Impacts of Balsam Woolly Adelgid on the Southern Appalachian Spruce-Fir Ecosystem and the North Carolina Christmas Tree Industry

Kevin M. Potter, John Frampton, and Jill Sidebottom

Department of Forestry and Environmental Resources,
North Carolina State University, Raleigh, NC 27695

ABSTRACT

The balsam woolly adelgid, an exotic aphid-like insect from Europe, has wreaked considerable ecological havoc on the boreal red spruce-Fraser fir ecosystem endemic to the Southern Appalachians. During the last 50 years, the adelgid has decimated the Fraser fir stands that exist on a handful of island-like high-elevation ridge systems, and has imposed significant economic costs on the regionally important Christmas tree industry. The virtual elimination of mature fir trees from their natural stands has altered the plant and animal communities unique to the red spruce-Fraser fir forest type. While firs appear to have regenerated well since the initial wave of adelgid-caused mortality, it is unclear whether future infestations will occur and, if they do, how they will impact the species. A mathematical model indicates that Fraser fir populations may be large enough, and the species' life cycle long enough, to avoid the extensive loss of genetic diversity over time unless the populations experience regularly repeated adelgid infestations. Work is under way to identify and propagate Fraser firs resistant to adelgid infestation and to conserve the existing genetic diversity of the species. These activities could allow for the eventual reintroduction of firs into their native stands, should such an effort become necessary.

KEYWORDS

Balsam woolly adelgid, Fraser fir, ecosystem, impact, genetic conservation.

INTRODUCTION

The high-elevation red spruce-Fraser fir forests of North Carolina, Tennessee, and Virginia together encompass a unique boreal ecosystem endemic to the southeastern United States. Never very extensive, this forest type has been reduced by poor forest management practices, and could face elimination as a result of global climate change. Currently, the most serious threat to its continued existence, however, is an insect that measures less than a millimeter in length – the balsam woolly adelgid (*Adelges piceae* Ratz.). During the last 50 years, this exotic invader from Europe has decimated mature natural stands of Fraser fir (*Abies fraseri* [Pursh] Poir.), causing significant changes to the spruce-fir ecosystem. It has also posed problems for North Carolina's $100 million annual Christmas tree industry, which relies almost entirely on plantation-grown Fraser fir.

In natural Fraser fir stands, this economically and ecologically important conifer occurs almost entirely above 1,300 meters, usually in association with red spruce (*Picea rubens* Sarg.), but it becomes the dominant tree species above about 1,800 meters (Busing et al. 1993, Cain 1935, Whittaker 1956). It exists in six major island-like populations (Figure 1): the Great Smoky Mountains in North Carolina and Tennessee; the Black Mountains, the Balsam Mountains, and Grandfather Mountain in North Carolina; Roan Mountain on the Tennessee/North Carolina border; and Mount Rogers in Virginia. Additionally, three minor populations exist in North Carolina: the Plott Balsams, Cataloochee Balsam, and Shining Rock. Whitetop Mountain in Virginia, near Mount Rogers, has red spruce but no Fraser fir.

Figure 1: The distribution of Fraser fir in the Southern Appalachians.

These populations are relicts of a boreal forest that extended across much of the Southeast during the peak of the most recent late-Wisconsin glacial period, from 18,000 years to 12,500 years before present (Delcourt and Delcourt 1987, Whitehead 1973, Whitehead 1981). At the full-glacial maximum, this boreal forest may have covered 1.8 million km^2 from Missouri to the Carolinas (Delcourt and Delcourt 1984). By 8,000 years ago, warming climate conditions eliminated lower-elevation spruce-fir stands in the Southeast. Much of the distri-

bution of fir shifted north, following the retreating ice into Canada, New England, and the Northern Appalachians; the fir species now occurring in those areas is balsam fir (*Abies balsamea* [L.] Miller), which is closely related to Fraser fir.

Since the late nineteenth century, logging and slash fires have dramatically reduced the distribution of Fraser fir and red spruce in the Southern Appalachians (Pyle 1984, Pyle and Schafale 1988, Saunders 1979). Failed regeneration caused by logging-site degradation may have reduced the extent of the highest spruce-fir forests, those above 1,670 meters, to less than half their former historical area, from 14,277 hectares to 6,881 hectares (Saunders 1979). Logging and fire in the Great Smoky Mountains, which encompass nearly three-fourths of all Fraser fir-red spruce forest (Dull et al. 1988), reduced the forest type across all elevations from 17,910 hectares to 13,370 hectares (Pyle 1984).

With nearly all the Southern Appalachian spruce-fir forest now occurring on public lands (Dull et al. 1988), poor management practices were no longer a serious concern by the 1950s. Since that time, however, the balsam woolly adelgid (BWA) has inflicted severe mortality on old-growth Fraser fir forest. Introduced into the northeastern United States in the early 1900s, probably on imported nursery stock, the adelgid was first detected on Mount Mitchell in the Black Mountains in 1957, but may have been present in the area as early as 1940 (Eager 1984). Within a few years, the infestation spread from the centrally located Black Mountains to all the other populations: Roan Mountain and Mount Rogers by 1962, the Great Smoky Mountains and Grandfather Mountain by 1963, and the Balsam Mountains by 1968 (Amman 1966, Dull et al. 1988, Eager 1984). By the 1980s, reproductively mature Fraser fir trees had experienced 67 percent mortality throughout the species' range, including 91 percent mortality in Great Smoky Mountains National Park (Dull et al. 1988), site of the largest Fraser fir population.

