ASSESSING THE IMPACTS OF BALSAM WOOLLY ADELGID (*ADELGES PICEAE* RATZ.) AND ANTHROPOGENIC DISTURBANCE ON THE STAND STRUCTURE AND MORTALITY OF FRASER FIR (*ABIES FRASERI* (PURSH) POIR.) IN THE BLACK MOUNTAINS, NORTH CAROLINA

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Abstract

Over the past several decades, naturally occurring populations of Fraser fir (*Abies fraseri)* in the Black Mountains of North Carolina have been heavily impacted by both direct and indirect anthropogenic disturbances, including logging and logging- associated fires, and high mortality rates due to the introduction of the exotic insect, balsam woolly adelgid (BWA) (*Adelges piceae*). The decline in Fraser fir is particularly concern because it serves as a foundation species within the spruce-fir forests of the Southern Appalachian Mountains. Our objectives for this research were to 1) use current stand structure to infer whether Fraser fir trees are experiencing a cycle of regeneration-mortality that will lead to eventual decline of the population, 2) determine what role, if any, the site-specific geographic variables of slope, elevation, aspect, and land use history have on stand structure, mortality, and BWA infestation level, and 3) analyze repeat aerial photography to examine broad trends of spruce-fir forest cover change caused by anthropogenic disturbance and the BWA. In order to understand stand structure, mortality, and infestation levels, we conducted detailed field surveys of Fraser fir trees throughout the Black Mountains using 44, fixed-radius circular sampling plots. These plots were placed throughout a series of aspects, elevations, and disturbance types in order to understand geographic variability among these variables. An analysis of 4 repeat aerial photographs and corroborating ground photographs revealed broad spatio-temporal trends of spruce-fir regeneration and mortality from 1954 to 2006. Our results indicate that Fraser fir stands at higher elevations are currently in a state of recovery; whereas stands at lower elevations appear to be more susceptible to BWA-induced mortality. Changes in forest cover area from 1954 to 2006 were influenced greatly by direct and indirect anthropogenic disturbance. Our results call attention to the significant impact that direct and indirect anthropogenic disturbance has had on Fraser fir stand structure, but also provide evidence for the ability of an imperiled ecosystem to recover from high rates of insect caused mortality.

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Chapter 1: Introduction and Statement of Purpose

1.1 Introduction

Southern Appalachian spruce-fir forests are currently a fragile and imperiled ecosystem. They face broad impacts from both direct and indirect anthropogenic disturbance and from natural disturbance (White et al. 1985, Nicholas and Zedaker 1989). Conserving and understanding southern Appalachian spruce- fir forests is important because they contain a number of endemic and rare plant and animal species (Smith and Nicholas 1998), are geographically limited, are valuable aesthetically to recreational users, and anchor the headwaters of mountain streams and improve downstream water quality (White 1984).

Furthermore, Fraser fir (*Abies fraseri* (Pursh) Poir.), the fir species of southern Appalachian spruce-fir forests, has been particularly at risk due the introduction of an exotic insect, balsam woolly adelgid (BWA) (*Adelges piceae* Ratz.). The decline of Fraser fir has threatened the ecological stability of the spruce-fir forest ecosystem since it serves as a foundation species for this community. Due to the Fraser fir's narrow distribution, limited to only seven disjunct regions in the southern Appalachians, it is listed as a significantly rare species in North Carolina, a federally designated species of concern, and a globally imperiled species that is vulnerable to extinction (Franklin and Finnegan 2004, Potter et al. 2008). The Black Mountains of North Carolina, one of the seven regions that provide critical habitat for Fraser fir, contain the second largest amount of spruce-fir forest area in the southern Appalachians (Dull et al. 1988).

The Black Mountains of North Carolina have been heavily impacted with human disturbance. Logging and logging-associated fires were the first major human caused disturbances introduced to the region in the early 1900s. The exotic BWA was first observed in these mountains in the mid-1950s and subsequently caused widespread mortality of Fraser fir (Speers 1958). Furthermore, acid rain and global climate change are other indirect anthropogenic disturbances that have impacted, and will likely to continue to impact, this region in the future (Bowers 2005).

The majority of intensive logging operations occurred in the Black Mountains from 1912 to 1922 by three major logging companies: the Brown Brothers, Carolina Spruce, and Perley and Crockett. By 1914, 1,000 acres of spruce-fir forest had already been cleared from the flanks of Mount Mitchell, Mount Gibbes, and Clingman's Peak. All trees over 4 inches in diameter were cut for both pulpwood and timber, and skidding destroyed smaller trees. Very few regions of the Black Mountains escaped the intensive logging activity, and entire mountainsides were often stripped bare (Pyle and Schafale 1988). Even after the major logging activity diminished in 1922, salvage logging of trees downed by wind-throw continued until 1929 (Hollingsworth and Hain 1991). Fires associated with the logging industry were also destructive to spruce-fir forests. Whether initiation of fires were accidental, or intentionally designed to remove slash, they could burn through litter and soil to a depth of one foot, killing the seed bank of red spruce and Fraser fir (Schwarzkopf 1985). As a result of the intensive logging and logging-associated fires, the current spruce-fir forest is estimated to be 10% to 50% of the area it occupied prior to the commercial logging industry (Nicholas et al. 1992, Smith and Nicholas 1999).

Though logging and logging-associated fires severely devastated the spruce-fir forests, perhaps the greatest threat, with long term consequences to Fraser fir, came in the decades after the logging operations ceased. An accidently introduced exotic insect, the BWA, caused devastating mortality rates in Fraser fir in the Black Mountains. The BWA was first introduced from Europe into Canada sometime prior to 1908 (Speers 1958, Busing et al. 1988). From

Canada BWA spread southward and westward and was first observed on Fraser fir at Mount Mitchell, within the Black Mountains, in October of 1957 (Speers 1958). High mortality rates of Fraser fir from BWA infestation have been well documented. Amman and Spears (1965) estimated tree mortality in the vicinity of Mount Mitchell to be over 1.5 million trees by 1965 – only eight years after the first sighting of BWA.

Other populations of Fraser fir in the southern Appalachians have been greatly impacted by BWA as well. For example, Dull et al. (1988) reported that parts of Great Smoky Mountain National Park (GSMNP) contained Fraser fir stands with mortality rates as high as 90%, and Nicholas et al. (1992) found a greater proportion of standing dead firs than standing live firs. Specifically, live fir densities were between 8-62% less than when sampled in the same location prior to BWA infestation (Oosting and Billings 1951). Smith and Nicholas (1998) reported almost 70% of total standing fir basal area was dead in their sample area of five high elevation mountains in GSMNP.

Regeneration of Fraser fir since BWA infestation has been investigated both in the Black Mountains and in the GSMNP. Witter and Ragenovich (1986) reported heavy regeneration of Fraser fir at Mount Mitchell and predicted that Fraser fir would continue to be an important species in the forest in the future. In the GSMNP, Fraser fir remained the dominant species at high elevations, despite high mortality rates, due to the abundant seedling recruitment (Busing and Clebsch 1988). Smith and Nicholas (1999) described a high density of Fraser fir seedlings within the forest understory in plots established in GSMNP. Jenkins (2003) explained that while the overstory density and basal area of Fraser fir had decreased since 1979 on Mt. LeConte, Tennessee, the understory density and basal area had increased since that time. Bowers (2005) re-sampled spruce fir forest plots established by Nicholas et al. (1992) in the Black Mountains of

North Carolina. Live stem density of Fraser fir was found to have increased at all elevations from 1986 to 2003, with the most dramatic and significant increases occurring at the highest elevations (1980 m). Bowers (2005) indicated that his finding supported statements by researchers in the early 1990s that the first wave of BWA induced mortality is nearly complete (Nicholas et al. 1992). However, he admitted that some uncertainty remains concerning the fate of Fraser fir, especially as more trees reach BWA susceptible size.

Regeneration is not the sole factor ensuring the success of the Fraser fir population surviving BWA attack. Currently, the survival ability of the latest generation of reproductive-sized Fraser fir is largely unknown due to the lack of recent research. The BWA is still present in the population and continues to feed on the bark of adult Fraser fir trees, where fissures are more prominent than in younger and smaller diameter trees (Witter and Ragenovich 1986, Smith and Nicholas 1999). Stem infestation by BWA generally occurs on stems > 4 cm dbh; whereas reproductive size is generally not reached until 15 to 17 cm dbh (Eager 1984, Smith and Nicholas 2000). Therefore, it is quite feasible that Fraser fir seedlings could rapidly grow in the understory, but be attacked by the BWA and die before they reach reproductive age (Eager 1984). If Fraser firs continue to die before reaching reproductive age, the Fraser fir population would likely decrease and eventually cease to exist in all of its range locations, with the exception perhaps of trees in the Mount Rogers area that have shown some resistance.

1.2 Statement of Purpose

The research objectives of this study were to 1) use current Fraser fir diameter distributions and stand structure to infer whether Fraser fir are experiencing a cycle of regeneration-mortality that could lead to eventual decline of the population, 2) determine what role, if any, the site-specific geographic variables of slope, elevation, aspect, and land use history have on stand structure, mortality, and BWA infestation level, and 3) use repeat aerial photography to examine broad trends of spruce-fir forest cover change caused by anthropogenic disturbance and the BWA. Objectives 1 and 2 relate to present day conditions of Fraser fir stands in the Black Mountains; whereas objective 3 seeks to understand how the spruce-fir forests have changed over time.

Current research was necessary to fill the gap of knowledge concerning Fraser fir population stand structure post-infestation by BWA. The Black Mountains, North Carolina was a prime research area for analysis in this context because of its large Fraser fir population (up to 66% of stand component is Fraser fir above 6000 ft., Hollingsworth and Hain 1991), high mortality rates caused by BWA in the past, complex land use history, and the need for updated research concerning stand structure. This study site was ideal for examining the spatial patterns of stand structure and mortality with respect to geographic and local site variables (such as elevation, aspect, slope, and land use history). In addition, no previous studies have used repeat aerial photographs to examine spruce-fir forest change in light of human disturbance activities and the BWA.

The findings from this research will contribute to the literature in the areas of invasive species, global climate change, and the role that disturbance plays in shaping forest structure. Invasive species are estimated to cost the United States approximately $120 billion each year. Furthermore, about 42% of the species listed as either federally threatened or endangered are there as a result of invasive species (Pimentel et al. 2005). Fraser fir, a federally designated species of concern, has suffered extensive mortality due to the invasive BWA. Understanding how this invasive species is currently impacting Fraser fir stands will provide information about the possible future economic impacts for control or management of this exotic insect. Long term changes in Fraser fir distribution and the increased threat of an exotic insect as a result of global climate change is also an important topic in the broader scope of understanding how vegetation distributions might shift as a result of mean increases in global temperature (Baker et al. 1995, Delcourt and Delcourt 1998). Understanding how anthropogenic disturbance has impacted forest stands could influence future decisions for natural resource managers concerning how best to manage and protect areas where southern Appalachian spruce-fir forests occur.

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Chapter 2: Literature Review

2.1 Introduction

This chapter provides a review of the literature regarding Fraser fir (*Abies fraseri* (Pursh) Poir.) and the spruce-fir forests of the southern Appalachian Mountains. In section 2.2, I discuss past and present distributions of Fraser fir. In section 2.3 I highlight the importance of Fraser fir as a foundation species. In section 2.4, I review research that addresses the impacts of the exotic insect balsam woolly adelgid (*Adelges picea* Ratz.) (BWA). Sections 2.5, 2.6, and 2.7 review the literature concerning BWA-induced mortality of Fraser fir, Fraser fir regeneration since BWA infestation, and the potential for a regeneration-mortality cycle of Fraser fir. Section 2.8 explores the theoretical concepts of island biogeography and source-sink populations. Section 2.9 investigates the influence human disturbance has had on southern Appalachian spruce-fir forests. Finally, section 2.10 discusses natural disturbance and stand dynamics.

2.2 Fraser fir Distributions: Past and Present

Between 23,000 and 18,000 yr BP, boreal forests covered an area of approximately 1,800,000 km^2 north of 34°N latitude in the southeastern U.S. (Delcourt and Delcourt 1981, 1984). The broad distribution of boreal forests can be attributed to cool and moist climatic conditions that resulted from their close physical proximity to the Laurentide ice sheet. It was during this time of glacial maximum that Fraser fir, balsam fir (*Abies balsamea* (L.) Mill), and bracted balsam fir (*Abies balsamea var. phanerolepsis* Fern.), likely constituted a single species of fir (Delcourt and Delcourt 1981). After 12,500 yr BP, the Laurentide ice sheet began to retreat north as climatic conditions ameliorated, and the fir population responded by reducing area and distribution throughout the southeastern U.S. Today, the southern Appalachian spruce-fir communities are restricted to only the highest elevations where a suitable damp and cold habitat can be found, resulting in their current "island-like" distribution on seven disjunct mountaintop regions (Oosting and Billings 1951). The retreat of fir separated populations and allowed them to evolve to their present day phenotypic expressions.

The present day distribution of balsam fir is largely contiguous and extends through Canada, southward into Minnesota, Michigan, New York, and northern Pennsylvania, with disjunct populations found in northern West Virginia and northern Virginia (Clark et al. 2000). Bracted balsam fir occurs within the range of balsam fir, but at higher elevations in the northeast, in lower elevations in Maine and the maritime provinces of Canada as well as in small stands in West Virginia and Virginia (Clark et al. 2000) (Figure 2.1).

Figure 2.1: Natural range of the balsam fir (*Abies balsamea* (L.) Mill) complex in the eastern United States and Canada (Brown 1999).

The present day distribution of Fraser fir within the southern Appalachians is restricted to seven disjunct high elevation mountain areas located between Mount Rogers, Virginia and Great Smokey Mountain National Park (GSMNP), North Carolina/Tennessee (Oosting and Billings 1951, Ramseur 1960, Rheinhardt 1984, Pauley and Clebsch 1990). These locations include

Mount Rogers/Whitetop, Virginia; Long Hope Mountain, North Carolina; Grandfather Mountain, North Carolina; Roan Mountain, North Carolina/Tennessee; the Black Mountains, North Carolina; the Balsam Mountains, North Carolina; the Plott Balsam Mountains, North Carolina; and GSMNP (Smith and Nicholas 1999) (Figure 2.1). Fraser fir dominates in nearly pure stands at elevations over 1900 m, giving it an island-like distribution at the top of the highest mountain peaks in the southern Appalachians (Whittaker 1956, Busing and Clebsch 1988, Smith and Nicholas 1998). Due to the narrow range of this species, it is listed as a significantly rare species in North Carolina, a federally designated species of concern, and globally as imperiled and vulnerable to extinction (Franklin and Finnegan 2004).

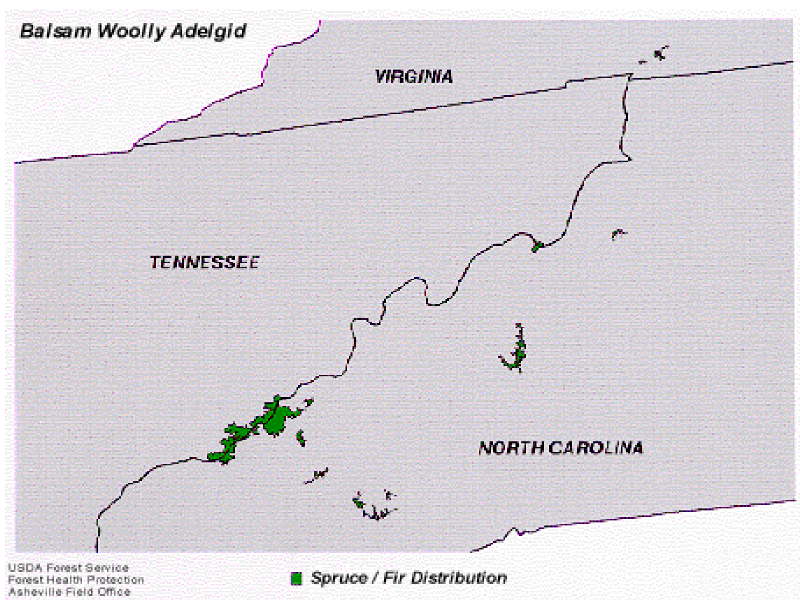

Figure 2.2: Distribution of spruce-fir in southern Appalachians. Source: USDA Forest Service Health Protection (2001).

2.3 Fraser fir as a Foundation Species

A foundation species is a locally abundant species that defines an entire ecosystem by either its functional or structural attributes. Therefore, the loss of a foundation species can have widespread ecological consequences. Throughout the world, foundation tree species are declining due to several factors including introduction of exotic pests and pathogens, over-harvesting, and high intensity logging (Ellison et al. 2005).

Fraser fir is a foundation species within the spruce-fir ecosystem because it is the dominant structural unit of the high elevations in the southern Appalachians (Smith 1984). The decline of Fraser fir has threatened the ecological stability of the spruce-fir forest communities. Negative impacts on species closely associated with the spruce-fir forests have already been observed and measured. For example, red spruce (*Picea rubens* Sargent) is dominant with Fraser fir at elevations ranging from 1675-1900 m (Whitaker 1956, Smith and Nicholas 1998, Smith and Nicholas 2000, Jenkins 2003); in the absence of Fraser fir, red spruce is more sensitive to wind-throw. Increased exposure or winter desiccation causes red spruce to experience slower growth rates (Harrington 1986, Goelz, et al 1999). Furthermore, an estimated ten of the eleven common territorial bird species present in 1974 declined as Fraser fir mortality reached high levels in GSMNP. Six of those eleven species declined by more than 50%, and some bird species are nearing local extinction (Rabenbold et al. 1998).

2.4 The Balsam Woolly Adelgid

BWA has been, by far, the most devastating natural disturbance to impact the high elevations of the southern Appalachians to date. Mortality rates of Fraser fir due to attack from the BWA has greatly reduced the sizes of populations within the range of Fraser fir, with the exception of trees in the Mount Rogers, Virginia area (Hollingsworth and Hain 1991, Smith and Nicholas 1998, Goelz et al. 1999). The reason why trees at Mount Rogers are less susceptible to BWA is not fully understood at this time; however, some researchers believe they may have genetic resistance. Hollingsworth and Hain (1991) noted that trees at Mount Rogers do become heavily infested; thus the relatively low mortality of these trees is not due to the absence of BWA in this location.

The BWA is an exotic species that was first introduced from Europe into Canada sometime prior to 1908 (Speers 1958, Busing et al. 1988). From Canada, BWA spread southward and westward and was first observed in the southeastern U.S. on Fraser fir at Mount Mitchell, North Carolina (located in the Black Mountains) in the mid-1950s (Speers 1958). Wind is the primary dispersal agent of the BWA, and it has been responsible for the dispersal of the BWA in the southern Appalachians for distances up to 64 km (Amman 1966). The Black Mountains has a north-south orientation within the otherwise southwest-northeast-oriented Appalachian mountain chain. Therefore, once the BWA was introduced to Mount Mitchell, it was in a location that allowed relatively easy dispersal to surrounding Fraser fir populations (Eager 1984). Indeed by 1962, the BWA had dispersed further south to locations in GSMNP, North Carolina/Tennessee and has since dispersed throughout the entire spruce-fir forest (Pauley and Clebsch 1990).

