Modeling the Distribution of Northern Hardwoods in Carolina Northern Flying Squirrel (*Glaucomys sabrinus coloratus*) Recovery Areas of the Southern Appalachian

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

Master of Science
in
Geography

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5/23/2013
Blacksburg, VA

Keywords

GIS, northern hardwood forest, southern Appalachians, predictive forest modeling, Carolina northern flying squirrel, DEM

Modeling the Distribution of Northern Hardwoods in Carolina Northern Flying Squirrel, (*Glaucomys sabrinus coloratus*), Recovery Areas of Western North Carolina and Southwestern Virginia

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Abstract

The northern hardwood forest type is a critical habitat component for the endangered Carolina northern flying squirrel (CNFS; *Glaucomys sabrinus coloratus*) for denning sites and corridor habitats between montane conifer patches where the squirrel forages. This study examined terrain data, and patterns of occurrence for the northern hardwood forest type in the recovery areas of CNFS in western North Carolina and southwestern Virginia with the purpose of creating a more robust predictive model of this forest type for spatial delineation. I recorded overstory species composition as well as terrain variables at 338 points throughout the study area in order to quantitatively define the northern hardwood forest type. These data were used in conjunction with digital terrain data for creation of the predictive model. Terrain variables we examined to attempt to differentiate northern hardwoods from other forest types included elevation, aspect, slope gradient, curvature, and landform index. I used an information-theoretic approach to assess six models based on existing literature and a global model. My results indicate that on a regional, multi-state scale, latitude, elevation, aspect, and landform index (LFI) of an area are significant predictors of the presence of the northern hardwood forest type in the southern Appalachians. My model consisting of **Elevation + LFI** was the best approximating model based on lowest AICc score. Our **Elevation + LFI** model correctly predicted northern hardwood presence at 78.2% of our sample points observed to be northern hardwoods. I then used this model to create a predictive map of the distribution of the northern hardwood forest type in CNFS recovery areas.

Acknowledgements

There are many people that have helped, advised, or provided me with support throughout the completion of this project. First, I am thankful for the guidance and direction I received from my advisor, Dr. Lynn Resler throughout the duration of this project. I also would like to thank my committee member, Dr. W. Mark Ford for guidance, and field support throughout the past two years. Dr. Steve Prisley, my other committee deserves a big thanks for guidance through the GIS portions, and all of the questions he was able to answer for me. I am particularly thankful to Rick Odom, for everything he helped with from getting the project off the ground to connecting me with the USFS personnel at the Southern Research Station. I would also like to thank Morgan Duncan, my dutiful field volunteer that climbed over mountains, wasn’t scared by wildlife encounters, and took excellent field notes. This project was funded by the USGS Fish and Wildlife Cooperative Unit at Virginia Tech, and the Sidman Poole Foundation Endowment to the Virginia Tech Department of Geography. I would not have been able to complete this project without the support and assistance from my friends and colleagues in the Virginia Tech Department of Geography’s graduate program, and would like to thank all of them, and specifically: Arvind Bhuta, Jason McVay, Justin White, and Taylor Seigler.

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Chapter 1: Introduction and Problem Statement

1.1 Introduction and Problem Statement

The high elevation montane forests of the southern Appalachians have long been recognized as a biodiversity hotspot and are home to a large number of endemic species (Braun, 1950; Stein, 2001). Due to past disturbances from logging, fire, and subsequent soil degradation, along with more current threats such acid rain/deposition, climate change, introduced forest pests, and recreational development, these forests are considered to be critically endangered (Noss *et al.*, 1995). Characteristics of these forests include disjunct populations of several northern or boreal species such as the endangered Carolina northern flying squirrel (CNFS; *Glaucomys sabrinus coloratus)* and forest types such as the red spruce (*Picea rubens*)-Fraser fir (*Abies fraseri*) and northern hardwood, that are typically found at much higher latitudes (Wells-Gosling and Heaney, 1984; Weigl *et al.*, 1999). Management decisions for endangered species such as Carolina northern flying squirrel play an integral role in policy making and management activities for these forests.

Northern hardwoods are typically found at the high elevation areas of the southern Appalachians above 1200 meters where lower elevation, more austral species such as yellow-poplar (*Liriodendron tulipifera*) are no longer stand components (Braun, 1950; Whittaker, 1956). The typical northern hardwood forest type is most often described as being composed of maple (*Acer* spp.), birch (*Betula* spp.), and American beech (*Fagus grandifolia*) with some variations including basswood (*Tilia americana*) and black cherry (*Prunus serotina*) (Bolstad *et al.*, 1998; Menzel *et al.*, 2004). The CNFS inhabits high elevation boreal forest above 1350 meters most often in red spruce-Fraser fir - northern hardwood ecotones or mixed forests where downed woody material and deep organic soils support abundant lichens, truffles, and other fungi as a food source for CNFS (Loeb *et al.*, 2000). The range of CNFS is limited to isolated areas along the Blue Ridge High Mountain ecoregion (Griffith *et al.*, 2002) in western North Carolina and eastern Tennessee to and just beyond the Virginia line, where nine to possibly twelve populations are believed to exist. The CNFS is a relict species from the last glacial period. Climate change (warming), and other disturbances the squirrel has been further restricted to remaining patches of mostly second growth forest that are of sufficient elevation and composition to still support spruce-fir and northern hardwoods with reasonable ecological integrity. The tree species of the northern hardwood forests often have cavities that serve as denning and nesting sites for a variety of species, including the CNFS or the Virginia northern flying squirrel, (VNFS; *Glaucomys sabrinus fuscus)* that occurs to the north in the central Appalachians in similar habitats (Wells-Gosling and Heaney, 1984; Payne *et al.*, 1989).