The adelgid, which has a complex life cycle in its native range, reproduces asexually through parthenogenesis in North America, where the species consists of only females. Having an egg stage, three larval instar stages, and the adult stage, an adelgid spends its entire life immobile except during the first instar, or "crawler," stage, during which it is often dispersed by air currents (Eager 1984). Amman (1966) concluded that wind was responsible for moving the adelgid up to distances of 64 kilometers in the Southern Appalachians. The adelgid feeds by inserting its stylet into cracks in the bark of older fir trees, and remains fixed at the same location throughout its adult life. The attack of thousands of the insects on a tree results in the production of abnormal xylem that conducts water poorly; the tree typically dies within two to nine years of infestation (Amman and Speers 1965, Eager 1984, Hollingsworth and Hain 1991).

The atmospheric deposition of acidic sulfur and nitrogen compounds from power plants and other facilities west of the Appalachians may increase the susceptibility of Fraser fir to the adelgid, although the impact of such pollution remains uncertain even after decades of research. Hain and Arthur (1985) hypothesized that atmospheric deposition, mostly from fog at high elevations, might predispose fir to adelgid mortality, or could be the final source of stress to already infested trees.

Pesticide application and extensive biological control efforts were both ineffective in combating BWA infestation in Fraser fir natural stands. The application of pesticides, including Lindane, potassium salt of oleic acid, and insecticidal soap, was of little practical use in controlling BWA at large scales, since the bole of each tree must be sprayed to the point of saturation for these chemicals to be effective (Dull et al. 1988, Eager 1984, Johnson 1980). During the 1960s, researchers conducted several biological control experiments that introduced dozens of potential BWA predators (Table 1) into infested fir stands in the Southern Appalachians (Amman 1970, Amman and Speers 1971), the Pacific Northwest (Mitchell and Wright 1967), and eastern Canada (Brown and Clark 1960). All the predators failed to reduce BWA populations, however, because of climatic differences between the predators' new and old environments, poor prey acceptance, ineffective synchronization of predator-prey cycles, poor searching ability by the predators, the high reproductive capacity of the BWA, and the rapid death of the host tree (Amman and Speers 1971, Eager 1984, Mitchell and Wright 1967).

ECOLOGICAL IMPACTS OF BALSAM WOOLLY ADELGID INFESTATION

The elimination of most old-growth Fraser fir by the balsam woolly adelgid has dramatically altered the character of the Southern Appalachian spruce-fir forests, an uncommon ecosystem that has considerable ecological, aesthetic, and economic value. In addition to the importance of Fraser fir to the Christmas tree industry, the spruce-fir forest type is a central attraction of several popular visitor destinations, including the Blue Ridge Parkway, Great Smoky Mountains National Park, Mount Mitchell State Park, and the private Grandfather Mountain preserve. It plays an important role in protecting the high-elevation portions for the watersheds of several major rivers. Perhaps most importantly, the Southern Appalachian spruce-fir ecosystem is rich in rare and endemic animals and plants, including one bird species, one mammal, six invertebrates, and 12 plants considered at risk of extinction (Table 2). Of these, two are federally listed as endangered and 10 are federal species of concern (Southern Appalachian Man and the Biosphere 1996).

While three frog species, 13 salamanders, and eight snakes occur in Southern Appalachian spruce-fir forests, only two species of herpetofauna – the pygmy salamander (*Desmognathus wrighti*) and the imitator salamander (*Desmognathus imitator*) – are endemic to this forest type (Mathews and Echternacht 1984). The deterioration of the spruce-fir forest could result in the loss of these species, but more research is needed in this area. The patchy high-elevation spruce-fir forests of the Southern Appalachians have historically hosted a distinctively boreal and unique bird community (Rabenold 1984). This community has changed significantly since the onset of the BWA infestation in the Great Smoky Mountains: 10 of 11 breeding species declined between 1974 and the 1990s, with some near local extinction. Five of the most strongly affected birds – black-capped chickadee (*Poecile atricapilla*), blue-headed vireo (*Vireo solitarius*), red-breasted nuthatch (*Sitta canadensis*), black-throated green warbler (*Dendroica virens*), and golden-crowned kinglet (*Regulus satrapa*) – are canopy- and subcanopy-nesting species characteristic of spruce-fir forests throughout the Appalachians. Meanwhile, bird species characteristic of open, disturbed forests – chestnut-sided warbler (*Dendroica pensylvanica*) and eastern towhee (*Pipilo erythrophthalmus*) – became abundant (Rabenold et al. 1998).

Table 1. Arachnids and insects tested as possible balsam woolly adelgid predators

Order	Species	Origin	Citation*
Acarina (ticks and mites)			
	Allothrombium michelli Davis	North Carolina	2
	Anystis sp.	North Carolina	2
	Leptus sp.	North Carolina	2
	unidentified bdellid	North Carolina	2
Coleoptera (beetles)			
	Adalia luteopicta Mulsant	India	3
	Adalia tetraspilota Hope	India/Pakistan	1,3
	Adonia variegata Goeze	India	1
	Aphidecta obliterata	Sweden/Germany	3
	Ballia diana Mulsant	India	3
	Ballia eucharis Mulsant	India/Pakistan	1,3
	Calvia sp.	India	1
	Chilocorus kuwanea Silvestri	Japan	3
	Exochomus ssp. (2 species)	Pakistan	3
	Harmonia breiti Mader	India/Pakistan	1,3
	Laricobius erichsonii	Germany/Czechoslovakia	3
	Leis dimidiata F.	India	3
	Mulsantina hudsonica Casey	North Carolina	2
	Oenopia sauzeti Mulsant	India	1,3
	Pullus impexus	Germany	3
	Scymnus pumilio Weise	Australia	3
	Synharmonia conglobata L.	India	3
Diptera (true flies)			
	Aphidoletes thompsoni Mohn	Germany/Czechoslovakia	2,3
	Cremifania nigrocellulata	Germany/Czechoslovakia	3
	Leucopis ssp. (3 species)	India	1
	Leucopis obscura	Europe	3
	Metasyrphus lapponicus Zett.	New Brunswick	4
	Neocnemodon coxalis Curr.	New Brunswick	4
	Pipiza sp.	North Carolina	2
	Syrphus torvus O.S.	North Carolina/New Brunswick	2,4
	unidentified syrphid	North Carolina	2
Hemiptera (true bugs)			
	Tetraphleps ssp. (3 species)	India/Pakistan	1
	Tetraphleps sp.	India/Pakistan	3
Neuroptera (lacewings)			
	Chrysopa ssp. (2 species)	India/Pakistan	1,3
	Hemerobius sp.	India	1
	Hemerobius ssp. (2 species)	North Carolina	2
	undetermined Hemerobiidae	India	3