The BWA has no known natural predators (Schwarzkopf 1985, Smith and Nicholas 1998), although attempts of biological control of BWA were made in the late 1950s and early 1960s with the release of predatory insects (Amman and Speers 1964). Attempts to control the insect through the use of chemicals have been problematic. Lindane, a gamma isomer of benzene hexachloride, was the main chemical agent used in attempts to control BWA in high recreation areas of Mount Mitchell during the 1960s (Cielsa et al. 1963, Eager 1984). However, in a forest setting spraying was inefficient and expensive since the entire bole of the tree must be sprayed from within the stand. Lindane also was investigated by the Environmental Protection Agency due to its persistence within the environment. Salt of oleic acid was suggested as a less toxic alternative because it has a biocidal effect on adelgids. Again, the use of this agent over widespread forested areas proved challenging and ineffective due to the large areal extent that needs to be covered (Eager 1984).

The BWA feeds by inserting its stylet into Fraser fir bark. Usually feeding occurs in the fissures of the bark in trees that are over 4 cm dbh (Smith and Nicolas 2000, Jenkins 2003).The tree responds by producing dense growth rings that interrupt the movement of water and carbohydrates (Dale 1991). As a result, sapwood conductance is reduced and water stress occurs (Amman and Speers 1965, Smith and Nicholas 1998). Fir trees in the native range of the BWA in Europe are not seriously affected by the BWA; however, Fraser firs of North America are one of the most susceptible fir species to mortality (Hain and Arthur 1985). This heightened susceptibility could be because the warmer and humid climate of the southern Appalachians allows BWA to complete 2-3 generations per year (Hollingsworth and Hain 1991). After initial infestation, death of trees can be slow but normally occurs within 2-5 years after initial infestation (Amman and Speers 1965, Aldrich and Drooz 1967, Hollingsworth and Hain 1991). Accordingly, an infestation in a particular area can have long-lasting effects on a population. In the past, most adult Fraser fir trees have died as a result of the BWA infestation (Pauley and Clebsch 1990, Jenkins 2003).

2.5 Fraser fir Mortality and Mortality Effects

High mortality rates of Fraser fir caused by BWA have been well documented. Amman and Speers (1965) estimated tree mortality in the vicinity of Mount Mitchell to be over 1.5 million trees by 1965 – only eight years after the first BWA sighting. Dull et al. (1988) reported that parts of GSMNP contained Fraser fir stands with mortality rates as high as 90%. Nicholas et al. (1992) found a greater proportion of standing dead firs than standing live firs in both GSMNP and the Black Mountains. Specifically, live fir densities in the GSMNP plots were between 8-

62% less than when they were sampled in the same location prior to BWA infestation (Oosting and Billings 1951). Smith and Nicholas (1998) reported that almost 70% of total standing fir basal area was dead in their sample area of five high elevation mountains in GSMNP.

Another important forest dynamic considered by researchers is the response of spruce-fir forest understory to gap created by fir mortality. DeSelm and Boner (1979) found a tenfold increase in smooth blackberry (*Rubus canadensis* L.) following mortality of Fraser fir. Pauley and Clebsch (1990) reported that Fraser fir seedlings were negatively associated with smooth blackberry density. At the summit of Mount LeConte, Tennessee, percent cover of smooth blackberry increased from 2% to 30% from 1979 to 2001 (Jenkins 2003). In addition, pin cherry (*Prunus pennsylvanica* L.f.) and American mountain ash (*Sorbus americana* Marsh.) percent cover increased, presumably as a result of overstory Fraser fir mortality, though these results were not statistically significant (Jenkins 2003). Busing and Clebsch (1988) noted that leaching of nutrients from the soil may result from Fraser fir mortality, since the above ground nutrient reserves are lost with tree mortality. These findings indicate that BWA infestation caused stand and understory restructuring as well as changes in vegetation composition.

2.6 Fraser fir Regeneration

In the late 1980s and early 1990s, research shifted from mortality to potential regeneration of Fraser fir because researchers began to study the long term ecological consequences of BWA and consider whether or not Fraser fir might be able to reproduce viable populations in the future (Witter and Ragenovich 1986). Witter and Ragenovich (1986) reported heavy regeneration of Fraser fir in the vicinity of Mount Mitchell. They predicted that Fraser fir would continue to be an important species in the forest in the future based on the abundance of smaller diameter trees. In GSMNP, Fraser fir remained the dominant species at high elevations, despite mortality rates, due to abundant seedling recruitment (Busing and Clebsch 1988). Smith and Nicholas (1999) described a high density of Fraser fir seedlings within the forest understory in plots established in GSMNP. Jenkins (2003) explained that while the overstory density and basal area of Fraser fir had decreased since 1979 on Mount LeConte, Tennessee, the understory density and basal area had increased since that time, indicating that Fraser fir regeneration was taking place.

Fraser fir regeneration has been studied within the context of competition. Some authors speculated that smooth blackberry might interfere with regeneration of overstory species through competition (Pauley and Clebsch 1990, Witter and Ragenovich 1986). Others, however, have reported that the regeneration potential for Fraser fir is extremely good, despite this understory. For example, Busing and Clebsch (1988) argue that since Fraser fir is shade tolerant and capable of rapid growth under a closed understory, regeneration rates should be fairly rapid. They conclude that young seedlings will be recruited and eventually replace dead trees in the canopy.

Allen and Kupfer (2001) utilized satellite imagery for analysis of mortality and regeneration trends in Fraser fir in GSMNP. They used tassle-cap indices, Landsat TM digital data, and change-vector analysis to study initial dispersal of the BWA and show how elevation and moisture gradients influenced infestation and could potentially influence regeneration. They concluded that regeneration is influenced by time since infestation, location (east-west topography) and upslope-downslope elevation.

Bowers (2005) re-sampled spruce-fir forest plots established by Nicholas et al. (1992) in the Black Mountains of North Carolina in order to investigate changes in spruce-fir basal area from 1986-2003. He found that live stem density of Fraser fir was greater across all elevation classes, with the most dramatic and significant increases occurring at the highest elevations (>

1980 m). Bowers (2005) indicated that his finding supported statements by researchers in the early 1990s that the first wave of BWA induced mortality is now complete. However, he admitted that some uncertainty remained concerning the fate of Fraser fir, especially as more trees reach BWA susceptible size.

2.7 Potential for a Cycle of Regeneration-Mortality

Regeneration is not the sole factor that assures the success of the long term survival of BWA-infested Fraser fir populations. Currently, the mortality rate of the latest generation of reproductive-sized Fraser fir trees is largely unknown due to the lack of recent research. The BWA is still present in Fraser fir populations and continues to feed on the bark of larger diameter trees, where fissures are more prominent than in smaller diameter trees (Witter and Ragenovich 1986, Smith and Nicholas 1999). Stem infestation by BWA generally occurs on stems larger than 4 cm dbh; whereas reproductive size is generally not reached until 15 to 17 cm dbh (Eager 1984, Smith and Nicholas 2000). Therefore, it is quite feasible that Fraser fir seedlings could rapidly grow in the understory, but be attacked by BWA and die before they reach reproductive size (Eager 1984). If this regeneration-mortality cycle occurs, the Fraser fir population would likely decrease and possibly cease to exist in all of its range locations, perhaps with the exception of trees in the Mount Rogers area that have shown some resistance to the insect.

Reaching reproductive size is likely the key component that will ensure future success of the Fraser fir population as a whole (Busing and Clebsch 1988). Smith and Nicholas (2000) examined age and size structure distributions of Fraser fir in GSMNP. They found overstory fir populations characterized by very few large fir trees and proportionately higher densities of small fir trees. This finding lead them to hypothesize that Fraser fir populations in the future would be characterized by decreasing numbers of even-aged patches in different stages of regeneration and mortality. This regeneration-mortality cycle is very similar to the one experienced by the American chestnut (*Castanea dentate* (Marsh.) Borkh.) after being attacked by the exotic pathogen, chestnut blight, (*Cryphonectria parasitica* (Murrill) Barr). Chestnut blight was originally introduced to North America around 1910, and by 1930 it had killed most mature individuals of American chestnut in eastern North America (Harmon et al. 1983). American chestnuts can still be found in eastern forests, but they do not survive long enough to reach reproductive age and only exist through sprouting.

The eventual extirpation of Fraser fir is not the only possible scenario resulting from BWA infestation; the possibility for a more favorable outcome does exist. In some locations previously infested by BWA, Fraser firs are beginning to enter the overstory due to rapid growth under an open canopy where they are positively influenced by increased levels of light. These rapidly growing trees could reach reproductive size more quickly than they did pre-BWA infestation and produce seed before succumbing to mortality (Smith and Nicholas 2000). Additionally, since bracted balsam fir is likely resistant to attack from the BWA, some Fraser fir individuals could also possess the gene combination that confers resistance to attack from BWA (Witter and Ragenovich 1986). Observations by Witter and Ragenovich (1986) showed that older trees with smooth bark, as opposed to rough bark with crevices, appeared to be more resistant to attack by BWA (Witter and Ragenovich 1986). Selective pressure could result in the survival of Fraser fir with some resistance feature, possibly smoother bark, resulting in the survival of the species as a whole. However, it is important to point out that development of genetic resistant could take many generations.

Several decades have passed since initial BWA infestation. Therefore, understanding if mature trees susceptible to BWA attack are surviving, (as opposed to focusing on regeneration alone), will be very important for the ongoing management of spruce-fir ecosystems. If the majority of the current generation of reproductive-sized Fraser firs is also succumbing to mortality from BWA, it is possible that extinction may be the fate of the species, unless certain management measures prove successful. As previously mentioned, the Fraser fir population at Mount Rogers appears less susceptible to BWA-induced mortality. One possibility for managers might be to repopulate BWA-infected areas with propagated Fraser firs from the Mount Rogers region that have resistance (Rheinhardt 1984).

2.8 Theoretical Context: Island Biogeography and Source-Sink Populations

The present-day distribution of Fraser fir, as previously described, is restricted to habitat "islands" of hospitable environment (high elevations of cool temperatures and relatively high moisture) surrounded by regions of inhospitable environment (lower elevations with somewhat warmer temperatures and relatively less moisture). The spruce-fir zone of the southern Appalachian montane forests experiences average annual temperatures of approximately 6˚ C to 9˚ C and average annual rainfall of approximately 200 cm (Oosting and Billings 1951, White 1984). The present day distribution of Fraser firs is restricted to mountain summit locations in the southern Appalachians, making it narrowly endemic (White 1984). This habitat scenario can be understood by the theory of island biogeography, which states that there is an important relationship between species abundance, composition, and area. The theory states that smaller islands support less diverse species composition when compared to larger islands, all other factors being equal. Furthermore, because of their isolation, islands tend to develop a unique species assemblage (MacArther and Wilson 1967).

Immigration and emigration rates are processes generally discussed in the context of biogeographical islands (MacArthur and Wilson 1967). An oceanic island that is closer to the “mainland,” or source area, is thought to have greater rates of immigration than emigration. Whereas, an island further from the mainland would likely have a higher emigration than immigration rate. However a “mainland” does not directly translate when considering mountaintop islands, as in this study. Therefore, an alternative way to consider immigration and emigration rates is through source-sink population dynamics. A source population is defined as one that has birth rates higher than death rates; whereas a sink population is defined as one that has death rates higher than birth rates (Pulliam 1988). This theory of source and sink population sites can be applied to both animal and plant species and can have important conservation and management implications.

As applied to Fraser fir populations, one can consider regeneration as being the equivalent of “birth rate” and mortality as the equivalent of “death rate.” Certain locations of Fraser fir could currently have greater regeneration rates than mortality rates, such as in the GSMNP and potentially in the Black Mountains. Other locations, however, may only have sparse coverage because the mortality rate still exceeds the regeneration rate. As a result, it becomes important to identify the source populations so that they be protected and kept from further perturbation.

In the context of source-sink population dynamics, dispersal among source populations is crucial. The longer two populations are separated from each other, the greater the potential for a speciation event to occur (Pielou 1991). The fragmented pattern of Fraser fir populations in the southern Appalachians can have negative genetic consequences. Small populations tend to suffer genetic drift and inbreeding. Isolation can mean lack of significant gene flow between populations (Young et al. 1996, Potter et al. 2008). Therefore, the potential exists for further speciation to occur between currently disjunct Fraser fir populations.

Research on genetic differentiation of Fraser fir populations has shown somewhat conflicting results. Auckland et al. (2001) found no significant differences in DNA content between Fraser fir populations, and the authors suggested that the frequency and severity of destabilizing events had not been large enough to cause a change in DNA content among populations. However, Potter et al. (2008) found small, though significant, differences in the amount of genetic differentiation of Fraser fir populations. Specifically, Fraser fir stands at Grandfather Mountain, North Carolina contained a high proportion of allelic richness and private alleles. The Mount Rogers, Virginia population, the most northerly population of Fraser fir, was found to be significantly differentiated from the other populations (Potter et al. 2008). Potter et al. (2008) noted that these differences have important implications for conservation efforts of Fraser fir, especially if the lower mortality rates of Fraser fir at Mount Rogers can be linked to these genetic differences.

2.9 Direct and Indirect Anthropogenic Disturbance

2.9.1 Introduction

Geographical research often seeks to understand how the Earth has been transformed by human action (e.g. Cutter et al. 2002). The Black Mountains of North Carolina have experienced a long history of direct and indirect anthropogenic disturbance activities. These activities included animal grazing, fires set by hunters prior to commercial logging, intensive commercial logging and logging-associated fires, tourism, acid rain, and the introduction of exotic species (Pyle and Schafale 1988). Here I will specifically discuss logging, fire, tourism, and acid rain and deposition, as they have a potential for influencing regeneration.

2.9.2 Logging and Fire

Logging and logging-associated slash fires were a major disturbance factor to the spruce-fir forests of the southern Appalachians during the early 1900s (Hollingsworth and Hains 1991, Nicholas et al.1992). Logging in the region was made possible with the advent of new technology in 1911: narrow-gauge track and low geared Shay and Climax engines for a railroad that could traverse the steep terrain of the region (Silver 2003). Completion of the first section of what became known by locals as the “Mount Mitchell Railroad” took one year. New sections of the railroad were continually added in order to reach new sections of forest in the mountains.

The majority of the logging activity occurred in the Black Mountains between 1912 and 1922 and was led by three main logging companies (Hollingsworth and Hain 1991, Silver 2003). Carolina Spruce Operations worked primarily in the north section of the Blacks and used another newly completed railroad line, the Black Mountain Railroad, to move logs. The Brown Brothers Operation worked on the western side of the Black Mountains along the Cane River Valley, and they built a spur of railroad that was tied in to the Mount Mitchell Railroad. The Dickey/Campbell Perley and Crockett Operations worked on the southern end of the Black Mountains between Mount Mitchell and Potato Knob and on the eastern slopes of Mount Mitchell north to Maple Camp Ridge (Silver 2003). The Dickey/Campbell Perley and Crockett Operations used the Mount Mitchell Railroad for their logging operations, and by 1914, they had cleared 1,000 acres of spruce-fir forest from the flanks of Mount Mitchell, Mount Gibbes, and Clingman’s Peak. Steam powered machines moved logs through the woods by pulling long sections of solid steel cable that were attached to downed trees (Pyle and Schafale 1988, Silver 2003). With such widespread logging activity on all sides of the Black Mountains, few areas were spared (Figures 2.3 and 2.5). Only the summit of Mount Mitchell, a few ridges of surrounding peaks, remote tracts of land north of Maple Camp Ridge, and a few isolated patches of trees sandwiched in the headwaters of the South Toe that could not be easily accessed were not logged (Silver 2003). Even after the major logging activity slowed down around 1922, salvage logging of trees downed by wind-throw continued until about 1929 (Hollingsworth and Hain 1991).

Logging activities took a toll on the landscape in several ways including wind-throw, erosion, and fire. Wind-throw became a problem in the remaining high elevation forests because the removal of many trees near the railroad made them vulnerable to strong wind. Bare patches with areas up to 5 acres were not uncommon. Erosion of mountain soils left bare by the logging also caused torrents of water to rush down the mountains. These torrents were often capable of cutting through the soil, leaving only bare rock and clay exposed (Silver 2003).

Fires also raged as result of logging activities. These fires were either set intentionally to remove logging debris, or they began accidently when piles of slash left to dry in the sun were ignited by sparks thrown by locomotives on nearby railroads (Schwarzkopf 1988). One such fire sparked in June of 1914 and was especially catastrophic, destroying an estimated $10,000 worth of timber on the eastern slopes of Mount Mitchell (Silver 2003). Logging fires could burn through the litter and soil to a depth of one foot, killing the seed banks of Fraser fir and red spruce (Hollingsworth and Hain 1991). With so many trees cut down and seedling banks destroyed, the ability for natural regeneration was severely impaired, especially in areas where grass had established and could outcompete other forms of vegetation. By the 1920s, the eastern face of Mount Mitchell, which had burned more than once since the 1914 fire, was covered by a large swath of grassland. The natural transition from grassland back to forest can be extremely slow, possibly taking up to 250 years (Silver 2003).

In order to aid the forest recovery process, artificial reforestation efforts were mounted in the late 1920s. More than 100,000 seedlings of Fraser fir, red spruce, and Norway spruce (an introduced species) were planted in the Black Mountains (Schwarzkopf 1985). Mount Mitchell State Park staff planted an estimated 105 acres between 1923 and 1933 (Hollingsworth and Hain 1991). As a result of logging and logging-associated fires, the current spruce-fir forest is estimated to be 10% to 50% of the area it occupied prior to the commercial logging industry (Nicholas et al. 1992, Smith and Nicholas 1999).

Figure 2.3: Sections of Mount Mitchell were stripped after intensive logging activities. Source: North Carolina Collection, Pack Memorial Public Library, Asheville. 1920-1933?

The increase in infrastructure in the Black Mountains allowed tourism to also increase because, for the first time, people had a source of transportation to the summit of Mount Mitchell other than by foot. Tourism began in earnest when Camp Alice was built by Perley and Crockett. Tourist activities centered on Camp Alice, where there was a rustic dining hall and platform tents available for those that wanted to spend the night (Schwarzkopf 1988) (Figure 2.4). In the summer of 1916 an estimated 20,000 people traveled by railroad to the camp. In

1922, an auto toll road opened and carried another 20,000 people in its first summer of operation. As more people wanted to travel to Mount Mitchell, the pressure for better access to the area also increased. The completion of the Blue Ridge Parkway in 1939 and of Highway 128 in 1948 provided visitors with paved access all the way to the summit of Mount Mitchell. As result, the number of visitors to the Mount Mitchell area in 1949 was estimated to be around 86,000 per year and by 1984 had increased to approximately 389,000 per year (Pyle and Schafale 1988). Current estimates of the number of visitors to Mount Mitchell State Park are approximately 500,000 per year (personal communication with Ranger Matt Mutel, March 6, 2009). With growing population numbers and an increased interest in natural areas, these visitor numbers will likely continue to rise (North Carolina Department of Environment and Natural Resources). The present-day impact of tourists in the Black Mountains has been due primarily to camping, firewood cutting, and damage to trees. Unfortunately, much of these activities have been centered in a small area of spruce-fir that has not previously been disturbed by logging or fires (Pyle and Schafale 1988).