Regionally, most of these forests are considered mature but still show evidence of both natural and human-induced disturbance factors over the much of the last century. Structurally, these stands are in the process of transitioning from the stem exclusion stage to an understory phase closer to the original old growth forest. This gap-phase disturbance and regeneration cycle differs from stand processes over the past 75-100 years. Previously stands had higher stem densities, which provided a variety of habitats to small birds and mammals (Whittaker, 1956; Oliver and Larson, 1996; Spies, 2004).

After the turn of the century, industrial logging practices began to move from selective cutting of large diameter tree species to value laden clear-cutting with the advent of the portable sawmill and expansion of railroads into the region (Frothingham, 1931). This shift in logging practices allowed for much of the area once occupied by northern hardwoods and other montane forest types to be harvested and then in some instances converted to pasture lands. During this shift in logging practices, stand replacing fire events were fed by high fuel loadings from logging residue or intentional burning. This led to considerable erosion and soil degradation, loss of seed sources, and altered woody regeneration composition (Cain, 1931; Fowler and Konopik, 2007). This shift was then followed by several decades of fire suppression that allowed for pioneer species such as fire cherry (*Prunus pensylvanica*) or oaks (*Quercus* spp.) to regenerate in logged areas on moderate to highly xeric sites, whereas northern hardwood types such as maple and birch were able to still regenerate on mesic aspects and slopes (Whittaker, 1956; Simon *et al.*, 2005; Boerner, 2006; Fowler and Konopik, 2007). Since those past disturbances, the forests in the study area have been heavily impacted by the balsam woody adelgid (BWA, *Adelges piceae*) and beech bark disease, in addition to other human-induced factors such as acid deposition that continued to affect these forests. Balsam woody adelgid primarily affected Fraser fir trees at the upper limits of the northern hardwood distribution in the southern Appalachians. Fraser fir stands experienced up to a 90% mortality rate following infestations of BWA (Bruck and Robarge, 1988). Following the loss of fir stands, increases in woody shrubs such as blackberry (*Rubus canadensis*), take over which in turn leads maintains the canopy gaps and ultimately influence stand composition in affected areas (Gandhi and Herms, 2010). Beech bark disease has a similar effect in beech gap areas, as well as northern hardwood and oak stands where beech is present. Beech gap forests are primarily composed of trees originating solely from root suckers or stump sprouts rather than new individuals, and thus tend to have low genetic diversity making them more susceptible to pathogens (Jenkins, 2007). Beech bark disease (BBD) is an insect-fungal pathogen caused by infestations of beech scale (*Cryptococcus fagisuga*), making it possible for two species of *Nectria* fungus (*N. coccinea* and *N. galligena*) to infect meristemic tissues (Vandermast, 2005). BBD caused mortality of more than 80% of trees it infects, which leads to the formation of canopy gaps allowing for maple and birch densities to increase in mixed stands. In beech gaps, beech tend to regenerate quickly due to root or stump sprouting which leaves them susceptible for future occurrences of BBD (Vandermast, 2005).

The natural and anthropogenic disturbances that have affected both the northern hardwood forests and other forest types in the study area have also severely impacted several animal species that occupy the northern hardwood forests and adjacent forests in the southern Appalachians. Two such species are the CNFS and the southern flying squirrel (*Glaucomys volans*). These species frequently use the large cavities found in many of the older specimens in northern hardwood stands as nesting areas. Degradation of these forests limits the available nesting areas to CNFS, thus leading to more interactions between CNFS and the southern flying squirrel (Weigl, 1978). The CNFS is limited to isolated high-elevations areas along the Appalachian crest in western North Carolina and eastern Tennessee and southwestern Virginia, where nine populations are believed to exist (U. S. Fish and Wildlife Service, 1990; Weigl *et al.*, 1999; Boynton and Kelly, 1999 (Updated in 2007); McGrath and Patch, 2003), whereas the southern flying squirrel is relatively common throughout much of the southeastern United States (Weigl, 1969). Expansion of mast-bearing species such as the northern red oak (*Quercus rubra*) into higher elevation areas, provides a high-energy food source that has allowed the southern flying squirrel to survive in these more thermically difficult environments. Hence it has become locally synoptic with CNFS (Weigl, 1969, 1978; Menzel *et al.*, 2004). Existing studies have also found that southern flying squirrels, despite their smaller size, are much more aggressive than CNFS in den-site competition, and are chronic hosts of an intestinal nematode (*Stongyloides robustus*) that is often lethal to CNFS (Weigl, 1978; Ford *et al.*, 2004; Menzel *et al.*, 2004; Menzel *et al.*, 2006; Weigl, 2007). Occurrence of *S. robustus* at higher elevations is believed to have contributed to further reductions in CNFS populations (Weigl, 1969, 1978; Pauli *et al.*, 2004; Krichbaum *et al.*, 2010).