* 1 = Amman and Speers 1971, 2 = Amman 1970, 3 = Mitchell and Wright 1967, 4 = Brown and Clark 1960

Table 2: Federally listed species and species with viability concern, from the red spruce-Fraser fir forest type

Species	Common Name	Type	Status*
Accipiter gentilis	northern goshawk	bird	FSC
Glaucomys sabrinus coloratus	Carolina northern flying squirrel	mammal	E
Cleidogona hoffmani	Hoffman's cleidogonid millipede	invertebrate	VC
Cleidogona lachesis	a millipede	invertebrate	VC
Hepialus sciophanes	a ghost moth	invertebrate	FSC
Mesodon clingmanicus	Clingman covert	invertebrate	FSC
Microhexura montivaga	spruce-fir moss spider	invertebrate	E
Semiothisa fraserata	Fraser fir geometrid	invertebrate	FSC
Abies fraseri	Fraser fir	plant	FSC
Aconitum reclinatum	trailing wolfsbane	plant	VC
Bazzania nudicaulis	liverwort	plant	FSC
Brachydontium trichodes	peak moss	plant	VC
Cacalia rugelia	Rugel's ragwort	plant	FSC
Chelone lyonii	purple turtlehead	plant	VC
Gymnocarpium appalachianum	Appalachian oak fern	plant	FSC
Leptothymenium sharpii	Mt. Leconte moss	plant	FSC
Plagiochila corniculata	liverwort	plant	VC
Solidago glomerata	goldenrod	plant	VC
Sphenolobopsis pearsonii	liverwort	plant	FSC
Stachys clingmanii	Clingman's hedgenettle	plant	VC

* E = endangered; FSC = federal species of concern; VC = species with viability concerns

White (1984) catalogued 132 vascular plant species that occur in the spruce-fir forests of the Great Smoky Mountains. Of these, eight species were endemic to high peaks in the Southern Appalachians and six were species that also occur at or above timberline in the high Northern Appalachians of New England, relict alpine flora that indicate that the southern mountains may have been cold enough for a tree line 12,000-20,000 years ago (Delcourt and Delcourt 1984). Additionally, old-growth Southern Appalachian spruce-fir stands sometimes host a conspicuous and diverse bryophyte cover that contains northern disjunct species (Southern Appalachian Man and the Biosphere 1996). Thirty-six species of mosses and liverworts frequently grow on the bark of Fraser fir, so the decimation of mature fir stands poses a major threat to the diversity and abundance of Southern Appalachian bryophytes, probably causing the decline and extirpation of some rare species (Smith 1984). Similarly, Fraser fir is the preferred substrate tree of roughly 20 of the 100 epiphytic lichen species that occur in these spruce-fir forests, so the loss of mature Fraser firs to BWA may make these species vulnerable to local extinction (Dey 1984).

Before balsam woolly adelgid infestation, the stand composition of old-growth red spruce-Fraser fir forests resulted from a natural disturbance regime dominated by small treefall-created canopy gaps (White et al. 1985). Dramatic Fraser fir mortality, however, quickly opened up large areas of the forest canopy, altering both overstory and understory dynamics in the spruce-fir forest community. The live basal area of Fraser fir was reduced considerably in the Great Smoky Mountains between the 1960s and 1980s as nearly all the firs in the canopy died, while the basal area and density of red spruce stems either increased slightly or remained the same (Busing and Clebsch 1988, Busing et al. 1988). Overall, stand basal area decreased 28 percent (Busing et al. 1988). The density of live fir has been shown to be positively associated with the time since the major wave of mortality in the Great Smoky Mountains (Smith 1997, Smith and Nicholas 1998). At the same time, the opening of the canopy has allowed an increase in sub-shrub coverage, most notably blackberry (*Rubus canadensis* L.) (DeSelm and Boner 1984, Rabenold et al. 1998, Smith 1997), and for a decrease in bryophyte coverage (DeSelm and Boner 1984, Smith 1997). The impact on the herbaceous and shrub layers are less certain, with Smith (1997) seeing an increase in herbaceous and shrub density in opened canopies, and Rabenold et al. (1998) finding a decline in herbaceous cover and in the abundance of shrubs, including hobblebush (*Viburnum alnifolium* Marshall) and mountain cranberry (*Vaccinium erythrocarpum* Michaux).

Fraser fir stands suffering extensive mortality from the balsam woolly adelgid apparently have been able to regenerate with vigorous and numerous offspring (Busing and Clebsch 1988, Witter and Ragenovich 1986), many of which are now 20 to 30 years old – the age of viable seed production for open-grown and overstory Fraser fir trees. The question now is whether these trees will live long enough to produce the next generation of fir before they, too, are severely infested by the adelgid.

Some researchers believe that large numbers of Fraser fir will continue to exist in the high-elevation forests of the Southern Appalachians. Based on research at Mount Mitchell in the 1970s, for example, Witter and Ragenovich (1986) predicted that viable seeds would continue to be produced before the firs are extensively damaged by the balsam woolly adelgid, and that, as a result, Fraser fir should continue to be an important component in the fir, spruce-fir, and spruce-fir-hardwood forest types. Additionally, adelgid populations are currently lower in the Great Smoky Mountains than in the early outbreak years of the 1970s and 1980s, and their reproduction rates are lower (Kristine Johnson, personal communication).