Figure 2.4: A rustic dining hall and platform tents were available for visitors who traveled to Mount Mitchell by railroad. Source: North Carolina Collection, Pack Memorial Public Library, Asheville ca. 1915.

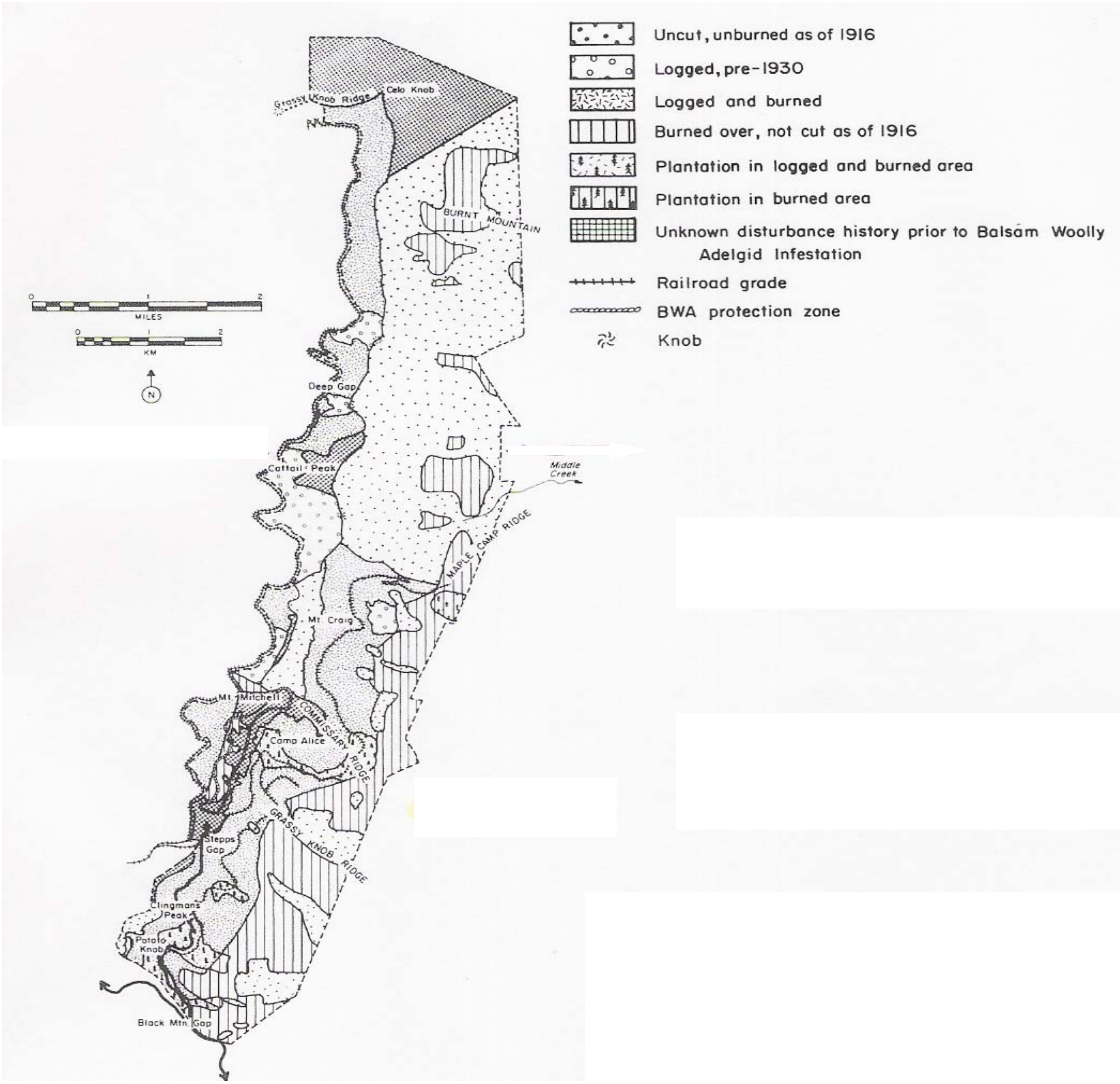

Figure 2.5: Map depicting disturbance history of the spruce-fir forest in the Black Mountains, North Carolina (Pyle and Schafale 1988).

2.9.3 Acid Rain and Acid Deposition

Atmospheric deposition and acid rain are other human-induced disturbance factors that have already severely impacted spruce-fir forests and will likely to continue to be detrimental in the future (Aneja et al. 1992). It is not known to what extent the impact of acid rain and deposition has had or will have in causing Fraser firs to be more susceptible to BWA- induced mortality (Hollingsworth and Hain 1991). For example, Hain and Arthur (1985) hypothesized that atmospheric deposition is a tree stress factor that could cause Fraser firs to be more susceptible to BWA attack by lowering their defense response.

Acid rain originates from nitrogen and sulfur dioxides released from the emissions of unregulated factories, coal-fired plants, and even vehicles, which become trapped in the atmosphere. Nitrogen and sulfur dioxides are converted to nitric and sulfuric acid in the presence of moisture and sunlight. These nitric and sulfuric acids mix with precipitation such as rain or snow, and then fall to the earth in the form of acid rain (Silver 2003). These pollutants can even become concentrated in fog and rime ice, allowing pollutants to be deposited directly onto trees. Acid rain and acid deposition are thought by many researchers to increase spruce and fir mortality, although, the extent to which they have influenced the decline of southern Appalachian montane forests has been difficult to pinpoint and often controversial due to conflicting viewpoints on the topic. One viewpoint is that acid rain is the final stress that causes death in Fraser firs already stressed by BWA infestation; whereas, the other viewpoint is that acid rain predisposes Fraser fir to mortality from BWA (Hain and Arthur 1985).

Research on acid rain in the southern Appalachian region began in the 1980s when a dramatic decline in spruce-fir forests was observed (Bruck et al. 1989). As reported by Bowers (2005), reasons used to explain forest decline included competition (LeBlanc et al. 1992), acid rain and acid deposition (Bruck 1989), increased soil acidification (Cowling et al. 1988), and severe ice storm damage (Nicholas and Zedaker 1989).

Much of the controversy surrounding spruce-fir forest decline focused specifically on red spruce, since BWA was usually acknowledged as the main reason for Fraser fir decline (Aneja et al. 1992). However even with the acknowledgement of BWA, its role was often downplayed or ignored and atmospheric deposition was used to explain forest decline. For example, while Bruck et al. (1989) briefly acknowledged the presence of BWA in plots in the Mount Mitchell, North Carolina area, the majority of their work discusses the role of acid rain and acid deposition in the region. Furthermore, Pitelka and Raynal (1989) cite instances where photographs of Fraser fir killed by BWA were incorrectly used as evidence to support forest decline due to acid rain and acid deposition. Skelly (1992) asserted that most of the photographs circulated to show forest decline in North America have been those of the high elevation forests of Mount Mitchell, where BWA has actually played the largest role in Fraser fir mortality. One prominent example is a photograph used by MacKenzie (1985) that features dead Fraser firs with the caption: "Air pollution is taking a heavy toll on U.S. trees and crops. This heavily polluted spruce-fir forest on Mount Mitchell, North Carolina appeared healthy the early 1980s." Furthermore, Skelly's (1992) personal communications with Dr. Chris Eager, USDA Forest Service scientist, revealed that sections of Fraser fir forest that had received BWA control measures (in the form of spray) prior to the 1970s could be easily distinguished from those sections that had not received any form of BWA control, indicating that BWA was indeed the likely cause of much of the decline.

Some acid rain proponents argued that the more recent regeneration of Fraser firs seen in the late 1980s to present may be attributed to the passing of the Clean Air Act in 1970 and its amendments in 1990, which placed restraints on annual sulfur and nitrogen emissions

(Environmental Protection Agency). However, fir trees in the Pacific Northwest that have not been impacted by acid rain or deposition have still shown BWA- induced mortality (Mitchell 1966, Nicholas et al. 1992). Furthermore, Mount Rogers in Virginia has air quality comparable to other southern Appalachian fir sites; however mortality of Fraser fir from BWA is much lower there (Mohnen 1992, Nicholas et al. 1992).

Even though BWA has been documented as the major reason for Fraser fir mortality (Dull et al. 1988), the potential negative consequences of acid rain and acid deposition should not be ignored. Acid rain and deposition have likely caused additional stress to an ecosystem already imperiled. As previously mentioned, atmospheric deposition could have exacerbated BWA mortality due to adding increased environmental stress (Hain and Arthur 1985). The most extreme effects of acid rain or acid deposition occur on the highest elevation peaks, where exposure to these pollutants is most frequent and concentrated (Aneja et al. 1992). High elevations where spruce-fir forests occur are more susceptible to damage from pollutants than lower elevations due to increased levels of precipitation and more frequent cloud immersion (White 1984).

Aneja et al. (1992) reported that winds from the prevailing direction (WNW) brought in clouds with a mean pH of 3.5 to Mount Mitchell; whereas winds from the second most common direction (ESE) had a mean pH of 5.5. His research indicates northwesterly winds originating from the highly industrialized Ohio River Valley region usher in increased levels of acid rain and acid deposition to the southern Appalachian region. Furthermore, Aneja et al. (1992) reported that Mount Mitchell was covered with clouds 25 to 40% of the time, with the non-precipitating clouds having very high acidity (pH ranging 2.5 to 4.5), and precipitating clouds being only somewhat less acidic (pH ranging 3.5 to 5.5).

2.9.4 Human Accelerated Climate Warming

The impacts of these activities on spruce-fir forests in the southern Appalachians is exacerbated and complicated by human-accelerated climate warming (e.g. IPCC 2007). Global climate change could potentially impact the already limited range of southern spruce-fir forests by reducing their climatic niche. A potential outcome of climate change on Fraser firs is a range shift to higher elevations with the possibility of complete loss of the species from the mountaintops (Delcourt and Delcourt 1998). Delcourt and Delcourt (1998) predicted the loss of southern Appalachian spruce-fir forests with a global mean temperature increase of 3˚C.

2.10 Natural Disturbance and Stand Dynamics

Forests are inherently dynamic both spatially and temporally. Changes in forests take place due to competition among tree species, interactions among trophic levels, and large scale disturbances. Disturbance can be defined as the death of trees that frees growing space by opening the forest overstory and allowing succession to occur (Wulder and Franklin 2007). Disturbance can be caused both by natural processes and those introduced due to human activities, and they have important implications for stand dynamics and structure.

Natural disturbance processes such as fire, wind-throw, drought, and succession commonly occur within forest stands. In the spruce-fir forests of the southern Appalachians, high moisture in fuel and high humidity limit the role that fire plays (White et al. 1985). However, processes such as creation of small tree fall gaps and wind-throw are thought to play an important role in succession and stand dynamics of old-growth southern Appalachian spruce-fir forests (White et al. 1985). Stand structure and dynamics of old growth forests also vary according to slope, elevation, and aspect position (Whittaker 1956, Crandall 1958, White 1984). In second growth spruce-fir forests, Nicholas and Zedaker (1989) stress the importance of large scale and more rapid disturbance factors such as ice storms in influencing stand dynamics. Despite the common occurrence of these natural processes, so much of the southern Appalachian spruce-fir forest has been impacted by human-induced disturbance that it becomes difficult to differentiate natural disturbance processes from those of human origin.

The BWA is one major human-induced disturbance factor that has greatly influenced Fraser fir stand dynamics. The primary influence of this exotic insect on fir forests is tree mortality, which changes stand dynamics by increasing light in the understory and altering the microclimate of dense fir stands (Harmon et al. 1983). An individual tree's response to forest gaps can vary as local abiotic factors, and the understory composition and structure change (Veblen 1989). Openings in the forest canopy allow for the release of successional shrubs and hardwoods such as pin cherry, yellow birch, mountain laurel, rhododendron, service berry and smooth blackberry in spruce-fir forests (Busing et al 1988, Nicholas and Zedaker 1989, Pauley and Clebsch 1990). Past land use history is another factor that can influence stand dynamics and patterns of succession (White 1984).

In the absence of Fraser fir, red spruce theoretically could increase in numbers due to less competition (Busing et al. 1988). However, mortality rates of red spruce have largely been shown to increase, due to greater wind and ice damage in the absence of Fraser fir (Busing 2004). Fraser fir is very tolerant to shade, but saplings also readily respond to canopy gap formation (White et al. 1985, Pauley and Clebsch 1990). Fraser firs have strong rates of ingrowth and gap capture, while red spruce has high survivorship and larger size due to greater longevity (Busing 1996). These dynamics likely explain the continued dominance of these two species at the highest elevations of the southern Appalachians.

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Chapter 2 Figures:

Chapter 3: Assessing the impacts of balsam woolly adelgid (*Adelges piceae* Ratz.) and anthropogenic disturbance on the stand structure and mortality of Fraser fir (*Abies fraseri* (Pursh) Poir.) in the Black Mountains, North Carolina[†]

[†]This manuscript is in preparation for submission to *Castanea*.

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Abstract

Over the past several decades, naturally occurring populations of Fraser fir (*Abies fraseri)* in the Black Mountains of North Carolina have been heavily impacted by both direct and indirect anthropogenic disturbances, including logging and logging-associated fires, and high mortality rates due to the introduction of the exotic insect, balsam woolly adelgid (*Adelges piceae*) (BWA). The decline in Fraser fir is worrisome because it serves as a foundation species of the spruce-fir forests of the Southern Appalachian Mountains. Our objectives for this research were to 1) use current stand structure to infer whether Fraser fir are experiencing a cycle of regeneration-mortality that could lead to eventual decline of the population, 2) determine what role, if any, the site-specific geographic variables of slope, elevation, aspect, and disturbance history have on stand structure, mortality, and BWA infestation level, and 3) use repeat aerial photography to examine broad trends of spruce-fir forest cover change caused by anthropogenic disturbance and the BWA. In order to understand stand structure, mortality, and infestation levels, we conducted detailed field surveys of Fraser fir trees throughout the Black Mountains using 44, fixed-radius circular sampling plots. These plots were placed throughout a series of aspects, elevations, and disturbance types in order to understand geographic variability among

these factors. Analysis of repeat aerial photographs acquired from four dates and corroborating ground-based photographs revealed broad spatio-temporal trends of spruce-fir regeneration and mortality from 1954 to 2006. Our results indicate that Fraser fir stands at higher elevations are currently in a state of recovery, whereas stands at lower elevations appear to be more susceptible to BWA- induced mortality at this time. Changes in forest cover area from 1954 to 2006 were influenced greatly by direct and indirect anthropogenic disturbance. Our results call attention to the significant impact that direct and indirect anthropogenic disturbance has had upon Fraser fir stand structure, but also provide evidence for the ability of an imperiled ecosystem to recover from such activity.

3.1 Introduction

Since the early 1900s, the Black Mountains of western North Carolina have been heavily impacted by both direct and indirect anthropogenic disturbances. Intensive logging (e.g. Lovelace 1994, Fetters 2007) and logging-associated fires (Pyle and Schafale 1988) were among the first major human-induced disturbances to directly and dramatically influence this landscape. Acid rain (Bruck et al. 1989, Aneja et al. 1992), global climate change (Delcourt and Delcourt 1998), and the introduction of an exotic pest, the balsam woolly adelgid (*Adelges picea* Ratz. (BWA) (Speers 1958), are among the recent indirect anthropogenic disturbances that have impacted, and will continue to profoundly impact this region in the future.

From an ecological perspective, the collective and individual impact of these human disturbances upon the southern Appalachian spruce-fir forests is of particular interest. Fraser fir (*Abies fraseri* (Pursh) Poir.), the fir species of the southern Appalachian spruce-fir forests and one of its foundation species, is of particular concern. Due to the Fraser fir’s restricted occurrence to seven disjunct regions in the southern Appalachians (Oosting and Billings 1951, Ramseur 1960), it is listed as a significantly rare species in North Carolina, a federally designated species of concern, and globally as imperiled and vulnerable to extinction (Franklin and Finnegan 2004, Potter et al. 2008). A foundation species is a locally abundant species that defines an entire ecosystem by either its functional or structural attributes (Ellison et al. 2005). The decline of Fraser fir has threatened the ecological stability of southern Appalachian spruce-fir forests. For example, negative consequences associated with Fraser fir decline have already been observed and measured (e.g. Harrington 1986, Rabenbold et al. 1998, Goelz et al. 1999).

The majority of logging operations occurred in the Black Mountains from 1912 through approximately 1922 (Pyle and Schafale 1988, Fetters 2007). Very few regions of the Black Mountains escaped the intensive logging activity, and entire mountainsides were often stripped. Even after the major logging activity diminished around 1922, salvage logging of trees downed by wind-throw continued through 1929 (Pyle and Schafale 1988, Hollingsworth and Hain 1991).

Fires associated with the logging industry were also a major disturbance factor for spruce-fir forests. Whether accidental, or intentional to remove slash, these fires could burn soil and litter to a depth of one foot, killing the seed bank of red spruce and Fraser fir (Schwarzkopf 1985). As a result of logging and logging-associated fires, the present-day spruce fir forest is estimated to be 10% to 50% of the area it occupied prior to the commercial logging industry (Nicholas et al. 1992, Smith and Nicholas 1999).

Though logging and logging-associated fires severely impacted spruce-fir forests, perhaps the greatest threat with long term consequences to Fraser fir came in decades after the logging operations ceased. The BWA, an exotic insect accidentally introduced to the United States, caused devastating mortality rates to Fraser fir in the Black Mountains. BWA was first introduced from Europe into Canada sometime prior to 1908 (Speers 1958, Busing et al. 1988). From Canada it spread southward and westward, and it was first observed on Fraser fir at Mount Mitchell, North Carolina in the mid-1950s (Speers 1958). High mortality rates of Fraser fir from BWA infestation have been well documented. Amman and Spears (1965) estimated tree mortality in the vicinity of Mount Mitchell, North Carolina to be over 1.5 million trees by 1965 – only eight years after the first sighting of BWA.