Previous studies of CNFS have indicated that red spruce-Fraser fir forests serve as foraging areas attributed in part to the presumed higher abundance of mycorrhizal fungi that makes up a significant portion of CNFS diet and serve as drey (twig or leaf nest) sites on a limited basis (Payne *et al.*, 1989; Weigl *et al.*, 1999; Loeb *et al.*, 2000; Bird and McCleneghan, 2005). The northern hardwood species of these second growth forests, most commonly yellow birch (*Betula alleghaniensis*) or American beech (*Fagus grandifolia*), provide nesting sites for CNFS in the form of large hollows and cavities as well as food cache sites, latrines, and natal sites (Weigl, 1978; Weigl *et al.*, 1999; Hackett and Pagels, 2003). Weigl (2007) and Meyer et al. (2005) found that these sites also provide substantial ground cover and closed canopies that provide a degree of protection from predators as well as quantities of wet, decaying wood that support the truffles, lichens, and beech nuts that make up a large portion of CNFS diet. Additionally, northern hardwoods can be relatively poor habitat for the competing southern flying squirrel and can serve has habitat corridors linking red spruce- Fraser fir patches that may constitute the preferred foraging habitat (Menzel et al. 2006).

The isolation of CNFS and current threats to the habitat have prompted the creation of a recovery plan, developed by the Northern Flying Squirrel Recovery Team in conjunction with the United States Fish and Wildlife Service (USFWS) for both CNFS and the Virginia northern flying squirrel (VNFS, *Glaucomys sabrinus fuscus*) in 1990. The goals of the recovery plan are to determine the exact distribution of the two subspecies, protect areas with suitable habitat, explore the ecology of the two subspecies and test the response of the subspecies to human action to their habitats (U. S. Fish and Wildlife Service, 1990). An improved understanding of the distribution of northern hardwoods in relation to CNFS recovery areas (figure 1.1) will contribute to those goals.

My primary goal was to determine if the geographic distribution and landscape configuration of northern hardwood forest types can be accurately determined from digital terrain modeling of CNFS recovery areas using Geographical Information Systems (GIS). Previous studies that created habitat model for CNFS of the forests of the central and southern Appalachians have most likely inadequately assessed it due to a lack of a resolute northern hardwood input or were limited in scope to a specific mountain range, or watershed (see (Odom *et al.*, 2001; McGrath and Patch, 2003).

1.2 Research Objectives and Hypothesis

The specific objectives of my research were to:

1. Define the species composition and extent of the northern hardwood forest type of southern Appalachia in the context of recovery areas of CNFS;

and

2. Create a predictive model of the northern hardwood forest type based on terrain variables that can be used throughout CNFS recovery areas in western North Carolina and elsewhere in the southern Appalachians.