Other research may signal cause for concern about the future of Fraser fir. Pauley and Clebsch (1990) found that 26 percent of fir seedlings at Mt. Collins in the Great Smoky Mountains had adelgid-caused gouting – a number that increased to 39 percent for seedlings older than 5 years. Additionally, they noted that blackberry plants may be inhibiting the establishment of fir seedlings in areas where the adelgid caused severe overstory fir mortality. As a result, they note, future fir establishment could be limited to shaded slopes and downed logs, where blackberry is unable to gain the upper hand. In a study of five summits in the Great Smoky Mountains, Smith and Nicholas (2000) found that firs may be growing faster under the open canopy caused by adelgid mortality, and therefore may reach reproductive maturity at a younger age. However, they predicted that as Fraser fir continues to regenerate, it will be re-infested by the balsam woolly adelgid. This could initiate a regeneration-mortality cycle that slowly reduces the size of fir populations because the adelgid may allow few trees to

reach reproductive maturity, and that results in a decreasing number of even-aged patches in different stages of regeneration and mortality (Smith and Nicholas 2000). Interestingly, Fraser fir mortality rates have recently declined, indicating that the initial wave of adelgid-caused mortality is virtually complete, although a new wave of mortality may have begun in the first generation of post-adelgid fir at Mount Mitchell, the first site impacted by the pest (Smith and Nicholas 1999).

MODELING THE IMPACTS OF BWA ON FRASER FIR GENETICS

A significant concern for the future of Fraser fir is that the BWA-caused demographic bottleneck could intensify the effects of genetic drift in the smallest Fraser fir populations. Genetic drift is the random fluctuation of allele frequencies as a result of "sampling errors" during reproduction; while it occurs in all populations, its effects over a small number of generations are most evident in very small populations (Hartl and Clark 1997). It can cause a loss of genetic variation within a population, eventually resulting in the fixation of alleles, which occurs with the elimination of heterozygosity in a gene system (Ellstrand and Elam 1993). Some of the alleles lost as a result of drift could be low-frequency alleles that might allow the population to adapt to environmental change. Decreased genetic variation and inbreeding depression, in turn, may increase a population's risk of extinction from pests, climate change, random events, reduced inbreeding viability, and demographic uncertainty (Barrett and Kohn 1991, Huenneke 1991, Lande 1999). Further, the loss of genetically differentiated populations could result in a serious loss of genetic diversity for the species, with fewer small populations remaining to represent its gene pool (Rajora and Mosseler 2001). However, the migration of genes among populations, in the form of long-distance pollen dispersal in the case of Fraser fir, may counter the disruptive effects of inbreeding and genetic drift by transferring genetic variation among populations (Hamrick and Nason 2000).

Predicting the long-term genetic impacts of balsam woolly adelgid infestation on Fraser fir stands is a complicated proposition for two reasons. First, it's unclear whether BWA infestations will continue to occur as existing young trees mature to an age at which they are susceptible to mortality from the adelgid. Second, both infestation-recovery cycles and intergenerational genetic drift occur over many decades, making them difficult to study over the course of a single career. To address these challenges, we have developed a mathematical model that allows us to test hypotheses about the impact of differing BWA infestation scenarios.

Our stage-structured population matrix model for Fraser fir is unique in that it simulates genetic dynamics in a long-lived forest tree species with overlapping generations. The specific objectives of the stochastic model are: 1) to investigate genetic drift and allele fixation in a two-allele, single-locus gene system in a series of hypothetical fir populations of varying sizes, initial allele frequencies, and number of BWA infestation bottlenecks, and 2) to compare the effect of drift to the impact of natural selection resulting from the presence of a hypothetical BWA-resistance gene in actual Fraser fir populations. We based the stage structure and reproductive characteristics of the modeled Fraser fir populations on field data, including age class distribution in the Great Smoky Mountains in the 1950s before the introduction of BWA (Oosting and Billings 1951) and remote sensing estimates of the spatial ex-

tent of Fraser fir populations (Dull et al. 1988). When data for other characteristics, such as pollen dispersal, were not available, we chose parameters to produce biologically plausible behavior.

The models of hypothetical Fraser fir populations showed that allele fixation is more likely with smaller populations, lower initial allele frequencies, and greater number of genetic bottlenecks (in the form of BWA infestations). These models revealed greater genetic drift in populations that are smaller (Table 3) and experiencing more infestations (Figure 2).

Models of real populations indicated that selection (in the form of a BWA-resistant genotype) had a considerably larger impact on allele frequencies and heterozygosity than genetic drift, even after a single infestation-caused bottleneck. With one or no infestation-caused bottlenecks, genetic drift in the smallest real population (Shining Rock, with roughly 5,900 mature trees) was almost indiscernible even after 10,000 years, while repeated bottlenecks resulted in large amounts of drift. In other words, taking into account overlapping generations, Fraser fir populations may be large enough and the species' life cycle long enough to avoid genetic drift unless the populations experience repeated BWA infestations. Other forces, such as natural selection, may be more responsible for existing differences in genetic diversity among populations.

Table 3. The standard deviation of change in recessive allele frequency after 1,000 years – a measure of the potential for genetic drift – increases with smaller hypothetical adult population size and with the number of infestations. (From 100 runs of each size-infestation number combination, with initial recessive allele frequency of 0.1).