Other Fraser fir populations in the southern Appalachians have also been greatly impacted by BWA. For example, Dull et al. (1988) reported that parts of Great Smoky Mountain National Park (GSMNP) contained Fraser fir stands with mortality rates as high as 90%, and Nicholas et al. (1992) found a greater proportion of standing dead firs than standing live firs. Specifically, live fir densities were between 8-62% less than when sampled in the same location prior to BWA infestation (Oosting and Billings 1951). Smith and Nicholas (1998) reported almost 70% of total standing fir basal area was dead in their sample area of five high elevation mountains in GSMNP.

Regeneration of Fraser fir since introduction of BWA has been an important topic of investigation in order to understand whether or not Fraser firs would survive current and future infestation by BWA. Over-all, previous research has revealed that regeneration has been occurring both in the Black Mountains and in GSMNP. Witter and Ragenovich (1986) reported heavy regeneration of Fraser fir at Mount Mitchell, which lies within the Black Mountains, and predicted that Fraser fir would continue to be an important forest species in the future. In GSMNP, Fraser fir has remained the dominant species at high elevations, despite mortality rates, due to the abundant seedling recruitment (Busing and Clebsch 1988). Smith and Nicholas (1999) described a high density of Fraser fir seedlings within the forest understory in plots established in

GMSNP. Jenkins (2003) explained that while the overstory density and basal area of Fraser fir had decreased since 1979 on Mount LeConte in Tennessee, the understory density and basal area had increased since that time, indicating that Fraser fir regeneration was occurring. Bowers (2005) re-sampled spruce-fir forest plots established by Nicholas et al. (1992) in the Black Mountains of North Carolina. Live stem density of Fraser fir was found to increase at all elevations from 1986 to 2003, with the most dramatic and significant increases occurring at the highest elevations (>1980 m).

Researchers have hypothesized that the Fraser fir population could enter into a cycle of “regeneration-mortality,” meaning that a massive die-off of older, dominant trees would be followed by regeneration (Eager 1984, Smith and Nicholas 2000). Relatively little recent research attention has been focused on this hypothesis; therefore, whether or not Fraser firs are experiencing this cycle is currently unknown. Since the threat of BWA- induced mortality is greatest for trees > 4 cm diameter at breast height (dbh), and because reproductive size is not generally reached until 15 or 17 cm dbh (Eager 1984), some trees may not survive long enough to reach reproductive size if infected by BWA. If a cycle of regeneration-morality were occurring, declining numbers of Fraser fir trees able to reach reproductive size in each successive generation would ultimately lead to a decrease in population size over time (Smith and Nicholas 2000). However, the rapid recruitment of presently un-infested understory Fraser fir trees in areas where the overstory has been removed by BWA- induced mortality, would allow other Fraser fir trees to reach reproductive size before being infested by BWA.

In this study, we assess if such a population decline scenario appears to be in progress, and how such a cycle might be affected by geography. Specifically, we suspected that elevation, slope, aspect, and disturbance history would be important variables to examine in the context of the regeneration-mortality cycle because undisturbed spruce-fir forests have been previously shown to be influenced by these factors (Oosting and Billings 1951, White et al. 1985).

The Black Mountains, North Carolina are a prime area for this research because they provide habitat for a large Fraser fir population (up to 66% of stand component is Fraser fir above 1830 m) (Hollingsworth and Hain 1991), and the Fraser fir population in these mountains have experienced high mortality rates caused by past BWA infestations. Furthermore, the landscape is characterized by a complex history of human disturbance.

To our knowledge, no studies have examined Fraser fir forest cover change over time in this region in light of human disturbance activities and the presence of BWA. The use of repeat aerial photographs offers an opportunity to examine longitudinal forest cover changes over a broad area. We identified this gap as an important subject of research attention in order to provide a more complete picture of the historical status, as well as the current status, of Fraser firs in the Black Mountains.

The goal of this study was to investigate the impacts of logging, logging- associated fires, and the BWA on current Fraser fir stand structure and mortality, as well as on spruce-fir forest cover over time. The research objectives of this study were to 1) use current stand structure to infer whether or not Fraser fir trees are following a cycle of regeneration-mortality that will lead to eventual local extirpation of the population, 2) determine what role, if any, the site-specific geographic variables of slope, elevation, aspect, and land use history have on stand structure, mortality, and infestation level, and 3) use repeat aerial photography to examine broad trends of spruce-fir forest cover change caused by anthropogenic disturbance and the BWA. Objectives 1-2 related to present day conditions of Fraser fir stands in the Black Mountains; whereas objective 3 sought to understand the broad trends in spruce-fir forest cover change over time and space.

Due to the many scale and format differences of the aerial photographs used in this study, we were not able to make quantitatively precise estimates of changes in forest cover area. However, by relating details recorded on the aerial photographs with corresponding details on ground-based photographs, we were able to uncover important trends in spruce-fir forest cover change, as they relate to historical disturbance and effects of BWA.

3.2 Methods

3.2.1 Geography of the Black Mountains and Study Area

The Black Mountains form part of the Blue Ridge physiographic province within the Appalachian mountains, and are situated approximately 40 km northeast of Asheville, North Carolina in western North Carolina (35.76˚ N, 82.27˚W) (Figure 3.1). The Black Mountains span a 19 km stretch of north to south oriented peaks, many of which exceed elevations of 1830 m. Mount Mitchell (2039 m), the highest peak east of the Mississippi River, is included in this range (Schwarzkopf 1985). Approximately 2,914 ha of spruce-fir forest, or about 11% of the spruce-fir type within the southern Appalachians, occur along the highest elevations of the Black Mountains (Dull et. al. 1988, Hollingsworth and Hain 1991).

Climate generally includes cold winters (average high in January 1˚ C) and mild summers (average high in July 67˚ C), with temperatures averaging 25-30˚ cooler than those at sea level (Silver 2003). The frost free period occurs from late May to early October. Rainfall is plentiful throughout all seasons, and on average 200 cm of rainfall occurs each year (Silver 2003). As a result of these climatic conditions, the high elevations of the Black Mountains support an assemblage of plants that are very similar in composition to the spruce-fir forests of the northern and central Appalachian Mountains (Oosting and Billings 1951).

3.2.2 Field Methods

Vegetative sampling for this research was performed in the area between Cattail Peak in the north, Potato Knob in the south, Big Tom Wilson Preserve in the west, and the Buncombe Horse Trail up to Commissary Hill in the east (Figure 3.1) from June through September 2008. We characterized the current stand structure of Fraser fir within the Black Mountains of North Carolina across a wide range of elevations, aspects, and disturbance types. Initially, 300 random point locations within the study area were identified, and then, 44 of those points were chosen because they represented a range across three elevation strata (1645-1767 m, 1768- 1889 m, and >1890 m), several historical disturbance types, and were relatively accessible. Red spruce and Fraser fir are dominant from approximately 1675-1890 m, and above 1890 m Fraser fir dominates (Whittaker 1956). Therefore the first two elevation classes were chosen to represent the ‘lower’ and ‘upper’ bounds of spruce-fir forest, and the third elevation stratum was chosen to represent pure stands of Fraser fir. We chose these elevation strata to identify whether elevation zones influenced Fraser fir mortality, structure, and BWA infestation. Historical disturbance types were obtained from a disturbance history map of the spruce-fir zone in the Black Mountains that was scanned and manually digitized (Pyle and Schafale 1988). Points that fell in locations that were inaccessible due to steep slopes (>50˚) or dangerous terrain (i.e. rock cliffs) were avoided. Geographic coordinates of selected points were uploaded into a Garmin® GPS, and then located in the field using GPS navigation.

Fixed-radius circular plots (227 m^2) delineated vegetation sampling boundaries; x,y coordinates of the random points were used as the centroid of plot (sensu Nicholas et al. 1992, Smith and Nicholas 2000). At higher elevations where pure Fraser fir stands are extremely dense, we used smaller plot sizes (28 m^2 and 64 m^2, respectively). Since Fraser fir increases in density with elevation in our study area, using a smaller plot at high elevations captured sample sizes comparable to those of the larger plots at lower elevations. Therefore, a 28 m^2 plot was used when tree density exceeded 2 trees/m^2, a 64 m^2 plot was used when tree density was greater than 1 tree/ m^2 but less than 2 trees/ m^2, and a 227 m^2 plot was used when tree density was less than 1 tree/ m^2. Elevation (m), slope (˚), and aspect (˚) were recorded at each plot's centroid. After field work, plots were assigned to a slope and aspect class in addition to their previously determined elevation and disturbance classes (Table 3.1).

Within each plot, diameter at breast height (1.67 m) was measured using a diameter tape for both dead and live standing Fraser firs. Trees < 1.67 m in height were not measured, but they were counted. Fraser fir diameter measurements were grouped into two classes: '< 4.0 cm' and '> 4.0 cm'. Rationale for selecting these two classes is based on previous research that has shown Fraser fir trees to be relatively unaffected by BWA mortality under 4 cm dbh (Eager 1984, Smith and Nicholas 2000).

The proportion of Fraser fir mortality at the plot level, as well as within each diameter class, was determined based on a visual inspection of crown condition (live versus dead). A Fraser fir was classified as "dead" if at least 90% of the canopy foliage was dead. Only standing dead Fraser firs were included in the mortality count.

As an indication of the health of live Fraser firs, presence or absence of BWA infestation and/or infestation symptoms were noted for every Fraser fir within the plot. Symptoms of infestation include gouting of stems and yellowing of needles, which can eventually turn to a deep red and brown color as the needles die (Amman and Speers 1965) (Figure 3.2). Presence of BWA is identified by a white, "woolly" coating on bark (Hollingsworth and Hain 1984) (Figure

3.3). Each tree was assigned a BWA infestation/symptom classification (Table 3.2), and proportions of trees occurring within each BWA class were determined by plot.

In addition, infested trees were also classified according to the degree of their infestation based on the following criteria: tree boles were categorized as either having minimal (<0.5%-1% of bole), light (2%-19% of bole), moderate (20-49% of bole), or heavy (>50% of bole) infestation. There were a few disadvantages of this technique; for example, it was difficult to see how much BWA was present on the upper bole of tall Fraser fir trees (e.g. Eager 1984). Furthermore, this technique did not account for BWA present on branches. Considered in retrospect, a more effective approach might have been to sample a small portion (perhaps a $1cm^2$) of each tree bole, as noted by Bowers (2005). However, since BWA infestation is often variable throughout a tree, sampling from a consistent location on each tree bole could lead to inaccurate representations of BWA infestation. Further investigation on how best to characterize BWA infestation on Fraser firs would be a valuable contribution to guide future research.

3.2.3 Statistical Analysis

All data were tested for normality and transformations (arcsine square root or logarithmic) were applied where appropriate (Zar 1999). A Wilcoxon test was used to compare mean dbh of live trees versus dead trees > 4 cm since dbh measurements were not normally distributed. One -Way Analysis of Variance (ANOVA) and Welch's ANOVA (when data were found to have a normal distribution but unequal variances), were used to investigate the significance of elevation class, aspect class, slope class, and disturbance class on mean proportion of mortality per plot, mean live and dead dbh per plot, mean proportion of BWA infested Fraser fir per plot, and mean proportion of Fraser fir per plot with BWA symptoms. Tukey's multiple comparison test was used for post-hoc testing. Chi-square analyses compared the proportions of Fraser fir '> 4 cm dbh' and '< 4 cm dbh' within the BWA infestation classes. Fisher's exact test, a test considered more accurate than Chi-square when the expected numbers are small, was used to compare the proportions of live and dead trees '> 4 cm dbh' and '< 4 cm dbh'. Significance levels were evaluated at the 0.05 level.

3.2.4 Analysis of Repeat Aerial Photography

Repeat aerial photographs of the Black Mountains covering a span of 60 years were obtained and analyzed in order to visualize broad scale trends of spruce-fir forest cover change caused by anthropogenic disturbance and the BWA.

We were confronted with numerous registration challenges when georeferencing the 1954 and 1964 images which offered very few reliable locations to place control points and inconsistencies among the control points we did use. In general, these challenges are inherent to the mountainous environment of our study area. Aerial photographs that depict mountainous relief are inherently problematic for quantitative interpretations because of relief displacement, varying aspects, heavy shadowing, and the undeveloped nature of the landscape (Baker et al. 1995). These challenges were further complicated by the varied resolution and emulsions among our aerial photographs and the absence of detailed information about the acquisition of older photographs. Therefore, our goal was to describe trends and advance understanding rather than to provide a precise estimate of change. To make our results more robust, we corroborated with historical ground photographs and field measurements in our interpretation.

The following panchromatic aerial photographs were used: 1954 (Tennessee Valley Authority), 1964 (North Carolina Department of Transportation), 1988 (United States Department of Agriculture-Forest Service Aerial Photo Field Office), and a natural color 2006 (National Agricultural Imagery Program). The 1954 photograph was chosen as the earliest for this analysis because it predated much of the BWA- induced mortality of Fraser fir trees, and therefore could serve as reference for comparison against changes recorded in photographs with later dates. The remaining aerial photographs were chosen to represent the decades following the 1950s, with the exception of the 1970s, for which no aerial photograph were available. At the time of this analysis, the 2006 photograph represented the most recent photograph available.

Analysis of repeat aerial photography involved two main tasks: i) photo monitoring of forest change and ii) identifying trends in forest cover through a change detection procedure. Photo monitoring involved describing changes that could be detected visually within a region of interest (ROI) (hereafter referred to as ROI #1) located north of Mount Mitchell to south of Big Tom (Figure 3.4). This ROI was chosen based on availability of ground photographs that could be paired with the aerial photographs based on date. Ground photographs were used in order to validate landscape changes observed on the aerial photographs. In all cases, dates of the ground photograph were within four years of the date of the aerial photograph. The seasons the photographs were taken in varied; however, this difference was not of concern since our focus was on evergreen vegetation. Sub-regions on the ground and aerial pairs, labeled ‘A’ and ‘B’, were identified in order to describe change in Fraser fir forest that could be visually observed in the photographs.

The second task involved identifying trends in spruce-fir forest cover change within a ROI on the 1954, 1964, 1988, and 2006 photographs (hereafter referred to as ROI #2) (Figure 3.5). ROI #2 was chosen based on two criteria: first the ROI needed to be present on all four aerial photographs, and second, the ROI needed to have been impacted by both the BWA and human disturbance activities over the time period. Though the original aim of this study was to focus upon changes in only Fraser fir forest cover from 1954-2006, the nature of the photographs (panchromatic and color, and differences in scale among photographs) inhibited us from differentiating Fraser fir from red spruce through manual photo-interpretation.

We adopted a manual photo-interpretation approach with the forest cover change detection because our photographs had different spectral representations of the same features and different spatial resolutions (Baker et al. 1995). Other reasons for manually digitizing forest classes included heavy shadowing and positional uncertainty due to relief displacement. Georeferencing of the 1954 and 1964 photos and all forest delineation was performed using ESRI® ArcGIS version 9.2 (ESRI 2009). Root mean square error (RMSE) errors were 54 m for the 1954 image and 71 m for the 1964 image; we attribute these RMSE errors to the differences among photographs and the challenges in photo interpretation described above. Additionally, these RMSE errors likely resulted from the difficulty in identifying reliable ground control points and extreme relief displacement characteristic of the region's extreme topographic relief. Despite these errors, we are confident that our results provide detail sufficient to detect trends in forest cover change. These issues were not a concern for the 1988 and 2006 photographs since they had already been georeferenced (NAD 1983 Zone 17N).

We developed a forest classification scheme for the manual photo-interpretation process adapted from Philipson (1997) and Green et al. 1993 (Table 3.6). "Forest Type" represented the dominant (>50%) type of tree cover found at a particular location (Table 3.3). "Forest Cover" classes (Table 3.3) were manually digitized in ArcGIS. Since Fraser fir is known to dominate the canopy above 1890 m and spruce and fir are known to be co-dominants between elevations of 1675 m to 1890 m (Whittaker 1956, Smith and Nicholas 1998), a topographic map aided us in distinguishing between Fraser fir-dominated and Fraser fir and red spruce dominated forests. For purposes of this study, spruce-fir hardwood forests (typically found below 1675 m) were not delineated, since seasonal differences among photographs could introduce bias and possible error in delineating forest types that included hardwoods.

Once ROI #2 was delineated in each photograph, the areas (ha) of each forest type were calculated. Next, percent changes of each forest type were calculated between years. Percent changes of each forest type were used for identifying broad-scale changes in spruce-fir forest cover due to human disturbance activities and the BWA.

3.3 Results

3.3.1. Field Study Results

Our first objective was to use current forest stand structure to understand if Fraser fir in the Black Mountains is following a cycle of regeneration-mortality. The diameter distribution for live Fraser firs resembles a reverse ‘J’ that is representative of uneven- aged stands that have experienced relatively little disturbance (Koop 1989). If a cycle of regeneration-mortality were in progress, we would not expect this distribution. Rather, we would expect to see a diameter distribution highly skewed towards smaller diameter trees with a notable absence of larger diameter trees. Furthermore, the diameter distribution of dead Fraser fir trees is mainly trees < 4 cm dbh, which is the size less susceptible to BWA induced mortality.

A Wilcoxon test revealed that statistically significant ($p < 0.0001$, $Z = -14.43$, df=1) differences existed between the mean dbh of live trees greater than 4 cm dbh ($\bar{x}$ = 9.89 cm ± 7.49) and the mean dbh of dead trees greater than 4 cm dbh ($\bar{x}$ = 5.44 cm ± 4.76).

Fisher’s exact test revealed that the proportion of dead trees > 4 cm dbh (0.12) and the proportion of dead trees < 4 cm dbh (0.15) were not significantly different and the proportion of live trees < 4cm dbh (0.37) and live trees > 4 cm dbh (0.35) were not significantly different (p =

0.09) (Figure 3.7). If a cycle of regeneration-mortality were in progress, the proportion of dead trees > 4 cm dbh would likely be significantly higher than the proportion of dead trees < 4 cm dbh.

Chi square analysis revealed that the proportion of trees within each BWA infestation class were found to differ significantly between trees > 4 cm dbh and trees < 4 cm dbh (χ^2= 433.27, df = 3, $p < 0.001$). Proportions of Fraser firs in BWA classes 3 and 4 were greater for trees less < 4 cm dbh (0.21, 0.04) than in trees > 4 cm dbh (0.04, 0.02) (Figure 3.8).

Our second objective was to determine how slope, elevation, aspect, and past disturbance influence the stand structure, mortality, and BWA infestation and symptoms of Fraser fir. Mean live Fraser fir dbh was significantly different by disturbance classes (F = 2.889, 4, 32, $p < 0.05$) and elevation classes (F = 4.30, 2, 41, $p < 0.05$) as determined by ANOVA. Specifically, Tukey's multiple comparison test indicated that the mean dbh of Disturbance Class 3 (logged and burned) (5.61 cm ± 1.23) was significantly different from the mean dbh of Disturbance Class 5 (no known disturbance prior to BWA) (11.96 cm ± 1.56) (Figure 3.9) , and mean dbh of Elevation Class 3 (> 1890m) (10.58 cm ± 0.96) was significantly different from Elevation Class 1 (1645-1767m) (6.06 cm ± 1.30) ($p < 0.05$) (Figure 3.10). ANOVA testing indicated that no significant differences were found in mean dbh of dead Fraser firs among disturbance, elevation, aspect, or slope classes.