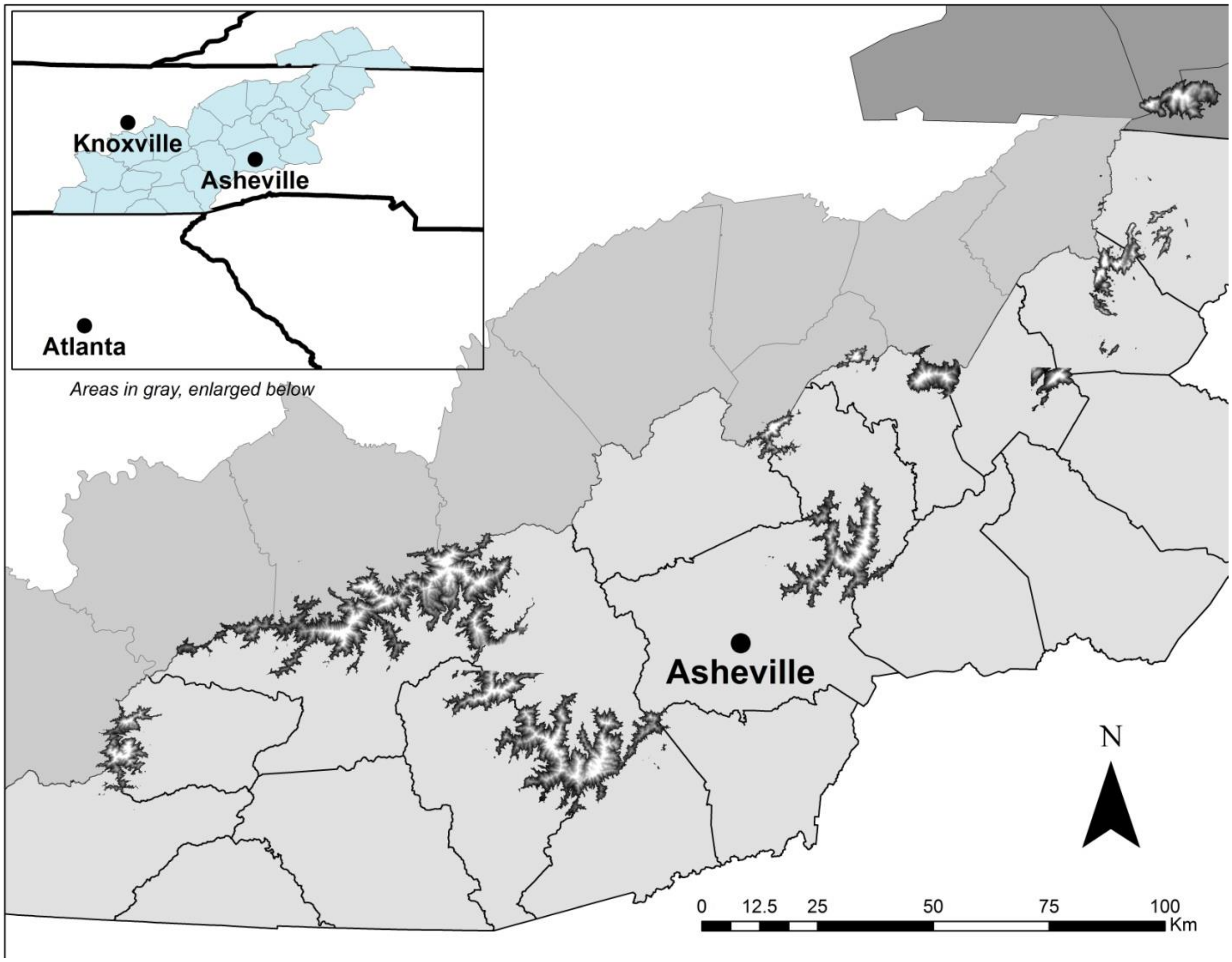
1.3 Significance

Current and existing research on CNFS shows that the species is associated with the northern hardwood and red spruce-Fraser fir ecotone or mixed forests in the southern Appalachians that provide foraging and denning habitats (Weigl, 1978; Hackett and Pagels, 2003). However, current habitat studies have been limited in their inference by the inability to accurately determine the extent and quality of the habitat occupied by CNFS, particularly discriminating or accurately delineating northern hardwoods from other, unused hardwood types (Odom and McNab, 2000; McGrath and Patch, 2003). By creating high accuracy maps of the northern hardwood forests in CNFS recovery areas, researchers and managers could better assess the connectivity of known habitat patches; identify areas where additional populations may exist for identification of areas for restoration or habitat enhancement. Additionally, mapping the extent of the northern hardwood forests in this area could provide insights into the impacts and predicted forest change as a result of climate change that is - where northern hardwoods will be vulnerable to replacement or conversely where expansion into red spruce-Fraser fir at higher elevations might occur.

My research should also provide a better definition of the northern hardwood forest type for the southern Appalachians in order to establish a level of consistency among researchers in this area. The northern hardwoods are generally defined by latitude and elevation but this does not account for other ecological variables that may have significant effects on stand composition and structure at smaller scales (Gentry, 1988; Bolstad *et al.*, 1998). This study will also examine other important ecological variables including soil characteristics and terrain variables in order to expand this definition. The structure and composition of these stands are not just influenced by current conditions but also are influenced by past disturbances and landscape history. The northern hardwood forest type is important in the role that it plays in the ecosystem encompassed in CNFS recovery areas. Studies have shown that northern hardwoods are crucial denning sites and CNFS used yellow birch bark almost exclusively as a nesting material (Payne *et al.*, 1989). This work constitutes an important step in defining the northern hardwood forest type and understanding the role it plays in the landscape of *G.s. coloratus* recovery areas. On a broader scale, this project will contribute to the existing body of research that examines and attempts to model the ecosystems of the montane forest of the southern Appalachians that currently exists.

The results of our research should provide valuable insight to the National Park Service (NPS), and U. S. Forest Service (USFS) personnel conducting other studies in these areas as well assist policy makers in conservation and forest management decisions as this forest type have been designated by the USFS as one of thirty-one terrestrial communities in the southern Appalachians in danger of disappearing due to climate change and knowing how and where to engage in forest community restoration (Hackett and Pagels, 2003). Additionally, our research will also help officials from the U. S. Fish and Wildlife Service (USFWS) better define areas to protect as recovery areas in western North Carolina and Tennessee for *G.s. coloratus* whereas these areas are currently only defined as areas above 1280 meters in elevation.