Hypothetical Population Size	Number of Infestations		
	0	1	11
100	0.0036	0.0103	0.0644
1,000	0.0010	0.0032	0.0232
10,000	0.0004	0.0009	0.0071

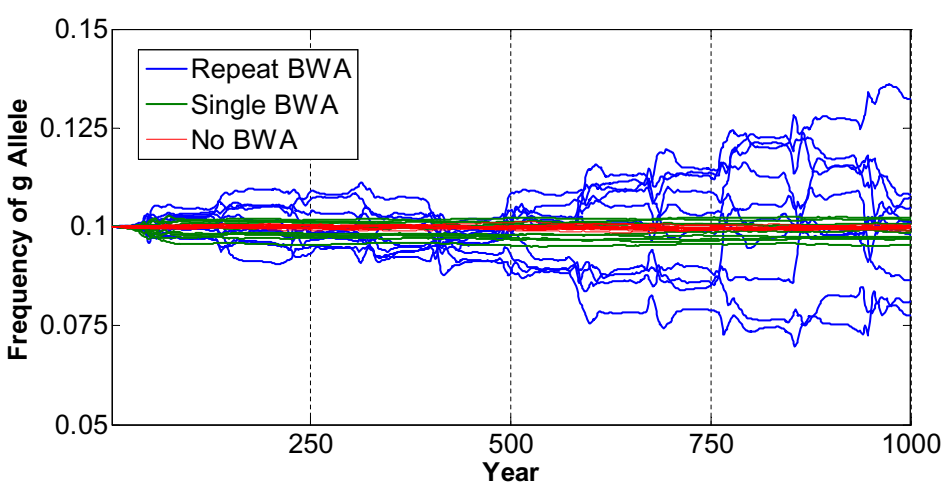

Figure 2. Genetic drift increased considerably with increasing numbers of adelgid-infestation bottlenecks. (From 20 model runs of each infestation level for a hypothetical population of 1,000 mature firs.)

THE SEARCH FOR GENETIC RESISTANCE

The continued existence of Fraser fir in its natural stands may depend on whether the species has genetic resistance to BWA, or the ability to develop it. Trees in the Mount Rogers population, for example, may have this resistance (Eager 1984, Rheinhardt 1984) as they have suffered less mortality than other populations despite having been exposed to the adelgid since 1962 (Eager 1984, Nicholas et al. 1992).

If genes for resistance to the balsam woolly adelgid exist in only a few scattered trees in any of the populations, they may be more likely to successfully produce offspring that are also less susceptible to death from adelgid attack. After several generations, many trees surviving in a stand could be resistant if the infestation is severe and continuous enough to kill off the more vulnerable firs. If such resistance exists and if Smith and Nicholas (2000) were correct that Fraser fir population size could be diminished by the adelgid, it is interesting to speculate which would happen first: the extirpation of smaller Fraser fir populations or the development of populations entirely resistant to the pest. It is unlikely we will know the answer to that question any time soon.

Efforts are underway by forest geneticists and entomologists at North Carolina State University to find and breed firs that are resistant to adelgid attack. With help from rangers at Great Smoky Mountains National Park, North Carolina, state researchers have collected branches from old-growth Fraser fir trees that may have survived the initial balsam woolly adelgid attack. These branches were grafted onto fir trees at the North Carolina Division of Forest Resources' Linville River Nursery and have been transplanted to the N.C. Department of Agriculture/NC State University Mountain Research Center at Laurel Springs. When they are older, these trees will be further multiplied via grafting and infested with adelgids to determine whether they are, indeed, resistant.

This project eventually could allow for the reintroduction of adelgid-resistant Fraser firs into their natural stands. It could also assist Christmas tree producers by facilitating the breeding of Fraser firs that are naturally less vulnerable to attack by the pest, saving growers the time and money required to spray their Christmas tree farms with pesticides.

CONSERVING FRASER FIR GENETIC DIVERSITY

Even if all nine major and minor Fraser fir populations survive depredation by the balsam woolly adelgid, they may face at least one more serious threat: global climate change. A recent model (Delcourt and Delcourt 1998) predicts the elimination of Southern Appalachian Fraser fir-red spruce forest with a possible global mean temperature increase of 3° C caused by greenhouse warming. Fraser fir is listed in North Carolina as an imperiled species, as a species of concern federally, and as a species imperiled and vulnerable to extinction globally (Ameroso and Finnegan 2002). Clearly, the limited distribution of Fraser fir and the threats to its survival in a natural setting are compelling reasons for the systematic conservation of its gene pool (Nicholas et al. 1999).

We are developing a gene conservation plan for Fraser fir that would help facilitate the restoration of the species to its natural stands if BWA or climate change makes such action necessary and would ensure the continued existence of a genetic resource base for Christmas tree breeding. While almost all Fraser fir stands are managed for the continued existence of the species, this is no guarantee that it will be able to evolve in response to rapid environmental changes. An *ex situ* (off-site) conservation plan will help ensure much of the genetic material of these populations is preserved in the event of their loss and could allow for the evolution of genes that, if introduced into natural Fraser fir populations, would make them better able to evolve and survive drastic environmental changes (Eriksson et al. 1993).

The plan will integrate existing Christmas tree breeding and gene conservation efforts with additional measures to archive Fraser fir genetic resources and to expand the amount of genetic variation included in off-site conservation efforts. Its components are likely to include: 1) a seed bank representing both major and minor Fraser fir populations and seeds generated by breeding efforts and in conservation plantings, 2) existing tree breeding elements (provenance and progeny tests, seed orchards, and clone banks), and 3) conservation plantings.

THE IMPACT OF ADELGID ON THE CHRISTMAS TREE INDUSTRY

North Carolina accounts for more than 12 percent of real Christmas trees produced in the United States and ranks second in the total number of trees harvested and first in the dollars made per tree. Nearly all the Christmas trees grown in the state are Fraser fir. In 1999, 1,600 North Carolina growers sold 3.7 million trees worth a reported value of more than $92 million (North Carolina Department of Agriculture and Consumer Services 2005). Virtually all Fraser fir Christmas trees in western North Carolina have to be treated for BWA one or more times during a 5- to 10-year rotation. This results in an annual cost to the industry estimated at $1.53 million. This estimate, however, does not include additional costs such as losses due to BWA damage or increased miticide control costs associated with BWA treatments.