Elevation class was found to significantly influence mean proportion of plot mortality as shown by Welch's ANOVA (F = 6.45, 2, 41, $p < 0.05$). Tukey's multiple comparison test indicated that mean Fraser fir plot mortality in Elevation Class 3 (>1890 m) (0.25 ± 0.04) was significantly different from mean plot mortality in Elevation Class 2 (1768- 1889 m) (0.08 ±

0.05) ($p < 0.05$) (Figure 3.11). Slope, aspect, and disturbance classes were not found to significantly influence mean proportion of morality.

Mean mortality of Fraser fir trees was analyzed based on tree size ('< 4 cm dbh' and '> 4cm dbh'). The purpose of this was to determine if elevation was related to tree mortality based on tree size. ANOVA testing revealed that the mean proportion of mortality was highly significant by elevation class for trees < 4 cm dbh ($F = 11.34, 2, 41, p < 0.0001$); whereas mean proportion of plot mortality for trees > 4 cm dbh was not significant by elevation class ($p = 0.39$). The mean proportion of mortality for trees < 4 cm dbh was greatest in Elevation Class 3 (1980 + m) (0.18 ± 0.19), as indicated by Tukey's multiple comparison test (Figure 3.12). Slope class, aspect class, and disturbance class were not found to significantly influence mean proportion of morality.

The interaction of elevation and aspect with respect to mean proportion of mortality was significant as determined by ANOVA ($F = 4.02, 10, 33, p < 0.001$), and results are represented by least squares (Figure 3.13). Mean mortality was greatest in plots classified in Elevation Class 3 and Aspect Classes 4 and 1. Alternatively, mean mortality for plots classified as Elevation Class 1 was greatest in Aspect Class 2 and Aspect Class 3. Mean mortality for plots classified as Elevation Class 2 was greatest in Aspect Class 3 and Aspect Class 4.

Means for the proportion of trees infested with BWA by plot (BWA Classes 2 and 4) were significantly different among slope classes as determined by ANOVA ($F = 3.60, 2, 41, p < 0.05$). Specifically, the mean proportion of trees infested in Slope Class 1 (0.52 ± 0.11) was significantly different from the mean proportions of trees infested in Slope Classes 2 and 3 (0.76 ± 0.10, 0.83 ± 0.12). Means for the proportion of trees with BWA symptoms by plot (BWA Class 1) were found to be significantly different by disturbance class ($F= 2.86, 4, 32, p < 0.05$);

however, Tukey's multiple comparison test did not reveal any significant differences among the disturbance classes. None of the other variables we tested were found to significantly influence the proportion of trees with BWA symptoms. Means for the proportion of trees with no BWA symptoms and no BWA infestation (BWA class 3) by plot were not significant by elevation, slope, aspect, or disturbance class.

3.3.2 Repeat Aerial Photography Results

Our third objective was to examine how human disturbance activities and the BWA have influenced spruce-fir forest cover over time through qualitative visual inspection of repeat aerial photography. The two components of this task were case studies of aerial and ground photograph pairs and a change detection procedure for spruce-fir forest cover change from 1954 to 2006.

3.3.2.1 Photo Monitoring Case Study Results

Region A on the 1954 (Figure 3.14) aerial photograph depicts an open area on the western slope between Mount Mitchell and Mount Craig that resulted from trees downed by wind-throw. Though Region A is not visible on the 1959 ground photo, other ground photographs of Mount Craig taken in the 1960s document wind-throw that took place in this area (records from Mount Mitchell State Park, Schwarzkopf 1985). Region B on the 1954 aerial photograph highlights the eastern slope between Mount Mitchell and Mount Craig where forest cover is sparse due to the impacts of logging and fire. Evidence of that logging and fire occurred in this region is provided by a land use history map of the Black Mountains (Pyle and Schafale 1988).

The 1964 aerial photograph (Figure 3.15), indicates that the wind-throw highlighted in region A has migrated upslope. In the wake of the 1954 wind-throw located in Region A, Fraser fir has regenerated. The 1964 ground photograph confirms that young Fraser fir growth is occurring on the back edge of the migrating wind-throw patch. In region B, both the aerial and ground photographs depict changes beginning due to recent BWA activity. A few standing tree skeletons north of the Mount Mitchell parking lot mark the presence of the BWA within the Fraser fir population.

No aerial photographs were available for the late 1970s. However, a1978 ground photograph (Figure 3.16) shows the continued upslope migration of the wind-throw patch, which is no longer positioned on the slope, as depicted in prior photographs, but is now located on the ridge connecting Mount Mitchell to Mount Craig in Region A. Region B continues to contain standing tree skeletons, a result of the BWA.

Fraser fir forest cover in Region A, as represented by both the 1988 aerial and ground photograph (Figure 3.17), has changed considerably since 1978. The wind-throw patch on the ridge has now been filled in with Fraser fir regeneration. The open linear feature located along the ridge is the Deep Gap Trail that runs the ridges north of Mount Mitchell. Another sizeable change has taken place in Region B, where BWA induced tree mortality has increased, as evidenced by standing dead tree skeletons. This mortality is especially evident on the 1988 aerial photograph, where an open region can be seen north of the Mount Mitchell parking lot. The 1989 ground photograph confirms that this open patch consists largely of standing dead tree skeletons. In addition, the eastern slope of the mountain in the 1988 shows an increase in fir and spruce cover when comparing the region to the 1954 aerial photograph.

The 1996 ground photograph (no aerial photograph was available) (Figure 3.18) depicts tree regeneration in Region B, replacing the many dead tree skeletons that were visible in the 1988 ground photograph. Region A remains closed canopy.

In the 2006 aerial photograph, Region A continues to maintain the closed canopy forest first seen in the 1988 aerial photograph (Figure 3.19) and 1996 ground photograph. Region B in the 2006 aerial appears to have had Fraser fir regeneration since 1988. Region B on the 2009 ground photograph confirms this regeneration by providing evidence of new growth filling in the once bare patch caused by tree death resulting from BWA-induced mortality.

3.3.2.2 Trends in Forest Cover Change

Trends in forest cover change are presented in Figures 3.20 and 3.21. From 1954 to 1964, all spruce-fir forest cover classes increased, FF4 area increased, and FF2 and FF3 areas decreased. From 1964 to 1988, a large (-72%) decrease is seen in FF1 area, while large gains are seen in FF2 and FF3 areas (416% and 99%, respectively). From 1964 to 1988, increases in forest cover area continue to be seen for the spruce-fir forest cover classes, with the exception of SF1, which has a 100% decrease. From 1988 to 2006, increases are seen in FF1, FF3, SF1, and SF4. Over-all trends of change across the 60 year period are as follows: Fraser fir forest types experience losses in area in the most dense cover class (FF1) and the least dense cover classes (FF4 and FF5). Spruce-fir forest increases in the three densest forest cover classes (SF1, SF2, and SF3); whereas spruce-fir forest decreases in the least dense cover classes (SF4 and SF5).

3.4 Discussion

3.4.1 Cycle of Regeneration-Mortality

Based on diameter distributions and the results of Fisher's exact test and Chi-square analysis, it does not appear that Fraser fir trees within the Black Mountains are succumbing to a cycle of regeneration-mortality. The diameter distribution of live trees (Figure 3.6) indicates that the majority of Fraser firs fall within the smaller diameter classes (0 -12 cm dbh), and that numbers of trees decrease with increasing diameter size. This reverse 'J' diameter distribution has been shown to indicate that a species will have a lasting role in the future (Koop 1989). The reverse 'J' distribution has traditionally been considered characteristic of uneven aged forests in equilibrium state (Westphal 2006). Numerous studies have reported reverse 'J' diameter distributions for old growth forests (Meyer and Stevenson 1943, Lorimer 1980, Leak 1996, and Cancino and Gadow 2002). While our study site is far from being considered old growth, the reverse 'J' diameter distribution provides possible evidence that the forest is in a process of recovery from widespread mortality in the overstory caused by BWA.

Though smaller diameter trees appear to be abundant, another issue tied to the regeneration mortality cycle is the survival of trees > 4 cm dbh. Presently, the proportion of live trees over 4 cm dbh exceeds the proportion of dead trees over 4 cm dbh (Figure 3.7), indicating that large scale overstory mortality is not likely in progress at this time, and if it is, it is restricted to small areas. Furthermore, the mean dbh of live trees exceeds the mean dbh of standing dead trees. While this result is somewhat biased in that it does not account for the diameter size of fallen dead trees, in general, it can be assumed that the current mean dbh of standing dead trees represents more recent tree deaths. It is likely that many Fraser firs > 4 cm dbh were removed from the canopy with the initial sweep of BWA induced mortality during the 1960s through the early 1990s. Our results indicate a shift toward natural stand dynamics.

Evidence for this shift is seen in the high mortality rate of trees < 4 cm dbh (Figure 3.7). Following the assumption that BWA- induced mortality generally impacts trees > 4 cm dbh (Eager 1984), then death as a result of competition for limited resources is likely the driving factor. A high death rate in seedlings is a natural consequence of the intense competition for limited resources (Peet and Christiansen 1987). It is important to note that approximately 40% of trees < 4 cm dbh did exhibit symptoms of BWA infestation and BWA was found on another 23%. Therefore it is possible that some mortality seen in trees < 4 cm dbh could be a result of BWA rather than competition. However, generally BWA has not been previously shown to affect smaller trees because they have young, smoother, bark that is not favorable for the BWA (Eager 1984).

We found that mortality of trees < 4 cm dbh was significantly related to elevation ($p < 0.0001$). Specifically, we found mortality to be highest for trees < 4 cm dbh within Elevation Class 3 (1940+ m). Though not statistically significant, mortality for trees > 4 cm dbh is highest within Elevation Class 1 (1645-1767 m). One possible explanation for this trend in elevation-associated mortality is that competition for space and resources causes mortality of seedlings at higher elevations; whereas BWA causes mortality of larger, mature trees at lower elevations. The majority of seedlings produced by a mature tree do not survive long enough to reach canopy position. Rather, they typically die as a result of their inability to compete for water, nutrients, or space, which has come to be known as self-thinning (Mohler et al. 1978, Peet and Christensen 1987). Alternatively, mortality of larger trees at lower elevations would more likely result from BWA- induced mortality for two reasons. First, Fraser firs at lower elevations are on the edge of their ecological niche. By being on the edge of their ecological niche, they may be experiencing increased stress due to exposure to warmer temperatures than are favorable. Stress causes physiological changes in trees that reduce the amount of energy they have to fight off pests and pathogens and therefore can make them more susceptible to death (Wargo 1996). Second, even slightly warmer temperatures at lower elevations could be favorable to the reproductive potential of BWA (Dale et al. 1991).

Though the relationship was not statistically significant, the largest proportion of trees deemed “heavily” infested by BWA was found within Elevation Class 1 (1645- 1767 m). Again, a possible explanation for this finding is related to temperature. The progression of BWA through its life stages is very dependent on temperature (Dale et al. 1991). Warmer than average temperatures can amplify the developmental rate of BWA and increase the number of generations in a year. For this reason, the relatively milder climate of the southern Appalachians as compared to the northern Appalachians has been offered as one explanation for why BWA has not caused mortality rates in northern Appalachian firs as high as those found in southern Appalachian firs (Eager 1984). Even within the Black Mountains, lower elevations experience milder temperatures than higher elevations, which could allow even a slight increase in population numbers at lower elevations than at higher ones. It also follows to reason that future climate change towards warmer temperatures could negatively impact Fraser fir survival in an integrated manner – first by creating a more favorable climate for BWA reproduction and survival, and second, by removal suitable habitat for Fraser fir. For example, an increase in mean July temperatures of 3˚C, may result in the extinction of spruce-fir forests in the southern Appalachians (Delcourt and Delcourt 1998).

The shift towards natural stand dynamics at higher elevations that we found is in agreement with Bowers (2005), who also concluded that a shift is occurring toward the stable, uneven aged stands that were likely found in the Black Mountains several decades ago, prior to major disturbance. In addition, Bower’s specifically suggests that the rapid recovery of Fraser fir is occurring at the high elevations.

The dynamic relationship between Fraser fir and BWA infestation is complex and often localized in nature. White (1984) discussed the possibility that a shifting ‘steady state’ of localized patches of infested and un-infested Fraser fir could occur, which would allow localized survival of Fraser fir. The rationale behind White's (1984) assertion is that, since seedlings and saplings are relatively unaffected by BWA mortality (Eager 1984), only the mature trees in a particular stand would be lost to BWA- induced mortality. Then the stand would be composed of trees of an unacceptable size for BWA predation, resulting in extremely localized BWA-devoid patches that would allow regeneration to occur, and potentially for saplings to reach reproductive size. If the stand could escape further infestation, then larger individuals would persist over time. While our results do not indicate widespread mortality of the overstory, the BWA is still present in Fraser fir > 4 cm dbh; therefore, future monitoring of Fraser fir in the Black Mountains will continue to be important.

Our results differ somewhat from White's (1984) hypothesis because we did find that there were trees exhibiting symptoms of BWA but that had no BWA infestation. There are a couple of explanations for this outcome. First, the Fraser firs > 4 cm dbh could be individuals that survived mortality due to some BWA resistance. Fraser firs > 4 cm dbh in the vicinity of Mount Rogers, Virginia have not suffered from as high of mortality rates as Fraser firs in the Black Mountains and in GSMNP (Witter and Ragenovich 1986). Eager (1984) noted that Fraser firs with smoother bark were less susceptible to BWA infestation; therefore it is possible that individuals in the Black Mountains may have been able to survive for this reason. Second, Fraser firs < 4 cm dbh are likely only to show symptoms of BWA because, according to Eager (1984), Fraser firs of this size do not generally build up large BWA populations. Finally, the possibility exists that during sampling the BWA was present but not seen on the tree; therefore in error we assigned it an inaccurate BWA classification. Though we were careful to avoid such an error, it remains a possibility, especially for very tall trees where identifying the presence of BWA was difficult.

3.4.2 The impact of elevation, slope, aspect, and past land use on stand structure, mortality, and BWA infestation and/or BWA symptoms

Previous research has shown that the structure and dynamics of undisturbed southern Appalachian spruce fir forest changes with elevation, aspect, and slope (Whittaker 1956, Crandall 1958). Despite the long history of human disturbance in the Black Mountains, we expected to see a relationship between these geographic variables and stand structure. We were interested in determining whether or not these variables influenced tree mortality and/or BWA infestation and symptoms.

3.4.2.1 Stand structure

While none of the geographic variables significantly influenced mean dbh of standing dead Fraser fir, we did find that the mean dbh of live Fraser fir was most influenced by elevation and disturbance type. The largest trees were found in Elevation Class 3 (>1980 m), and in Disturbance Class 1(no known disturbance prior to BWA). These results agree with assessments of tree size in an undisturbed GSMNP spruce-fir forest, where maximum tree size increased with elevation (Whittaker 1956), and therefore provided prime habitat for Fraser fir.

The occurrence of the largest mean diameter size (10.58 cm) within plots that have not had logging or logging associated fires is a logical outcome, since the growth of the trees was not heavily impacted by these disturbance activities. We found without exception, that the mean dbh of live Fraser fir trees decreased with increasing disturbance. The largest trees were found in a location that has had no known prior human disturbance other than BWA infestation, and the second highest mean was found in plots that had been uncut, unburned as of 1916. The third largest class of trees was located in plots that had been burned, but not cut. This class was followed by the fourth largest class of trees, located in plots that had been logged prior to 1930, but not burned. Finally, the smallest class of trees was located in plots with the most extensive disturbance history, characterized by both logging and fire. In agreement with our results, Nicholas et al. (1992) found that the distribution of spruce-fir basal area was skewed toward stems diameters < 45 cm dbh in logged regions of the Black Mountains; whereas the distribution of spruce-fir basal area in unlogged areas of GSMNP was skewed towards stems > 45 cm dbh. Smith and Nicholas (1999) reported lower spruce basal areas and densities in stands that had been logged compared to un-logged stands across the seven disjunct sites that spruce-fir occurs within the southern Appalachians.

Our results highlight the major influence that elevation has on live Fraser fir stand structure as well as the profound impact that human disturbance has had in the Black Mountains over the past several decades.

3.4.2.2 Mortality

We found that elevation significantly influenced BWA- induced mortality (regardless of tree size). The highest proportion of mortality was found within Elevation Class 3 (> 1890 m). Though not statistically significant according our criteria ($p = 0.08$), the highest proportion of mortality by aspect was found within Aspect Class 4, or the northwest aspect, which is the direction of the prevailing winds in the Black Mountains. These variables likely contribute to high Fraser fir mortality because high elevation locations facing the northwest aspect receive the brunt of the coldest temperatures, strongest winds, highest levels of acid deposition, and ice damage within the Black Mountains (Aneja et al. 1992, Nicholas and Zedaker 1989, Bowers

2005). These conditions can amplify the stress of trees that are suffering from BWA infestation and cause an increase in mortality (Wargo 1996).

We also found that mortality within Elevation Class 1 (1645- 1767 m) was not significantly different from Elevation Class 3 (> 1890 m), indicating that though mortality is great at high elevations, it is also active at lower elevations. Least means revealed that at high elevations, mortality is more prevalent in the northwest and northeast aspect classes. At low elevations, however, mortality is more prevalent in the southeast and southwest aspect classes, and much lower in the northeast aspect class (no plots were sampled in the northwest aspect). Again, the concept of the ecological niche is applicable. The locations where mortality was highest represents the extremes of the ecological niche for Fraser fir. High elevations in the northwest receive extreme cold temperatures, rime ice, strong winds, and increased levels of atmospheric deposition. Low elevation locations in the southeast and southwest are more sheltered and receive the warmest temperatures of the Fraser fir population in the Black Mountains. As previously mentioned, lower elevations may be also be especially susceptible to BWA infestation since warmer temperatures facilitate the reproductive potential of the insect (Eager 1984, Dale et al. 1991).

3.4.2.3 BWA infestation and BWA symptoms

We found that the proportion of trees infested with BWA was significant related to slope class, but not by any of the other geographic and disturbance variables. Specifically, the proportion of trees infested with BWA in Slope Class 1 (0˚-10˚) was significantly lower than the proportions of trees infested within Slope Classes 2 (15˚-29˚) and 3 (30˚-45˚). Previous research has shown that elevation and aspect have been influential in the spread of BWA (Allen and Kupfer 2001). One possible explanation for why we found Slope Class 1 to be significant could be that the majority of plots within Slope Class 1 in this study were found along or on a ridge. Ridge and slope positions in our study correspond to the high elevation locations where Fraser firs may be in a state of recovery from BWA.