Figure 1: Geographic Recovery areas of the Carolina Northern Flying Squirrel in western North Carolina, eastern Tennessee, and southwest Virginia (*Glaucomys sabrinus coloratus*)



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Chapter 2: Review of the Literature

2.1 Ecology of Carolina Northern Flying Squirrel Recovery Areas

The habitat of the Carolina northern flying squirrel (CNFS; *G.s. coloratus*) is restricted to high elevation forests of the montane boreal-northern hardwood ecotone above 1200 meters in the southern Appalachians. The Blue Ridge portion of the southern Appalachians, extending from northern Georgia to central Virginia (Simon *et al.*, 2005) have been labeled as a "biodiversity hotspot" due to the unique ecosystems and number of imperiled species that occur here (Stein, 2001). Natural and anthropogenic disturbance history has significantly altered the landscape and continues to impact the habitat of endangered species such as CNFS (Weigl *et al.*, 1999; Weigl, 2007). Their habitats in the study area of my research are comprised of yellow birch (*Betula alleghaniensis*), American beech (*Fagus grandifolia*), maple (*Acer rubrum* and *Acer saccharum*); as well as red spruce (*Picea rubens*) and Fraser fir (*Abies fraseri*) both as mature forests of that type and/or as an understory component in northern hardwood types. In most of the study area, the forests are primarily considered to be mostly mature second-growth, though some scattered patches of old-growth or stands with old-growth legacies and attributes do occur, providing ecological benefits to CNFS with abundant coarse woody debris, and large mature trees and snags (McGrath and Patch, 2003) (Payne *et al.*, 1989). In defining the forest types of the southern Appalachians, other factors must also be considered besides elevation including substrates, soils, climatic variables, as well as topographic variables such as position in the landscape (McNab, 1996).

At high elevations in the southern Appalachian Mountains, aspect and soil depth play the largest role in determining forest type; most soils in these areas are acidic and typically fall into the mesic and frigid temperature regimes as a result of the cool to cold, moist climate (Lee

Daniels, Virginia Polytechnic Institute and State University, personal communication). Generally, these high elevation soils have a relatively low percentage of clay in their composition and increasing organic layer depth as elevation increases. The soils in the study area are most often classified as ultisols or inceptisols and fall into the Wayah soil series with an O horizon of partially decomposed organic matter at depths from 0-10 centimeters that are favorable for the growth of mycorrhizal fungi (truffles). It should also be noted that effects of aspect and soil depth are inversely related with aspect playing a larger role stand composition at lower elevations and soil depth playing a larger role at higher elevations above 1372m (Cain, 1931; Daniels *et al.*, 1999; Simon *et al.*, 2005).

Soils also play a crucial role in stand determination as well as the presence of mycorrhizal fungi (truffles); in particular *Geopora* and *Elaphomyces*. *Geopora* and *Elaphomyces* make up a large component of CNFS diet (Loeb *et al.*, 2000). Several species of northern hardwoods, including American beech, have been associated with the presence of mycorrhizal fungi. However, these fungi are more typically associated with the red spruce and Fraser fir forest, which are the primary foraging areas for CNFS (Loeb *et al.*, 2000; Ford *et al.*, 2004; Weigl, 2007). The presence of the fungi is largely due to the symbiotic relationship between these tree species roots and the fungi, whereby the hosts gain expanded access to water, nitrogen, and phosphorus and the fungi receive a steady supply of carbon (Bird and McCleneghan, 2005; Smith, 2007). Loeb et al. (2000) found that the presence of truffles in any amount was negatively correlated to the presence of some hardwoods such as yellow birch in the study plots but also concluded that this may be due to the patchy distribution of truffles in the southern Appalachians. They also noted that based on capture studies by Weigl et al. (1999) and others there was higher capture rates in those areas containing yellow birch, that is used preferentially for denning and for nesting material (shredded bark), in close proximity to red spruce. These findings lead researchers to conclude that distribution of these habitat types across the landscape may be just as important as stand age, structure, size, and stand composition in assessing the quality of habitat they provide for CNFS (Weigl *et al.*, 1999; Loeb *et al.*, 2000).

In addition to soils, stand characteristics also play an important role in the habitat; CNFS are known to choose trees that are older and taller than those of the surrounding stand for den sites. Second growth stands are frequently used in addition to old growth stands provided these stands contain some old forest trees or are bordering old growth stands. This denning behavior is likely due to the propensity of these older trees to contain decay that encourages cavity creation or facilitates primary excavator activity (Hackett and Pagels, 2003). In second growth stands of northern hardwoods, and near the ecotone between pure northern hardwood and red spruce-Fraser fir stands, CNFS has been shown to move freely between the two, often foraging among the spruce-fir species though denning in the northern hardwoods (Weigl *et al.*, 1999; Ford, 2012). Several species of northern hardwoods have also been shown to be crucial to CNFS in that they provide both places to nest and nesting material such as birch bark that is used exclusively by CNFS (McGrath and Patch, 2003). Previous studies conducted on nest tree usage by *G.s. coloratus* in Tennessee and North Carolina have shown that yellow birch and American beech are the trees most often used for denning, with abandoned woodpecker holes and hollows formed by decay used particularly during the winter months. During the warmer months of the year, northern flying squirrels have been shown leaf or “drey” nests in the northern hardwood red spruce- Fraser fir ecotone as well for purposes such as nocturnal feeding stations, and daytime sleeping sites (Wells-Gosling and Heaney, 1984).