Generally, the only Fraser fir Christmas tree plantations escaping BWA infestations are those isolated from natural stands, other Christmas tree production areas, and Fraser firs grown as yard trees. Producing Christmas trees near infested yard trees or abandoned Christmas tree plantations greatly increases insect pressure. Growers are encouraged to scout for the BWA yearly, and 68.5 percent of growers did so in 2000. The first and most easily recognized symptom of a BWA infestation is the loss of apical dominance in the affected tree, meaning that the tree produces a crooked top rather than a straight one. When trees with crooked tops are found in the field, the trunk can be examined for the presence of the insect. Growers may also find BWA infestations when they harvest trees: trees infested with BWA produce hard, red-colored reaction wood, which makes the trees harder to cut down.

The threshold for treating a Fraser fir plantation is a single infested tree, although culling symptomatic trees may slow the spread in some instances. Several general predators feed on BWA, including the *Harmonia* ladybeetle, but will not eliminate an infestation. Fraser fir is extremely sensitive to adelgids, and even a few of this pest will impact tree quality. With the introduction of the exotic hemlock woolly adelgid (*Adelges tsugae* Annand) into the eastern United States, there is increased interest in predators and parasitoids of adelgids, which could result in greater natural controls of the BWA in the future.

In treating a Christmas tree plantation for BWA, insecticides must be applied with a high-pressure sprayer using 300 to 800 gallons per acre, depending on tree size and density. The entire tree must be wetted with the insecticide because the adelgids can occur on buds, shoots, and branches in addition to the trunk. Trees are treated from two directions as the applicator pulls 200 to 300 feet of hose up and down rows. Only two or three rows can be treated at a time. About half the Christmas tree growers own this type of equipment, but others must hire someone to treat their trees at a cost of $300 to $500 per acre. Because of the cost and difficulty of these treatments, growers hope to achieve up to three years of BWA control with one treatment.

Materials used for control include:

Lindane 20 EC (lindane): Lindane has traditionally been the primary chemical used to control BWA. Lindane was used on 21.7 percent of Christmas tree acres in 1994 and 23.8 percent in 2000. It is no longer being manufactured, however, and its use is declining.

Asana XL (esfenvalerate): Asana, the primary replacement for Lindane, was used on 16.6 percent of Christmas tree acres in 2000, up slightly from 11.8 percent in 1994. Growers have not felt that they are receiving as long-lasting control with Asana as they had with Lindane. Additionally, growers have reported having more problems with hemlock rust mite during the year following Asana applications.

Thiodan 3EC (endosulfan): Because of the concerns associated with Asana, a 24(c) Special Local Need label was granted for two years for Thiodan 3EC. This chemical cannot be used within 300 feet of surface water because of concerns about its effects on aquatic life. In 2000, it was used on 2.2 percent of acres, but that number has since increased.

Horticultural oil: Horticultural oil is currently used on only 0.1 percent of Christmas tree acres. Treatments with oil to control the BWA are only effective during the winter, when no eggs are present. Oils can burn Fraser fir foliage depending on the rate and the time of year used.

Other Insecticides: Provado 1.6F (imidacloprid), Metasystox-R (oxydemeton-methyl), and Lorsban 4E (chlorpyrifos) are labeled for adelgid control, but are not frequently used. Control has not been long-lasting with these materials. Growers are currently inter-

ested in two other synthetic pyrethroids: Astro (permethrin) and Talstar (bifenthrin). Astro has provided up to 18 months of control in pest-control trials.

The use of broad spectrum insecticides for BWA control results in outbreaks of spruce spider mites (*Oligonychus ununguis*) and hemlock rust mites (HRM) (*Nalepella tsugifoliae*). Since the mid-1990s, when the use of synthetic pyrethroids such as Asana started to become more common for BWA, rust mites have become an increasing problem. In 2000, 20.2 percent of growers used insecticides and/or miticides to control HRM, compared to fewer than 2 percent in 1994. In fact, if Fraser fir in western North Carolina did not require BWA treatment, growers could use more biological control measures for spider mites, rust mites, and the balsam twig aphid (*Mindarus abietinus*), which are all cosmetic pests. Many native predators exist for these pests, but their numbers are reduced with BWA control.

CONCLUSIONS

Over the course of a few decades, balsam woolly adelgid has drastically altered a boreal relict ecosystem endemic to the Southeastern United States. While it appears that Fraser fir will remain a part of this forest community, it is uncertain whether repeated adelgid infestation would reduce its genetic diversity and its status as a codominant canopy species in this ecosystem. Additional research is needed to determine whether a second wave of adelgid mortality is beginning, and to quantify the impacts of adelgid infestation on the flora and fauna of the red spruce-Fraser fir forest type. Efforts to locate and propagate adelgid-resistant firs and to conserve the genetic diversity of the species could become important in any future plans to restore or augment Southern Appalachian spruce-fir forests in which Fraser fir becomes diminished. These measures could also help reduce the time and financial costs borne by the economically important Christmas tree industry to control adelgids in Fraser fir plantations.

REFERENCES

Ameroso, J.L. and J.T. Finnegan, Eds. 2002. *Natural Heritage Program List of the Rare Plant Species of North Carolina*. Raleigh, North Carolina, North Carolina Department of Environment and Natural Resources, North Carolina Natural Heritage Program.

Amman, G.D. 1966. Some new Infestations of balsam woolly aphid in North Carolina with possible modes of dispersal. *Journal of Economic Entomology* 59(3):508-510.

Amman, G.D. 1970. Phenomena of *Adelges piceae* populations (Homoptera-Phylloxeridae) in North Carolina. *Annals of the Entomological Society of America* 63(6):1727-1734.

Amman, G. D. and C.F. Speers. 1965. Balsam woolly aphid in the Southern Appalachians. *Journal of Forestry* 63:18-20.

