data also indicated a consistent underestimation of growth. Bias ($\overline{D}_i$) was lowest for spruce measured in the Smokies (.441 cm/10 years) and largest for the Black Mountains (.968 cm/10 years).

Besides a longer increment period needed for the development of a better stand projection model, a completely independent data set is needed for the validation of the model. While individual components of the model were validated by randomly splitting individual tree stem data performing tests for bias and precision, because of the widely varying stand histories, species composition, and levels of insect infestation, it would be inappropriate to validate the predicted stand projections by data splitting the relatively small total sample size (142 plots). One alternative would be to simply verify the model by remeasuring the plots in several years for a comparison of actual versus simulated data.

While the stand projection model has some limitations, it does represent the only effort to provide a wide ranging description of future stand conditions of the southern Appalachian spruce-fir that considers the realities of the ongoing balsam woolly adelgid infestation, the shifts in species composition with environmental gradients, and varying stand histories. Where the adelgid has been dominating fir mortality patterns for several decades, in areas such as the Black Mountains, overall little change is expected. For most elevations basal area is projected to be stable while stem densities decrease, a expected response of the aging of a relatively young forest. In the Smokies, where little fir is found at or below 1675 m elevation, stand structure is predicted to change little during the 20 year period. However, the highest elevations of the Smokies (Clingman's Dome Road area) are predicted to eventually be similar to the current stand structure of high elevations of the Black Mountains. The adelgid infestation of the peaks of the central Smokies lagged by twenty-some years behind the infestation at the Black Mountains and the model predicts a deterioration of fir as well as spruce. The biggest uncertainty of the model lies with prediction of the Mt. Rogers area. While Fraser fir there is currently resistant to the adelgid, a long string of mild winters has resulted in continually high population levels of infestation. If fir resistance deteriorates (possibly due to combined stresses such as the prolonged drought of 1986-1988, etc.), stand structure changes will be more rapid than predicted.

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Chapter V

SYNOPSIS AND CONCLUSIONS

Numerous studies examining different abiotic and biotic components of the southern Appalachian spruce-fir ecosystem as well as other forest types have referred to a possible red spruce (*Picea rubens* Sargent) decline suggesting causal factors such as pests, pathogens or diseases, changing climatic conditions, but most often stress related to atmospheric deposition. However, there is only scattered direct evidence of decline symptomology. This project makes no effort to determine if a red spruce decline has occurred or is occurring, since assessment of decline should seem to involve a rigorous quantification of past forest status. Possibly the definition of decline may need some further clarification, prior to future surveys. In fact, in recent meetings to assemble a compendium on red spruce in the eastern United States (Eagar and Adams 1992) the eighteen authors gave up all attempt to provide a definition of decline since agreement among participants was impossible.

The purpose of this project was to determine the current rate of forest change and to allow for an uncompromised future assessment of forest condition. Baseline status of stand structure and composition, forest productivity, mortality and growth rates are provided for a range of geographic locations, varying elevations, and different land use histories. Little reliable historical information was previously available for a model of expected stand behavior especially for second-growth stands and for sites with substantial balsam woolly adelgid-caused (*Adelges piceae* Ratz.) Fraser fir (*Abies fraseri* (Pursh) Poiret) mortality. Inference space from past research was minimal because most previously published studies on forest condition and trends were based on small sample sizes, non-random sampling locations, unmarked trees and plots, and short monitoring periods. This study was designed to formulate and establish a rigorous sampling protocol and a stratified, randomly located permanent plot system to allow future researchers substantial opportunities to examine ongoing issues related to spruce-fir stand dynamics.

Several important conclusions can be made at this point. In the absence of tree planting, spruce-fir species distribution still tends to follow an elevational gradient for both old-growth and second-growth stands: spruce dominance changes to fir as elevation increases. Disturbed or second-growth stands have lower basal area and LAI and higher densities than old-growth stands on comparable sites even 60 years or more after logging. Red spruce, a species claimed to be declining by some, has the lowest mortality rate of the four dominant overstory species of the southern Appalachian spruce-fir. Instead, mortality levels of mountain-ash (*Sorbus americana* Marshall) appear to be quite high. A short-term projection of current stand condition using current rates of change indicates few major changes are expected by the year 2009 with the exception of stand deterioration at the high peaks in the Great Smoky Mountains where low ingrowth and growth rates cannot compensate for the rate of overstory mortality.

Provision of a baseline seems to call for future monitoring. *Further research is needed* may be a tired sop for a conclusions section but really further monitoring is the only way to detect true change. Besides needed remeasurements to update stand descriptions and truly verify the stand projection model, some additional data and analysis would provide a better basis for these conclusions. Better fitting equations for estimating leaf area may be pursued. However it must be cautioned that the seemingly perpetual insect infestation of yellow birch (*Betula lutea* Michaux f.) leaves and the ongoing adelgid infestation of fir may preclude getting significantly better models. A more rigorous application and definition of the crown condition variable (amount of intact needles) may allow for a confident prediction of individual spruce and fir mortality. A longer sampling period is probably needed in order to build prediction models of understory ingrowth from overstory conditions. Further modeling efforts of understory vegetation are needed to better understand the transition of seedlings and saplings to the overstory. Better fitting basal area increment equations are quite likely possible with the availability of inside bark diameter increment measurements. Finally a designed field experiment is needed to study the response (regeneration, ingrowth, mortality and growth rates) of codominant canopy species to rapid adelgid-caused fir mortality in fir-dominated stands.

LITERATURE CITED

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VITA

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