Many of the northern hardwood and spruce-fir stands in the southern Appalachians would fall into Oliver and Larson's (1996) stem exclusion stage or understory stage. The stem exclusion stage occurs after a disturbance has occurred and is the stage of a closed canopy where new individuals are absent and some existing stems die off allowing surviving stems to continue to grow (Oliver and Larson, 1996). In these stands, it is typical for individual tress to compete for canopy gaps and, over time, subdominant trees are crowded out by taller individuals. Such competition can be both inter- and intra- specific, and species change can occur because some species are better at gap capture and height growth (Rentch *et al.*, 2010). In other cases, shade tolerant species will subsist in the understory and then take over following a disturbance (Oliver and Larson, 1996). In the southern Appalachians, the stem exclusion and understory reintiation stages characterize many of the areas that were heavily disturbed in the past. In many of these disturbed areas, northern red oak (*Quercus rubra*), and fire cherry (*Prunus pensylvanicum*) most likely were the pioneer species followed by northern hardwood species. In areas pioneered by northern red oak and fire cherry, it is common to see northern red oak making up the highest or "A" stratum of the canopy with northern hardwoods making up the "B" stratum just below the *Quercus* canopy, especially on more southerly aspects versus northerly aspects where sugar maple (*Acer saccharum*) or red maple (*Acer rubrum*) are more likely to make up the "A" stratum.

In the understory stage, some of the species, such as northern red oak, which made up the "A" stratum in the previous stage, will be replaced during the next disturbance with new canopy gaps fill by woody species from the "B" stratum. During this stage herbaceous and woody shrub growth, in addition to advance woody regeneration development in the understory will occur (Oliver and Larson, 1996). This understory stage is also applicable to the red spruce-Fraser fir forests and the ecotone shared with northern hardwoods where introduced pests such as balsam woody adelgid (BWA, *Adelges piceae*) in the red spruce- Fraser fir or bark disease in the northern hardwoods may have killed off individuals allowing sunlight to reach the forest floor. In spruce-Fraser forest, loss of mature Fraser fir trees has been shown to allow red spruce to become the dominant species in the canopy or in mixed stands hardwood species such as yellow birch and maple quickly captures those spaces (Harmon *et al.*, 1984; Rentch *et al.*, 2010). Vandermast (2005) found that in beech stands infected with bark disease that other canopy species such as sugar maple declined as well indicating a community level effect in the loss of beech trees but also noted an increase in red spruce in these stands.

Copenheaver et al. (2006) describes the disturbance induced development pattern in southwest Virginia where droughts in the 1950's and 1960's allowed more xeric-adapted hardwood species such as oak and hickory (*Carya* spp.) to largely dominate previously disturbed areas, however more recently, more mesic species have begun to dominate the understory (Fowler and Konopik, 2007) possibly an indicator of future shift in overstory composition (Copenheaver *et al.*, 2006). This shift from xeric oak communities to shade-tolerant, fire-sensitive species can be attributed to changes in disturbance regimes. Fire or fire surrogates previously maintained the balance between heliophytic species such as oak and mesic northern hardwood species. Without the disturbance from fire, mesophytic and late-successional species outcompete and rapidly replace heliophytic species (Nowacki and Abrams, 2008). At high elevations in the southern Appalachians, this possible shift could move current stands dominated by oak back to mesic, shade-tolerant northern hardwoods.