Amman, G. D. and C.F. Speers. 1971. Introduction and evaluation of predators from India and Pakistan for control of balsam woolly aphid (Homoptera-Adelgidae) in North Carolina. *Canadian Entomologist* 103(4):528-533.

Barrett, S.C.H. and J.R. Kohn. 1991. Genetic and evolutionary consequences of small population size in plants: implications for conservation. *Genetics and Conservation of Rare Plants*. D.A. Falk and K.E. Holsinger, eds. New York, Oxford University Press: 3-30.

Brown, N.R. and R.C. Clark. 1960. Studies of predators of the balsam woolly aphid, *Adelges piceae* (Ratz.) (Homoptera: Adelgidae) VIII. Syrphidae (Diptera). *Canadian Entomologist* 92(11):801-811.

Busing, R.T. and E.E.C. Clebsch. 1988. Fraser fir mortality and the dynamics of a Great Smoky Mountains fir-spruce stand. *Castanea* 53(3):177-182.

Busing, R.T., E.E.C. Clebsch, C.C. Eagar and, and E.F. Pauley. 1988). Two decades of change in a Great Smoky Mountains spruce-fir forest. *Bulletin of the Torrey Botanical Club* 115(1):25-31.

Busing, R.T., P.S. White and M.D. MacKenzie. 1993. Gradient analysis of old spruce-fir forests of the Great Smoky Mountains circa 1935. *Canadian Journal of Botany* 71(7):951-958.

Cain, S.A. 1935. Ecological studies of the vegetation of the Great Smoky Mountains. II. The quadrat method applied to sampling spruce and fir forest types. *American Midland Naturalist* 16(4): 566-584.

Delcourt, H.R. and P.A. Delcourt. 1984. Late-Quaternary history of the spruce-fir ecosystem in the Southern Appalachian region. *The Southern Appalachian Spruce-Fir Ecosystem: Its Biology and Threats*. P.S. White, ed. Atlanta, Georgia, United States Department of the Interior, National Park Service: 22-35.

Delcourt, P.A. and H.R. Delcourt. 1987. Long-term Forest Dynamics of the Temperate Zone. New York, Springer-Verlag.

Delcourt, P.A. and H.R. Delcourt. 1998. Paleoecological insights on conservation of biodiversity: a focus on species, ecosystems, and landscapes. *Ecological Concepts in Conservation Biology* 8(4):921-934.

DeSelm, H.R. and R.R. Boner. 1984. Understory changes in spruce-fir during the first 16-20 years following the death of fir. *The Southern Appalachian Spruce-Fir Ecosystem: Its Biology and Threats*. P.S. White, ed. Atlanta, Georgia, United States Department of the Interior, National Park Service: 51-69.

Dey, J.P. 1984. Lichens of the Southern Appalachian Mountain spruce-fir zone and some unanswered ecological questions. *The Southern Appalachian Spruce-Fir Ecosystem: Its Biology and Threats*. P.S. White, ed. Atlanta, Georgia, United States Department of the Interior, National Park Service: 139-150.

Dull, C.W., J.D. Ward, H.D. Brown, G.W. Ryan, W.H. Clerke and R.J. Uhler. 1988. Evaluation of Spruce and Fir Mortality in the Southern Appalachian Mountains. Atlanta, Georgia, United States Department of Agriculture, Forest Service, Southern Region: 92.

Eager, C. 1984. Review of the biology and ecology of the balsam woolly aphid in Southern Appalachian spruce-fir forests. *The Southern Appalachian Spruce-Fir Ecosystem: Its Biology and Threats*. P.S. White, ed. Atlanta, Georgia, United States Department of the Interior, National Park Service: 36-50.

Ellstrand, N.C. and D.R. Elam. 1993. Population genetic consequences of small population size: implications for plant conservation. *Annual Review of Ecology and Systematics* 24:217-242.

Eriksson, G., G. Namkoong and J.H. Roberds. 1993. Dynamic gene conservation for uncertain futures. *Forest Ecology and Management* 62(1-4):15-37.

Hain, F.P. and F.H. Arthur (1985). The role of atmospheric deposition in the latitudinal variation of Fraser fir mortality caused by the balsam woolly adelgid, *Adelges piceae* (Ratz.) (Hemipt, Adelgidae): A hypothesis. *Journal of Applied Entomology* 99(2):145-152.

Hamrick, J.L. and J.D. Nason. 2000. Gene flow in forest trees. *Forest Conservation Genetics: Principles and Practice*. A.G. Young, D. Boshier and T.J. Boyle, ed. Collingwood, Australia, CSIRO Publishing: 81-90.

Hartl, D.L. and A.G. Clark (1997). *Principles of Population Genetics*. Sunderland, Massachusetts, Sinauer Associates, Inc.

Hollingsworth, R.G. and F.P. Hain. 1991. Balsam woolly adelgid (Homoptera, Adelgidae) and spruce-fir decline in the Southern Appalachians: Assessing pest relevance in a damaged ecosystem. *Florida Entomologist* 74(2):179-187.

Huenneke, L.F. 1991. Ecological implications of genetic variation in plant populations. *Genetics and Conservation of Rare Plants*. D.A. Falk and K.E. Holsinger, ed. New York, Oxford University Press: 31-44.

Johnson, K.D. 1980. Fraser fir and the balsam woolly aphid: A problem analysis. Knoxville, Tennessee, Southern Appalachian Research/Resource Managment Cooperative: 62.

Lande, R. 1999. Extinction risks from anthropogenic, ecological, and genetic factors. *Genetics and the Extinction of Species: DNA and the Conservation of Biodiversity*. L.F. Landweber and A.P. Dobson, ed. Princeton, New Jersey, Princeton University Press: 1-22.