Disturbance class significantly influenced the proportion of trees with BWA symptoms. Though Tukey's multiple comparison test failed to find any significant differences among groups, the highest proportions of trees with BWA symptoms were found within Disturbance Class 3 (uncut, unburned) and 5 (logged pre-1930). At this time we are unclear concerning why these two land use classes might have higher proportions of trees showing symptoms of BWA. Further investigation would be valuable for future research.

3.4.3 Aerial Photograph Interpretation

3.4.3.1. Photo Monitoring

Changes seen in the photo monitoring portion of this research are widely applicable to the rest of the spruce-fir forest within the Black Mountains. Two major responses are seen: forest cover change as a result of human disturbance activity (logging and logging fire) and forest cover change as a result of the BWA. First, we will address the changes associated with logging and logging fires.

The patch of wind-throw featured in the 1954, 1964, and 1988 photographs likely originated from logging activities further down-slope on the mountain during the 1920s. The western side of Mount Craig is known to have been logged and burned at its lower elevations (Pyle and Schafale 1988). Logging and fire would have opened up the forest edge, allowing for trees to be more easily blown down by winds. Wind-throw is known to occur following cutting of mature forest, especially along boundaries of areas that have been clearcut (Alexander 1964).

The upslope migration of the wind-throw patch seen in the photographs, and the simultaneous regeneration of trees behind it, is very similar in nature to the “fir waves” that have been described in northern Appalachian spruce-fir forests (Sprugel 1976). Fir waves can be described as an upslope wave-like movement of tree death that occurs on an exposed slope which is followed by tree regeneration behind the dieback zone (Sprugel 1976, Reiners and Lang 1979). While the phenomenon seen here cannot be considered a true “fir wave,” since fir waves result from natural disturbance rather than human disturbance such as logging, the dynamics associated with the two phenomena are very similar.

Another major change evident throughout the time sequence represented in the photographs on the eastern slopes of ROI #1, is an infilling of fir and spruce trees. The infilling is most apparent when comparing the 1954 aerial photograph to the 1988 aerial photograph and is a sign of recovery from logging activities. While recovery cannot be considered totally complete, and forest cover remains more open that it was historically, the increase in trees over the time period is notable. Complete recovery on burned areas on the eastern slopes may take longer to transition back to natural forest, since much of that area is covered by grassland (Silver 2003).

Forest changes associated with the BWA can also be detected in the photo sequence. The changes in these photographs in relation to the BWA are centered within an area north of the Mount Mitchell parking lot (Region B). BWA-induced mortality first becomes evident in the 1964 photo pair. Mortality peaks in the late 1980s, and is followed be regeneration seen in the 1996 ground photograph. Although some standing dead tree skeletons are still in the 2009 ground photograph, there are no new outbreaks of major mortality, which provides further evidence for recovery of high elevation forests, at least within the area captured by these photographs. The trends seen in these photographs correspond to what researchers have reported on the ground concerning BWA and mortality in the Black Mountains. In the 1960s, Amman and Spears reported 1.6 million trees dead in the Mount Mitchell area as a result of BWA, and Aldrich and Drooz (1967) estimated 21.3 ± 1.0 dead fir per acre in the same area. In the 1980s, Dull et al. (1988) described high mortality of Fraser firs in the Black Mountains resulting from BWA infestation. Nicholas et al. (1992) stated that the first wave of BWA-caused mortality was nearly complete upon completing field work that was conducted in the Black Mountains in the mid-1980s. They also mentioned that the area formerly protected from BWA was heavily infested and starting to show signs of increasing mortality. Bowers (2005) re-sampled the plots used by Nicholas et al. (1992) and indicated recovery of Fraser fir stands, particularly at highest elevations.

Over-all, pairing of historical ground photographs with aerial photographs provides valuable insights into the changes associated with forest cover over 60 years. The changes we found within ROI # 1 are also characteristic of other locations within the Black Mountains during the time periods described. While no research attention has been given to patterns of wind-throw movement resulting from logging in the Black Mountains, we present evidence of its occurrence and importance in the forest disturbance regime. The trends associated with increasing BWA induced mortality from the 1960s through the late 1980s, followed by regeneration of Fraser fir in the 1990s, and finally a possible recovery of high elevation forests in the present day are in agreement with prior research (Aldrich and Drooz 1967, Witter and Ragenovich 1986, Nicholas et al. 1992, Bowers 2005).

3.4.3.2 Forest Cover Change Detection

Forests are inherently dynamic and complex entities, and forest change is frequently a result of numerous variables occurring on a multiple of spatio- temporal scales. Here we examine spruce-fir forests change within the context of logging and logging associated fires, and the BWA. The introduction of these disturbance events are offset from one another by about 30-50 years, with the majority of the logging and logging fire activity having taken place in the early 1900s, and the first BWA observation in the mid-1950s (Speers 1958). Spatially, these disturbance events impacted much of the same area, with the exception of the highest Fraser fir stands within ROI # 2, which were left intact.

Explanation of observed change in spruce-fir forest cover classes between 1954-2006 were confounded by the influence of two disturbance events that were occurring simultaneously. Some cover classes saw increases in over time, which we think are a result of forest recovery from logging and logging fires, while others saw decreases, which were likely due to the influence of BWA. Since the major focus of our field work was on Fraser fir stands, we decided to dedicate the majority of our analysis of the changes associated with Fraser fir dominated cover classes.

Our forest cover change analysis is useful in modeling the changes in Fraser fir stands associated with BWA. Allen and Kupfer (2001) used used tassle-cap indices, Landsat TM digital data, and change-vector analysis to study initial dispersal of the BWA in GSMNP to show how elevation and moisture gradients influenced infestation and could potentially influence regeneration. They concluded that BWA moved upslope and from east to west over time and in GSMNP. We find a similar pattern of BWA movement in the Black Mountains, as evidenced by loss of the densest Fraser fir forest cover class (FF1). The FF1 cover class was useful in modeling the movement of BWA over time since it was relatively unaffected by logging and therefore any changes could be attributed to BWA since no other insect outbreaks or disturbance factors have been contributed to the widespread mortality of Fraser fir there. Upon examination of Figures 3.21 through 3.23, the FF1 cover class retreats upslope from 1954 to 1988. The FF1 cover class also retreats from east to west. In 1988, a small section of FF1 covers class remains along the western summit of Mount Mitchell and in patches along the road, mainly west of the road (Figure 3.23). It is important to point out that the region where these changes in FF1 cover class area occur are over 1920+ m, indicating that this area should, and has historically been, densely covered by Fraser fir, and that the differences in elevation within this small area are not great.

There are two possible explanations for this trend of movement. First, some researchers have speculated that BWA was introduced to the Black Mountains from imported nursery stock that was used to replant areas impacted by logging and fire (Silver 2003). The tree plantations were located to the east and downslope from the FF1 cover class in ROI #2 (Pyle and Schafale 1988). Therefore it is possible that wind currents could have carried the BWA upslope and in an east to west direction. Further investigation would be necessary in order to confirm the trend we see here, especially since the Forest Service claimed that the insect probably arrived from similar tree plantings in areas surrounding Mount Mitchell, but not the ones used to replant Mount Mitchell (Nagel 1959). Therefore the exact source of BWA infestation remains largely a mystery.

A second explanation for why the Fraser fir population is maintained at the highest elevations within ROI #2 may work either independently or dependently with the proposed BWA spread. The area surrounding the road and summit of Mount Mitchell was part of the

"BWA protection zone," in which trees were sprayed in the 1960s and 1970s (Eager 1984, Pyle and Schafale 1988). Regardless of the mechanism behind this movement, our findings provide a possible pattern the spatial movement of BWA throughout the Black Mountains.

From 1988 to 2006 (Figures 3.24 - 3.25), the FF1 cover class expands in area, which supports the thought that Fraser fir stands, at least at high elevations, are now in a state of recovery. Barring major future outbreaks of BWA and an increase in mean global temperatures, Fraser firs in the future may be able to recover and continue expanding outward, as evidenced by increased forest cover.

As with any manual photo interpretation, error is inherent and is something that must be addressed for our study. Large RMSE errors (positional errors), associated with georeferencing of the 1954 and 1964 photographs, is one main concern. These registration errors likely influenced the accuracy of our forest cover class areas, and in turn calculations of percent forest cover change between years. While we would have hoped for more accurate registration, we were very limited in the amount of accurate control points we could obtain on the photographs due to the fact that ROI # 2 was largely undeveloped and located within extremely rugged terrain (Baker et al. 2005).

One way to address the amount of error in our forest cover areas is to make comparisons to previously reported values. Bolstad (1992) reported percent errors ranging from 1.9 to 9.7% in polygons with areas from 1-100 ha in aerial photographs with 500 m of terrain range. In our study, the terrain range for ROI #2 was approximately 342 m, and forest cover polygons ranged from 0 – 103 ha. Therefore, we might expect similar percent errors in our polygon areas as those reported by Bolstad (1992).

Despite inherent errors in this process, we feel that our results are still very useful for addressing trends in spruce-fir forest cover change. Based on the numerous limitations we faced, using repeat aerial photography was the best available option. For example, the use of satellite imagery would not have the level of detail necessary for this study, nor would it have allowed our analysis to extend as far back in time. Furthermore, more algorithm-related techniques would not have worked well based on differences in spectral signatures and scales among the photographs.

Our results do not indicate that Fraser firs are following a cycle of regeneration- mortality at this time. Our data suggest that high elevation stands of Fraser fir are in a process of recovery. Whereas, some uncertainty remains concerning the fate of low elevation stands of Fraser fir due to the role that global climate change may play in removing suitable Fraser fir habitat and causing warmer temperatures favorable for BWA reproduction. Elevation and land use type strongly influence stand characteristics and mortality, illustrating the complex interaction that exists between anthropogenic influence and a geographical variable in shaping the landscape. Photo monitoring results showed forest recovery, both from logging and fire, and also from the BWA. Analysis of the FF1 cover class changes from 1954 to 1988 revealed that BWA may have spread upslope and from east to west in the Black Mountains. Increases in FF1 cover class in 2006 support our conclusion of forest recovery at high elevations.

3.5 Acknowledgements

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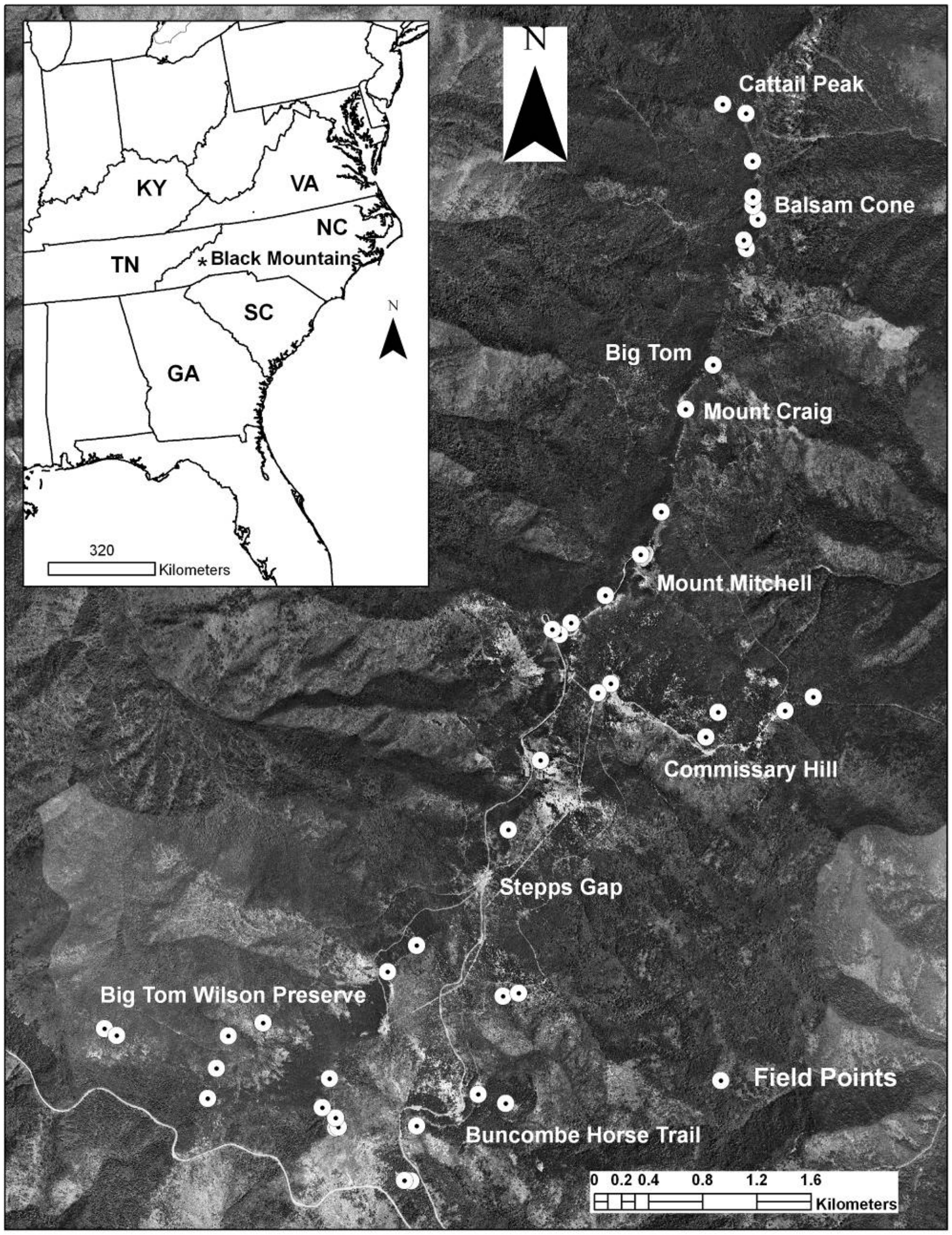


Figure 3.1: Map of Study Site and Locations of Sample Plots (Source: United States Department of Agriculture-Forest Service Aerial Photo Field Office)

Table 3.1: Elevation, aspect, slope, and disturbance classes used for plot classifications.

Elevation Class	
1	1645- 1767 m
2	1768 – 1889 m
3	1890 + m

Aspect Class	
1 - northeast	0 - 89˚
2 - southeast	90 - 179˚
3 - southwest	180 - 269˚
4 - northwest	270 - 359˚

Slope Class	
1	0˚ - 14˚
2	15˚ - 29˚
3	30˚- 45˚

Disturbance Class	
1	unknown disturbance prior to BWA
2	logged and burned
3	uncut, unburned as of 1916
4	burned over, not cut as of 1916
5	logged pre-1930

Figure 3.2: Gouting of a Fraser fir (*Abies fraseri* (Pursh) Poir.) stem. Gouting is one symptom of balsam woolly adelgid (*Adelges piceae* Ratz.) infestation.

Figure 3.3: Balsam woolly adelgid (*Adelges piceae* Ratz.) infestation on the bole of a Fraser fir (*Abies fraseri* (Pursh) Poir.).

Table 3.2: Balsam woolly adelgid (*Adelges piceae* Ratz.) infestation classification regime.

BWA infestation Class	Explanation
1	Symptoms of BWA only
2	BWA present with infestation symptoms
3	No BWA present and no symptoms of BWA
4	BWA present with no infestation symptoms

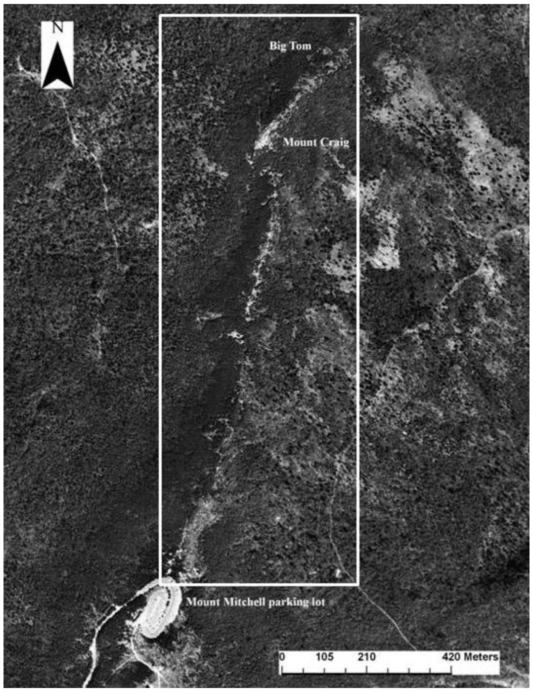


Figure 3.4: Region of interest (ROI # 1) for ground photo/aerial photo pairing case study. ROI #1 included the ridgeline and surrounding area between Big Tom and Mount Mitchell in the Black Mountains, North Carolina (Source: United States Department of Agriculture-Forest Service Aerial Photo Field Office).

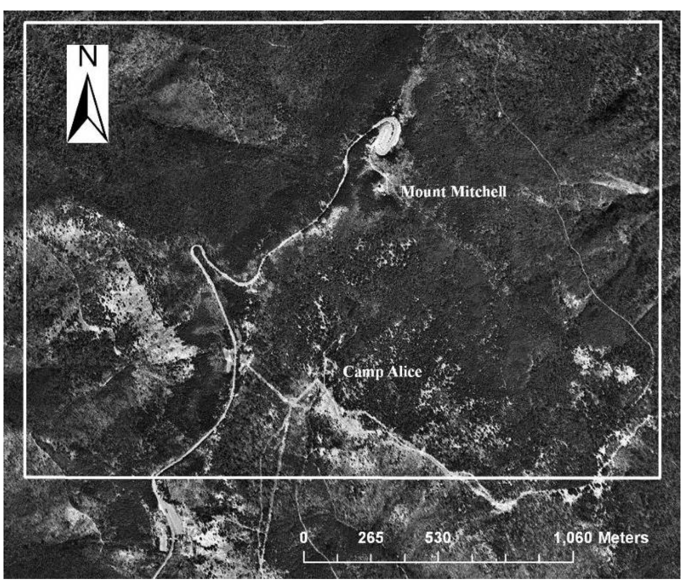


Figure 3.5: Region of interest (ROI # 2) used to analyze trends in spruce-fir forest cover change from 1954 to 2006 (Source: United States Department of Agriculture-Forest Service Aerial Photo Field Office).

Table 3.3: Forest classification scheme used for manual photo delineation of forest cover.