2.2 Defining the Northern Hardwood Forest Type

The northern hardwood forest type is generally well defined for North America, but definitions vary due to the concomitant diversity in overstory species in context of extant stands in the southern Appalachians (Cain, 1931; Simon *et al.*, 2005). The northern hardwoods in the southern Appalachians typically have a much higher sugar maple component, whereas in the northern parts of its range that species has been impacted by drought, soil acidification, and insect defoliation (Jenkins, 2007). However, in other studies it has been documented to be similar to those in the northern latitudes (Pittillo *et al.*, 1998). Canopy species that define northern hardwood forest types often vary by region (see descriptions by Braun, 1950; Whittaker, 1956; Ulrey, 1999). For example, in Great Smoky Mountains National Park, the high elevation hardwood forest type designation is based on an elevation criteria greater than 1040 meters and includes the northern hardwood sub-group, composed of yellow birch, American beech, and sugar maple, and high elevation montane oak communities (composed of northern red oak and even white oak *Quercus alba*). In other areas of the southern Appalachians, northern hardwoods definitions contain several other subgroups including northern hardwoods, and slopes, boulder fields, yellow birch and red spruce, rich cove, and high elevation red oaks (Ulrey, 1999) or as being dominated by yellow birch, American beech, sugar maple and yellow buckeye (*Aesculus octandra*) (Wharton, 1977; Odom and McNab, 2000). Beech gaps are often found within a surrounding stand of other high elevation forest types, and are stands of almost exclusively American beech. Almost all beech gap forests are primarily composed of trees originating solely from root suckers or stump sprouts rather than new individuals. Therefore, low genetic diversity makes these stands susceptible to pests such as the beech bark beetle, *Cryptococcus fagisuga* (Jenkins, 2007). The beetle facilitates fungal infections of the bark by two types of fungi *Nectria galligena,* a native fungus, and *Nectria coccinea,* an exotic fungus, that collectively create a insect-fungal pathogen (Mahoney *et al.*, 1999). Infestations of beech bark disease cause an annual mortality rate of approximately 5-6% in stands with low rates of infection to nearly 100% mortality in highly infected stands (Vandermast, 2005). Forested boulder fields are characterized by areas of large rocks and boulders dominating the upper soils and the ground, and are believed to have formed during the Pleistocene glaciations through freeze-thaw weathering processes (Chafin and Jones, 1989). Yellow birch, yellow buckeye and American basswood (*Tilia americana*) tend to dominate stand composition and the canopy in these areas will tend to have a well-developed herbaceous layer due the frequent canopy openings (Chafin and Jones, 1989; Ulrey, 1999). Trees in the boulder fields often have numerous prop roots wrapping around boulders, and tend to sprout from decomposing woody debris that is used as a “nurse log” (Jenkins, 2007). Additionally, forested boulder fields are less likely to have been disturbed by fire in the past due to extremely moist conditions and rocks dominating the ground that have prevented fire from carrying through these stands (Pauley, 2008).

Figure 2.1: Examples of three basic forest types of high elevation areas in the southern Appalachians. From Left to Right: red spruce-Fraser fir, northern red oak, and northern hardwood. Red spruce-Fraser fir forest are often dominated by red spruce in lower latitudes of the southern elevations, and co-dominated by both species as you move north. Northern red oak forests are typically dominated by northern red oak specimens but American beech is often present as well. Northern hardwood forests are often co-dominated by at least two of the following species: American beech, yellow birch, or red maple

2.3 GIS Modeling of Forests and Mapping Techniques

Predictive vegetation mapping of vegetation composition and distribution through GIS typically involves the use of mapped environmental variables. This type of mapping begins with the development of a statistical model followed by the application of the model using the mapped environmental variables. Predictive vegetation mapping is based on niche theory and gradient analysis through the manipulation of direct and indirect environmental variables such as terrain measurements (Franklin, 1995). The use of environmental variables, both direct and indirect, uses niche theory in that it identifies a minimum set of basic habitat requirement for a given species that are constant through its distribution (Rotenberry *et al.*, 2006). Direct variables are defined as soil, site moisture, past and current disturbance and climatic factors; whereas indirect variables are defined as those relating to terrain such as slope, aspect, and landscape topography. The use of indirect terrain variables builds on this idea through the use of known terrain gradients, such as elevation or aspect, of vegetation communities that have been previously observed (McNab *et al.*, 1999; Frances *et al.*, 2002). These variables are referred to as indirect due to their effect on the environment and not necessarily directly to the vegetation. For example, elevation affects direct variables such as temperature and precipitation regimes, and slope affects direct variables such as soil moisture, and exposure of a site (Franklin, 1995). Predictive vegetation mapping can then be used to map habitat suitability for animal species because of vegetation's direct importance for shelter or food purposes (Scott *et al.*, 1993). Most recently this approach has been used to identify areas for conservation of endangered species and their habitats (Guisan and Zimmermann, 2000).

The existing body of research conducted on the macro- and micro- habitat of the endangered CNFS has used both direct and indirect environmental variables in order to map forest types in relation to CNFS habitat (Odom *et al.*, 2001; Hackett and Pagels, 2003; McGrath and Patch, 2003; Ford *et al.*, 2004; Menzel *et al.*, 2004; Hough and Dieter, 2009). However, there have been relatively few successful studies that have examined how to best combine these relationships between indirect variables in order to model northern hardwood forests, and thereby the habitat of CNFS, through the use of digital elevation models (Bolstad *et al.*, 1998; McGrath and Patch, 2003; Flanigan, 2010). Previous studies that have attempted to connect these factors with vegetation types have taken four basic approaches (Horsch, 2003):

1. Associating vegetation types with site factors using primary data
2. Interpolating vegetation type and site factors using digital elevation models (DEMs)
3. Relating vegetation type to spatially interpolated direct and indirect site factors
4. Relating vegetation types to indirect topographic or landform site characteristics

Associating vegetation types with site factors using primary data and Interpolating vegetation type and site factors using digital elevation models (DEMs)