Mathews, R.C., Jr. and A.C. Echternacht. 1984. Herpetofauna of the spruce-fir ecosystem in the Southern Appalachian Mountain regions, with emphasis on the Great Smoky Mountains National Park. *The Southern Appalachian Spruce-Fir Ecosystem: Its Biology and Threats*. P.S. White, ed. Atlanta, Georgia, United States Department of the Interior, National Park Service: 155-167.

Mitchell, R.G. and K.H. Wright. 1967. Foreign predator introductions for control of balsam woolly aphid in Pacific Northwest. *Journal of Economic Entomology* 60(1): 140-147.

Nicholas, N.S., C. Eager and J.D. Peine. 1999. Threatened ecosystem: high-elevation spruce-fir forest. *Ecosystem Management for Sustainability: Principles and Practices*. J.D. Peine, ed. Boca Raton, Florida, Lewis Publishers: 431-454.

Nicholas, N.S., S.M. Zedaker and C. Eager. 1992. A comparison of overstory community structure in three southern Appalachian spruce-fir forests. *Bulletin of the Torrey Botanical Club* 119(3): 316-332.

North Carolina Department of Agriculture and Consumer Services. 2005. Christmas Trees. www.ncagr.com/markets/commodit/horticul/xmastree/index.htm, January 27, 2005.

Oosting, H.J. and W.D. Billings. 1951. A comparison of virgin spruce-fir forest in the northern and southern Appalachian system. *Ecology* 32(1): 84-103.

Pauley, E.F. and E.E.C. Clebsch. 1990. Patterns of *Abies fraseri* regeneration in a Great Smoky Mountains spruce-fir forest. *Bulletin of the Torrey Botanical Club* 117(4): 375-381.

Pyle, C. 1984. Pre-park disturbance in the spruce-fir forests of Great Smoky Mountains National Park. *The Southern Appalachian Spruce-Fir Ecosystem: Its Biology and Threats*. P.S. White, ed. Atlanta, Georgia, United States Department of the Interior, National Park Service: 115-130.

Pyle, C. and M.P. Schafale. 1988. Land use history of three spruce-fir forest sites in Southern Appalachia. *Journal of Forest History* 32:4-21.

Rabenold, K.N. 1984. Birds of Appalachian spruce-fir forests: Dynamics of habitat-island communities. *The Southern Appalachian Spruce-Fir Ecosystem: Its Biology and Threats*. P.S. White, ed. Atlanta, Georgia, United States Department of the Interior, National Park Service: 168-186.

Rabenold, K.N., P.T. Fauth, B.W. Goodner, J.A. Sadowski and P.G. Parker. 1998. Response of avian communities to disturbance by an exotic insect in spruce-fir forests of the southern Appalachians. *Conservation Biology* 12(1):177-189.

Rajora, O.P. and A. Mosseler 2001. Molecular markers in sustainable management, conservation and restoration of forest genetic resources. *Genetic Response of Forest Systems to Changing Environmental Conditions*. G. Mueller-Stark and R. Schubert, ed. Boston, Kluwer Academic Publishers. Vol. 70 (For. Sci.):187-202.

Rheinhardt, R.D. 1984. Comparative study of composition and distribution patterns of subalpine forests in the Balsam Mountains of southwest Virginia and the Great Smoky Mountains. *Bulletin of the Torrey Botanical Club* 111(4):489-493.

Saunders, P.R. 1979. The vegetational impact of human disturbance on the spruce-fir forests of the Southern Appalachian Mountains. *Department of Forestry and Environmental Studies*. Durham, North Carolina, Duke University: 170.

Smith, D.K. 1984. A status report on bryophytes of the Southern Appalachian spruce-fir forests. *The Southern Appalachian Spruce-Fir Ecosystem: Its Biology and Threats*. P.S. White, ed. Atlanta, Georgia, United States Department of the Interior, National Park Service: 131-138.

Smith, G.F. 1997. Southern Appalachian fir and spruce-fir forest community changes following balsam woolly adelgid infestation. *Department of Forestry*. Knoxville, Tennessee, University of Tennessee: 128.

Smith, G.F. and N.S. Nicholas. 1998. Patterns of overstory composition in the fir and fir-spruce forests of the Great Smoky Mountains after balsam woolly adelgid infestation. *American Midland Naturalist* 139(2):340-352.

Smith, G.F. and N.S. Nicholas. 1999. Post-disturbance spruce-fir forest stand dynamics at seven disjunct sites. *Castanea* 64(2):175-186.

Smith, G.F. and N.S. Nicholas. 2000. Size- and age-class distributions of Fraser fir following balsam woolly adelgid infestation. *Canadian Journal of Forest Research* 30(6):948-957.

Southern Appalachian Man and the Biosphere. 1996. The Southern Appalachian Assessment. Asheville, North Carolina, USDA Forest Service, Southeastern Forest Experiment Station.

White, P.S. 1984. The Southern Appalachian spruce-fir ecosystem: an introduction. *The Southern Appalachian Spruce-Fir Ecosystem: Its Biology and Threats*. P.S. White, ed. Atlanta, Georgia, United States Department of the Interior, National Park Service: 1-21.

White, P.S., M.D. Mackenzie and R.T. Busing. 1985. Natural disturbance and gap phase dynamics in Southern Appalachian spruce-fir forests. *Canadian Journal of Forest Research* 15(1): 233-240.

Whitehead, D.R. 1973. Late-Wisconsin vegetational changes in unglaciated eastern North America. *Quaternary Research* 3:621-631.

Whitehead, D.R. 1981. Late Pleistocene vegetational changes in northeastern North Carolina. *Ecological Monographs* 51(4):451-471.

Whittaker, R.H. 1956. Vegetation of the Great Smoky Mountains. *Ecological Monographs* 26(1):1-80.

Witter, J.A. and I.R. Ragenovich. 1986. Regeneration of Fraser fir at Mt. Mitchell, North Carolina, after depredations by the balsam woolly adelgid. *Forest Science* 32(3):585-594.