Class Code	Dominant (> 50 %) Forest Type	Forest Cover
FF1	Fraser fir	> 60 %
FF2	Fraser fir	40 - 59 %
FF3	Fraser fir	25 - 39 %
FF4	Fraser fir	10 - 24 %
FF5	Fraser fir	< 10 %
SF1	Red spruce-Fraser fir	> 60 %
SF2	Red spruce-Fraser fir	40 - 59 %
SF3	Red spruce-Fraser fir	25 - 39 %
SF4	Red spruce-Fraser fir	10 - 24 %
SF5	Red spruce-Fraser fir	< 10 %

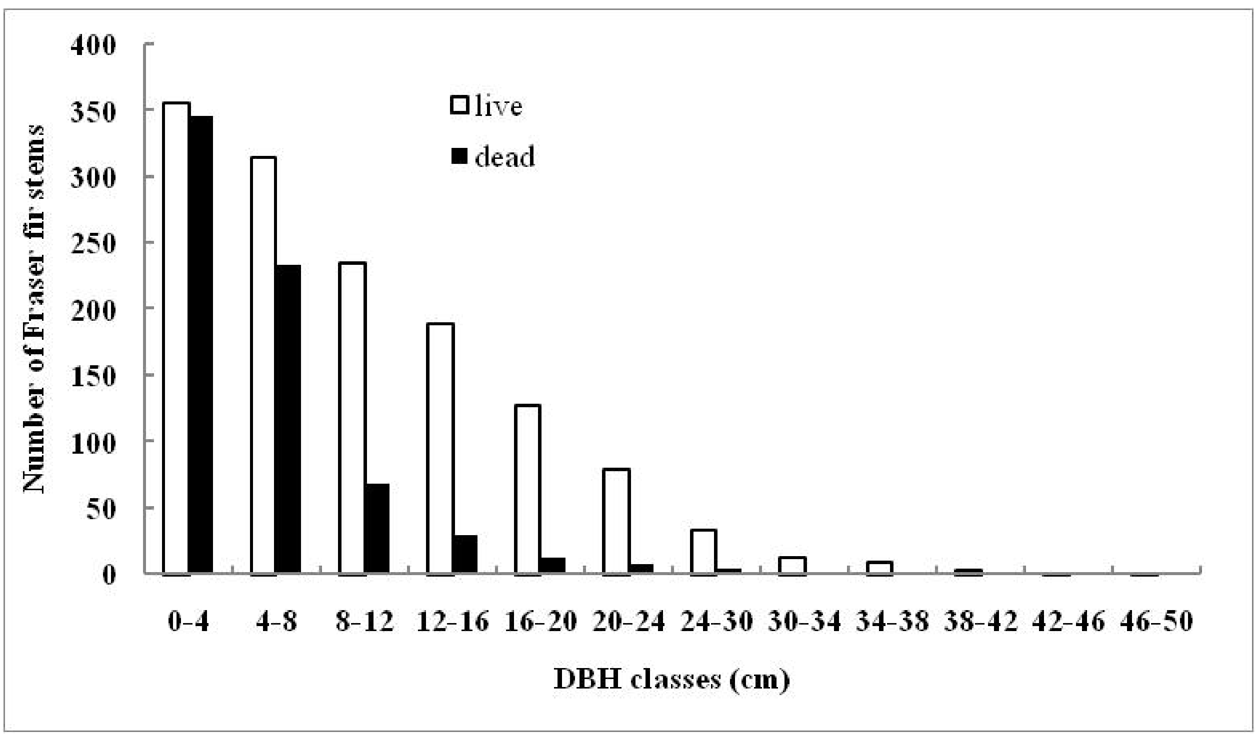


Figure 3.6: Diameter at breast height (dbh) distribution of live and dead Fraser fir (*Abies fraseri* (Pursh) Poir.) sampled in 44 plots in the Black Mountains, North Carolina.

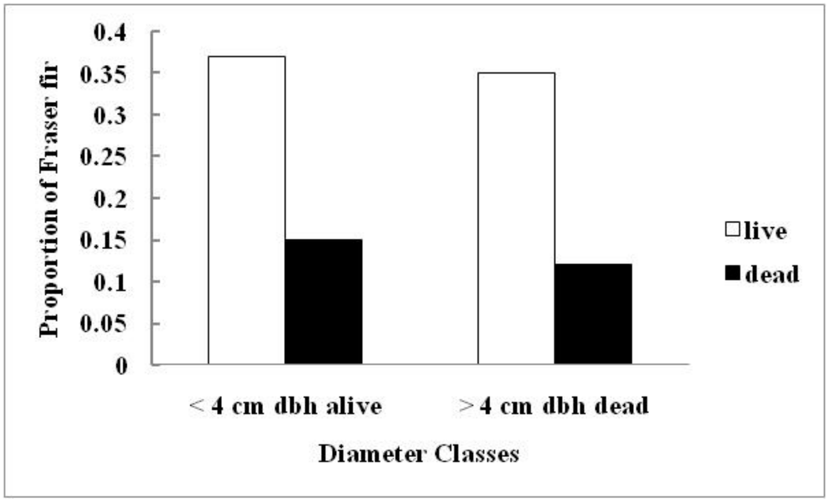


Figure 3.7: Proportions of live and dead Fraser fir trees (*Abies fraseri* (Pursh) Poir.) ' < 4 cm dbh' and '> 4 cm dbh' occuring in the Black Mountains, North Carolina. (Live trees < 4 cm dbh, n= 451; dead trees < 4 cm dbh, n= 1088; live trees > 4cm dbh, n = 1011; dead trees > 4 cm dbh, n= 364.)

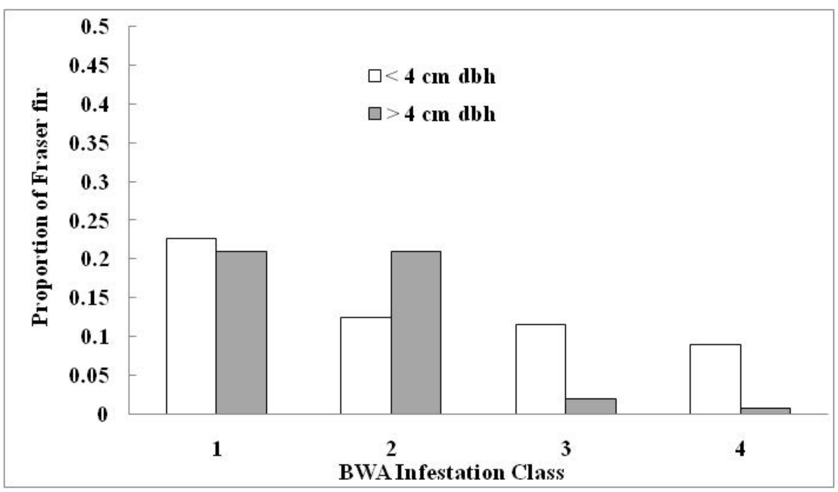


Figure 3.8: Proportions of Fraser fir trees (*Abies fraseri* (Pursh) Poir.) '< 4 cm dbh' and '> 4 cm dbh' within each balsam woolly adelgid (BWA) infestation class. Class 1 was assigned to trees that exhibited symptoms of BWA infestation only. Class 2 was assigned to trees with presence of BWA and symptoms of infestation. Class 3 was assigned to trees with no BWA or symptoms. Class 4 was assigned to trees with BWA present but no symptoms of infestation. (BWA 1 < 4 cm dbh, n = 626; BWA 1 > 4 cm dbh, n=585; BWA 2 <4 cm dbh, n=344; BWA 2 > 4 cm dbh, n= 585; BWA 3 < 4 cm dbh, n= 316; BWA 3 > 4 cm dbh, n= 316; BWA 3 > 4cm dbh, n=55; BWA 4 < 4cm dbh, n= 212; BWA 4 > 4 cm dbh, n= 22).

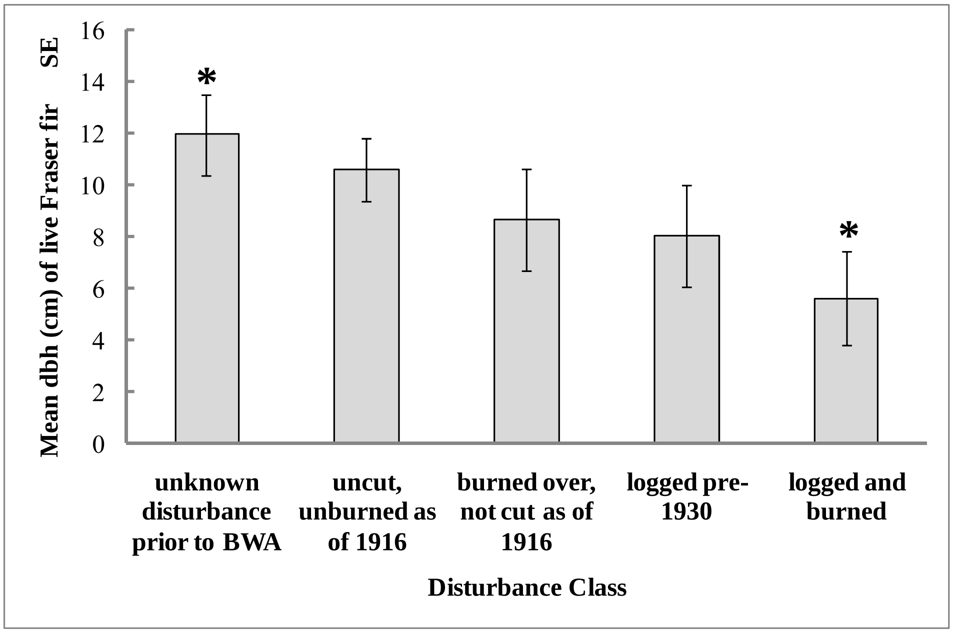


Figure 3.9: Mean diameter at breast height (dbh) (cm) of live Fraser fir (*Abies fraseri* (Pursh) Poir.) by disturbance class in the Black Mountains, North Carolina. * Indicates classes are significantly different from each other (n= 44, $p < 0.05$).

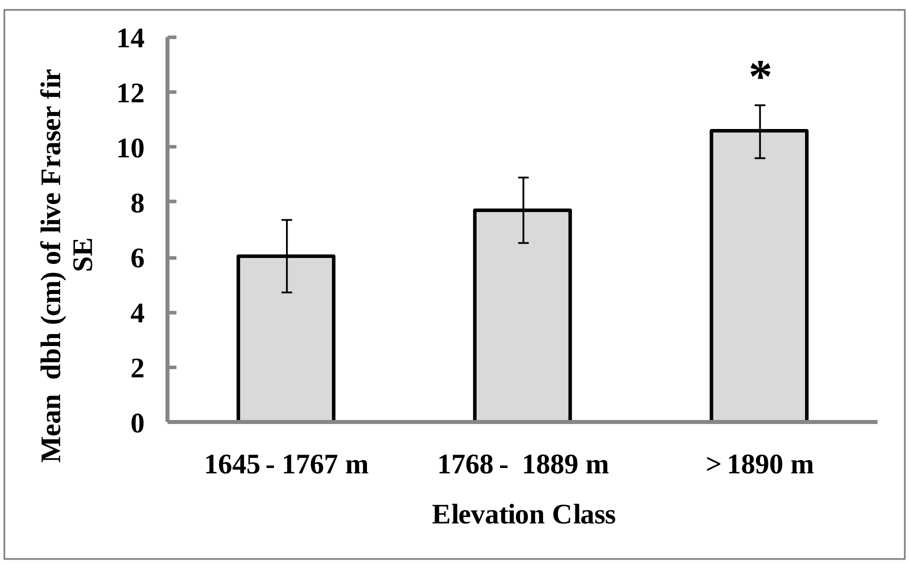


Figure 3.10: Mean diameter at breast height (dbh) of live Fraser fir (*Abies fraseri* (Pursh) Poir.) by elevation class in the Black Mountains, North Carolina. * Indicates this class is significantly different from the other classes (n= 44, $p < 0.05$).

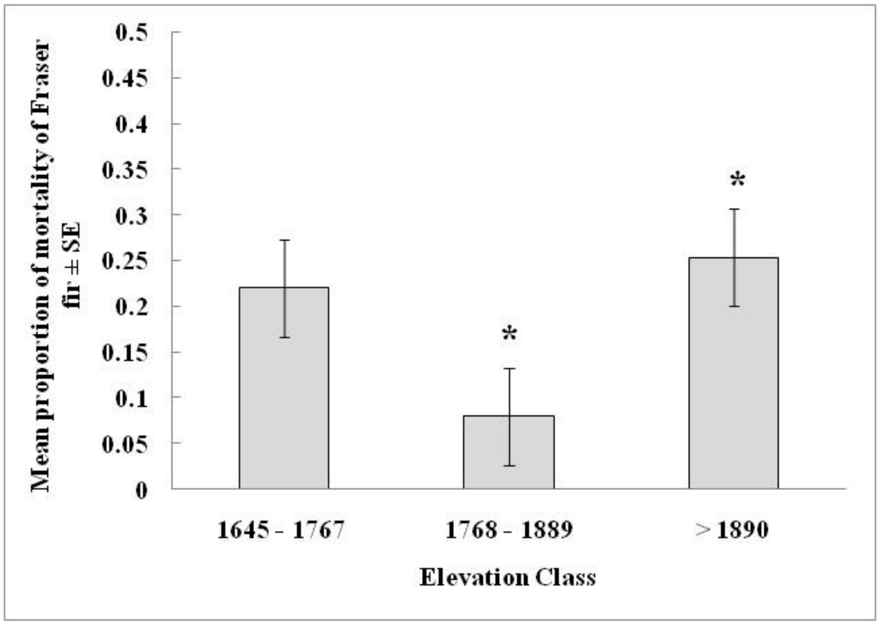


Figure 3.11: Mean proportion of mortality in Fraser fir (*Abies fraseri* (Pursh) Poir.) by elevation class in the Black Mountains, North Carolina. * Indicates that these two classes are significantly different from each other (n = 44, p < 0.05).

Figure 3.12: Mean proportion of mortality in Fraser fir (*Abies fraseri* (Pursh) Poir.) trees < 4cm dbh by elevation class in the Black Mountains, North Carolina. * Indicates that the elevation class is significantly different from the other two classes (n = 44, p < 0.05).

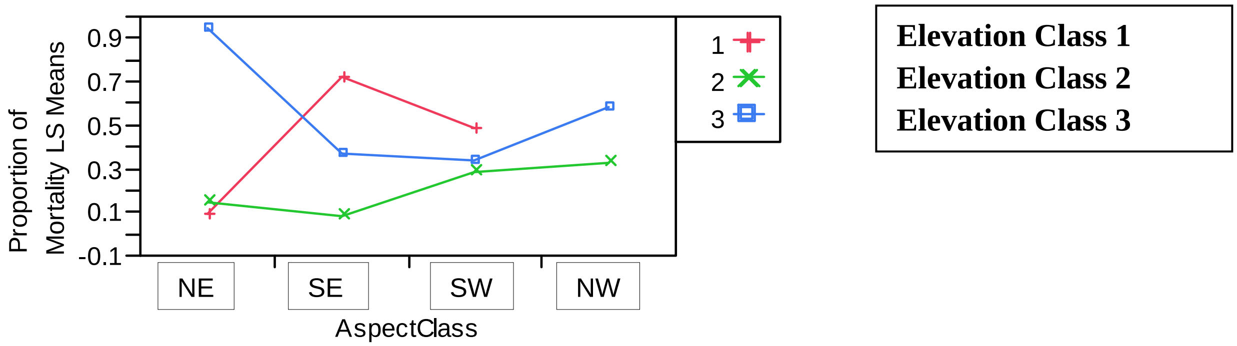
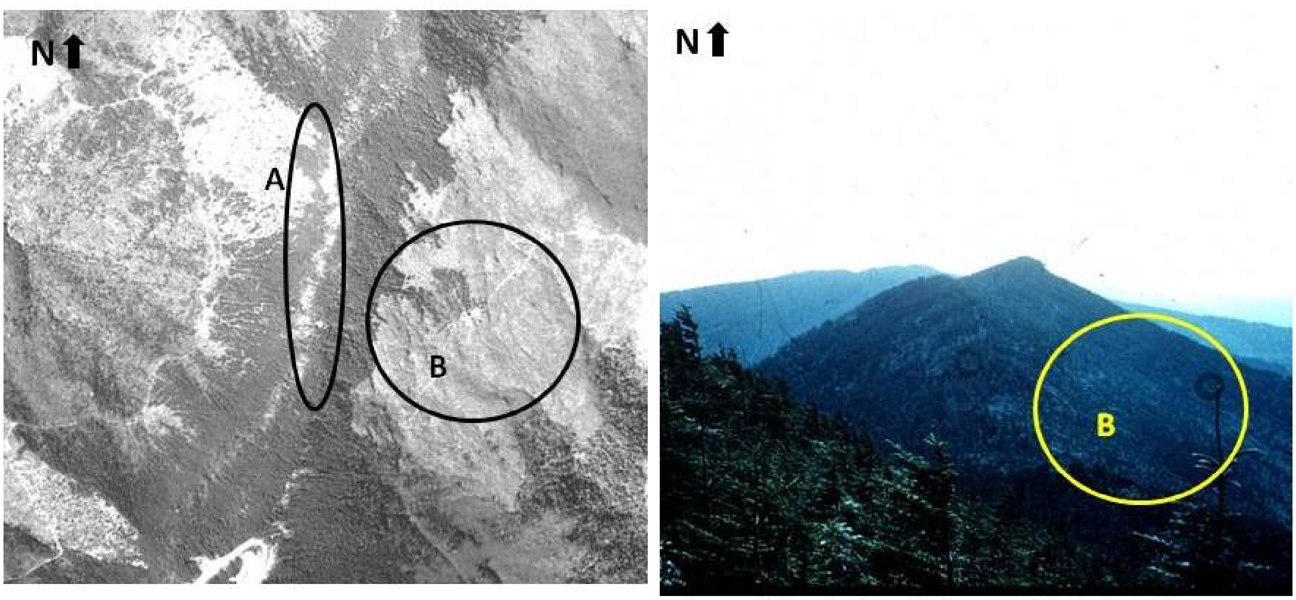


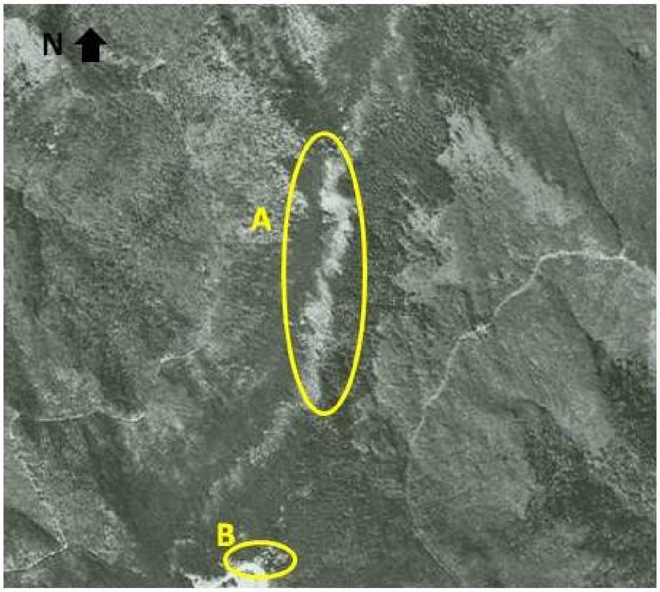
Figure 3.13: Least squares means plot of mortality proportions for elevation and aspect classes.



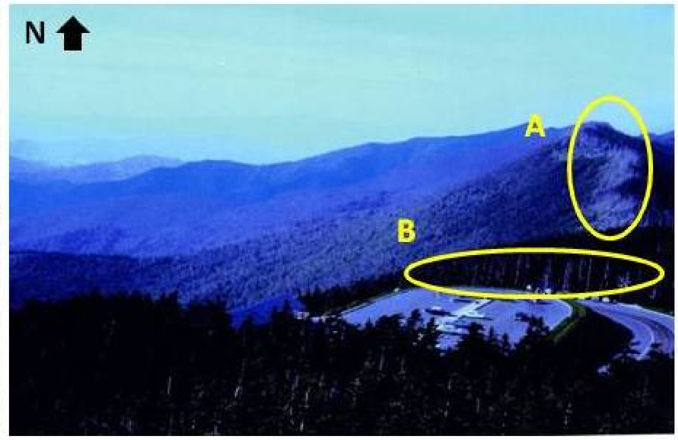
Aerial view N of Mount Mitchell 1954
(Source: Tennessee Valley Authority

Ground Photo N of Mount Mitchell 1959
(Source: Mount Mitchell State Park)

Figure 3.14: Aerial and ground photo pair of ROI #1, 1954

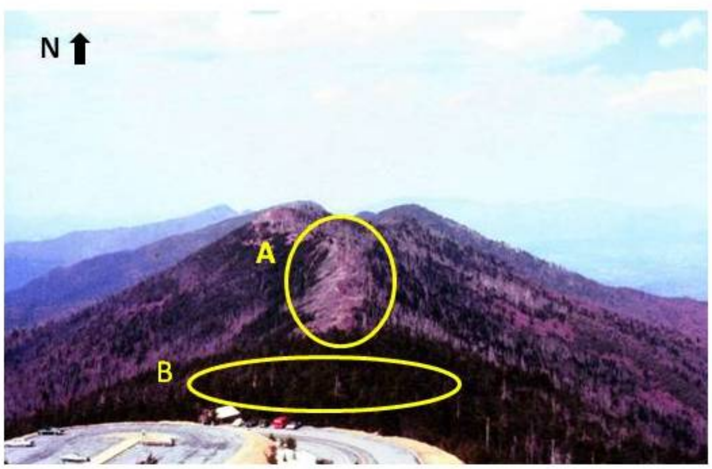


Aerial view N of Mount Mitchell 1964 (Source: North Carolina Department of Transportation)



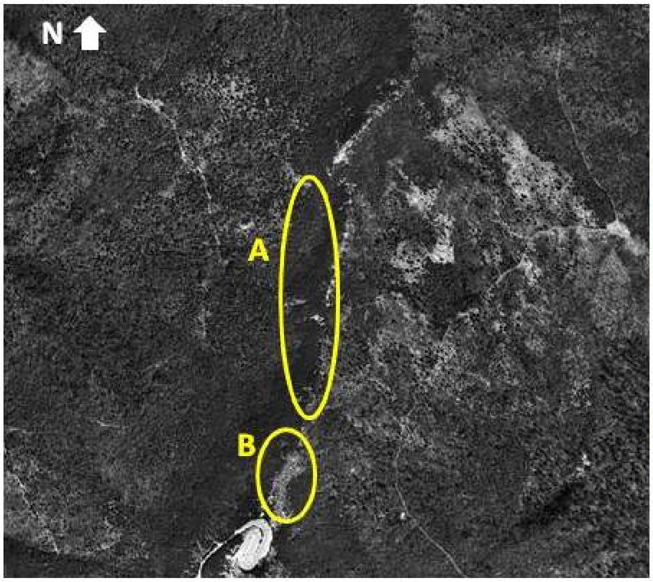
Ground Photo N of Mount Mitchell 1969 (Source: Mount Mitchell State Park)

Figure 3.15: Aerial and ground photo pair of ROI #1, 1964

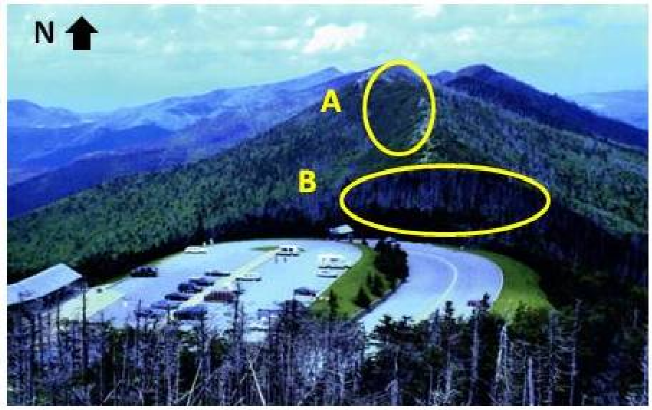


Ground Photo N of Mount Mitchell 1978 (Source: Mount Mitchell State Park)

Figure 3.16: Ground photo of ROI # 1, 1978

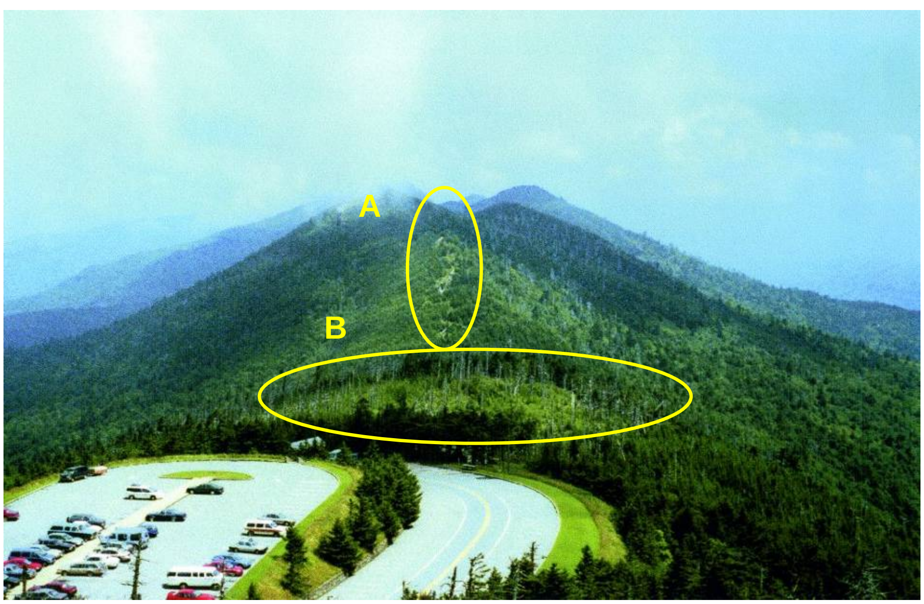


Aerial view N of Mount Mitchell 1988 (Source: United States Department of Agriculture-Forest Service Aerial Photo Field Office



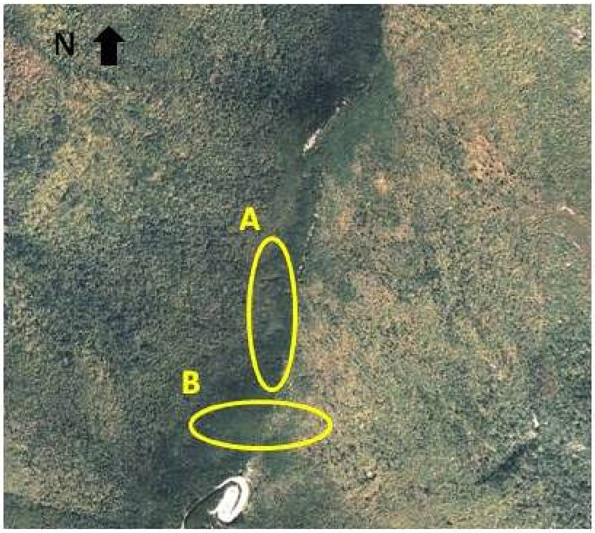
Ground Photo N of Mount Mitchell 1989 (Source: Mount Mitchell State Park)

Figure 3.17: Aerial and ground photo pair of ROI #1, 1988

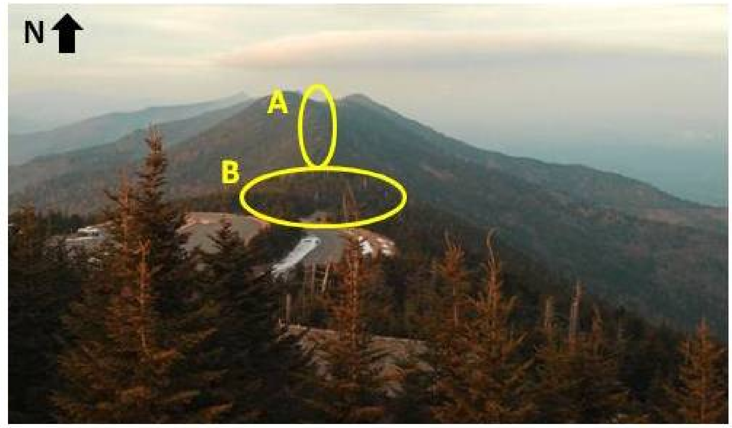


(Source: Mount Mitchell State Park)

Figure 3.18: Ground photo of ROI #1, 1996



Aerial view N of Mount Mitchell 2006 (Source: National Agricultural Imagery Program



Ground photo N of Mount Mitchell February 2009 (Source: Ranger Matt Mutel; Mount Mitchell State Park)

Figure 3.19: Aerial and ground photo pair of ROI #1, 2006

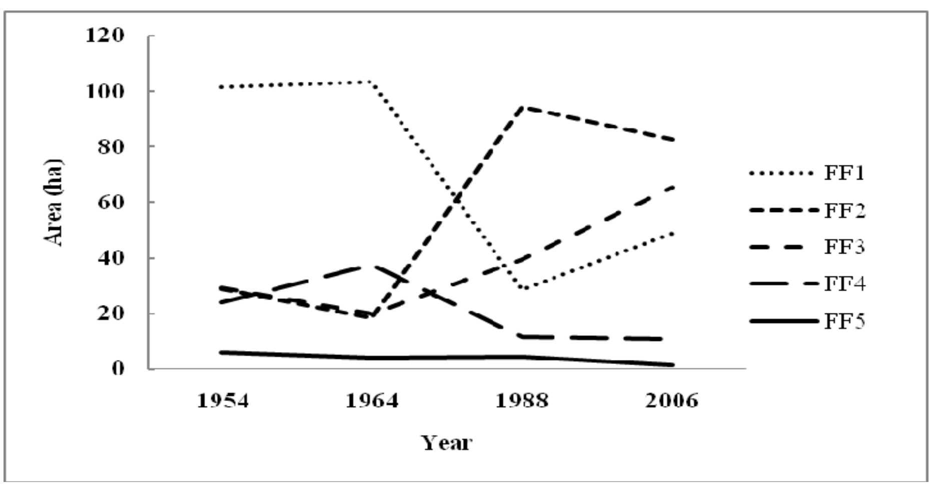


Figure 3.20: Changes in Fraser fir (*Abies fraseri* (Pursh) Poir.) dominated (> 50%) forest in ROI # 2 from 1954 to 2006. FF1 represented areas where Fraser fir forest cover is > 60%. FF2 represents areas where Fraser fir forest cover is 40-59%. FF3 represents areas where Fraser fir forest cover is 25- 39%. FF4 represents areas where Fraser fir forest cover is 10- 24%. FF5 represents areas where Fraser fir forest cover is < 10%.

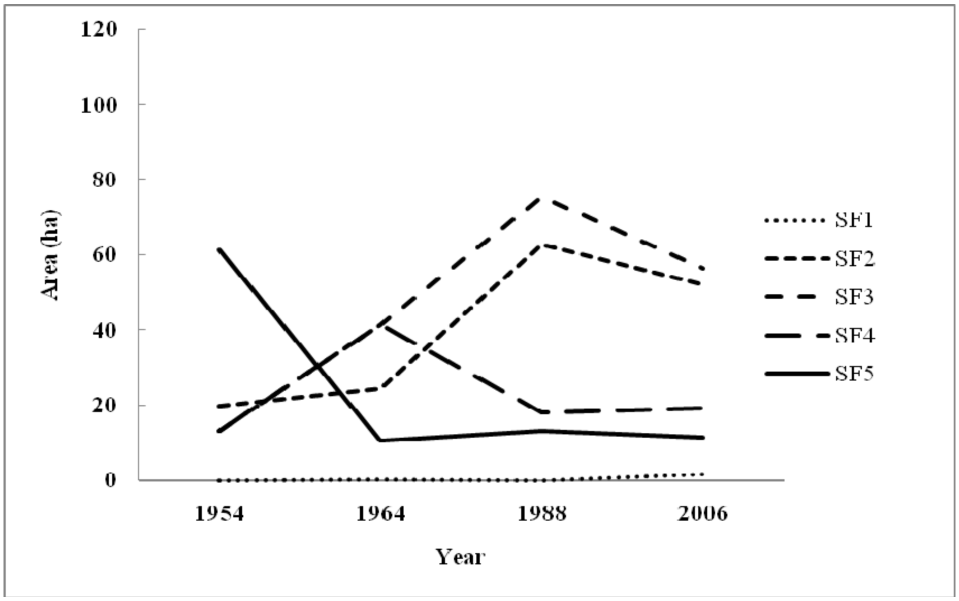


Figure 3.21: Changes in spruce-fir dominated (> 50%) forest in ROI # 2 from 1954 to 2006. SF1 represented areas where spruce-fir forest cover is > 60%. SF2 represents areas where spruce-fir forest cover is 40-59%. SF3 represents areas where spruce-fir forest cover is 25- 39%. SF4 represents areas where spruce-fir forest cover is 10- 24%. SF5 represents areas where spruce-fir forest cover is < 10%.

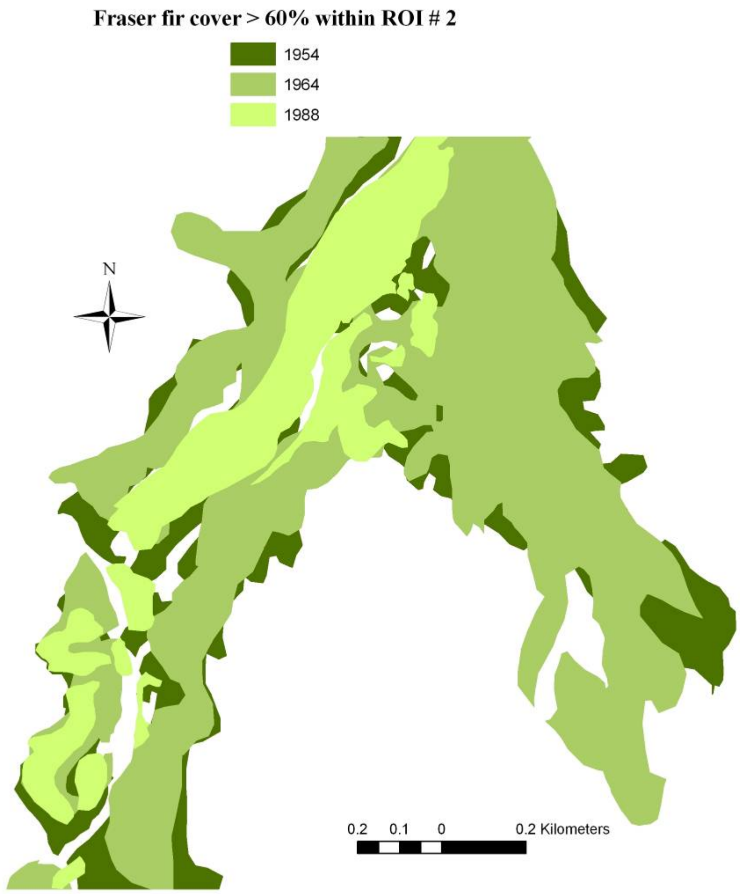


Figure 3.22: Fraser fir (*Abies fraseri* (Pursh) Poir.) forest cover > 60% (FF1) in 1954, 1964, and 1988 within ROI # 2. Forest cover > 60% (FF1) from 2006 was left out in this figure for visual clarity.

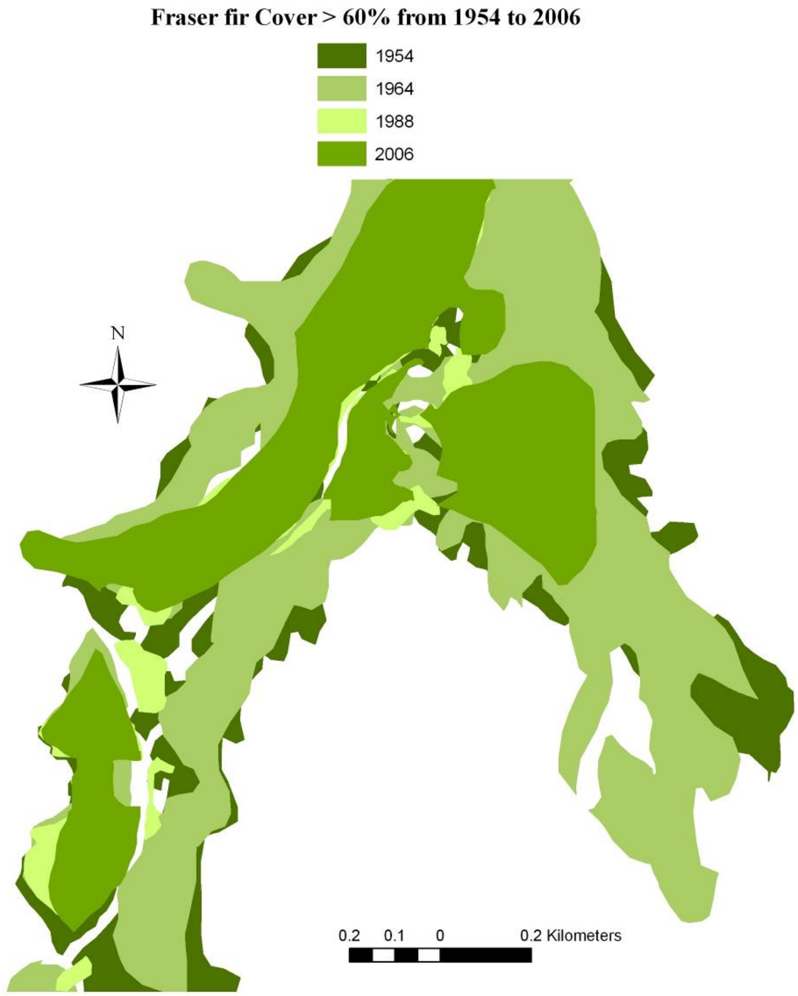


Figure 3.23: Fraser fir (*Abies fraseri* (Pursh) Poir.) forest cover > 60% (FF1) in 1954, 1964, and 1988, and 2006 within ROI # 2.

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Chapter 3 Figures:

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