There are three main modeling approaches developed from these approaches: those exclusively using primary data, those exclusively using direct or indirect variables, and those that use a combination of direct and indirect variables. Primary data is based on field measurements and observations, whereas direct and indirect variables are spatially interpolated to a particular site through the use of digital data and maps. These two methods are used by researchers that either investigated the effect of human influences on vegetation or conversely, focused solely on natural direct site factors. However, extensive data on direct factors in mountainous areas at higher resolutions is largely unavailable in many areas and that substantial interpolation is required to produce digital maps, which introduces a level of uncertainty to the model (Shi, 2010). Hack and Goodlett (1960) first hypothesized the correlation between terrain's influence on the moving of water and distribution of vegetation in a study on the geomorphology and forest ecology in the central Appalachians in the 1960's. This theory was then used to develop methods relating vegetation type to spatially interpolated direct and indirect site variables in the 1980's when further research indicated the use of topographic variables could potentially improve prediction models (McNab, 1989). This method combines both direct and indirect factors into a single model; however there is often a high level of redundancy in the factor data, model analysis is more complex, and some relationships may be masked by others within the results (Horsch, 2003). The final approach exclusively uses indirect topographic factors for the prediction of vegetation. Using topographic variables is widely applicable in areas where data on direct site factors may not be available; in addition, continuous DEMs are relatively more accurate than point vector data for direct site factors (Horsch, 2003).

Relating vegetation type to spatially interpolated direct and indirect site factors

Previous vegetation studies have attempted to develop a set of specific indirect factors that were indicative of a vegetation community and then use those to develop a predictive vegetation map (McNab, 1989; Moore *et al.*, 1991; McNab, 1993; Bolstad *et al.*, 1998; Odom *et al.*, 2001; Petersen and Stringham, 2008; Flanigan, 2010; Shoutis *et al.*, 2010). Such studies frequently integrate field vegetation data with readily available digital data, and use a GIS program to examine correlations between vegetation communities and land cover types (McGrath and Patch, 2003; Taverna *et al.*, 2005; Hall, 2008) through the analysis of contingency tables for model development of specific vegetation types (Horsch, 2003). Indirect factors typically have moderate to high correlation with vegetation composition (Bolstad *et al.*, 1998; Narayanaraj *et al.*, 2010). The spatial pattern of montane forest types can be explained and simulated to a large extent through the use of indirect factors alone. Resolution of data also has been found to play a significant role on prediction accuracies and that more research on the role of data resolution has on prediction is needed (Bolstad *et al.*, 1998; Horsch, 2003).

Relating vegetation types to indirect topographic or landform site characteristics

Generally relationships exist between vegetation and indirect topographic factors such as latitude, and elevation. Other environmental factors, such as climate and soil type, also modify the potential of a site for use as habitat for vegetation communities (Bailey, 1996; McNab, 1996). Indirect topographic factors include terrain measurements such as elevation, slope and aspect. Landform site characteristics describe a site's relationship and position with the surrounding landscape using indexes such as landform index (LFI) and terrain shape index (TSI). For example, McNab (1996) investigated associations between local scale vegetation communities with environmental features and detailed their spatial patterns of occurrence with regard to temperature, moisture, and soil fertility gradients. McNab's (1996) principal objective was to identify the predominant vegetative communities on both a landscape and local scale, and classify them to fit a hierarchical model as described by Bailey (1988). This model describes local and landscape ecological types based on site and landscape mosaics and scale. Local scale ecological types can occupy ten to hundreds of hectares and generally consist of a single vegetative community on a single landform type, such as a cove or ridgeline. Landscape scale ecological types occupy areas of roughly 100,000 hectares and encompass areas of similar landform, climate, soils, and vegetation (Bailey, 1988; McNab, 1996).

For field data, McNab (1996) focused on tree-like vegetation greater than 10 centimeter diameter at breast height and soil variables derived from USDA soil survey map. Multivariate statistical analyses identified local scale ecological types. The researchers used a centroid seed technique, and then a canonical discriminant analysis to identify relationships between the previously classified plots to topographic and soil variables for the study area (McNab, 1996). From these relationships, two landscape types were identified: mountain highlands of moderate elevation and intermontane basins. These landscape types were composed of five local scale tree communities that were characterized by a unique set of topographic and soil variables (McNab, 1996). Landscape types were shown to correlate with both topographic and soil variables along temperature and moisture gradients. Landscapes identified solely on the basis of statistical grouping of soil and topographic variables without vegetation data were not successful in identification of ecological types at this scale. However, these methods typically are only applicable locally so extrapolation to larger landscapes may not be appropriate (McNab, 1996).

Terrain variables used by several studies conducted in the southern Appalachians included slope, aspect, elevation, and terrain shape index (a function of the elevation minus the focal mean of a cell in a five by five window) (McNab, 1991; Bolstad *et al.*, 1998; Odom and McNab, 2000; Narayanaraj *et al.*, 2010). A subset of independent field data points are typically withheld to perform a cross validation. Results from studies that use such methods revealed no significant relationships between any of the species examined and slope and aspect, and additionally that forest types in the southern Appalachians changed congruently with elevation and terrain shape. Inconsistencies in species composition and abundance was also found to exist within each forest type and forest types often exhibited a large amount of spatial overlap in the study area (Bolstad *et al.*, 1998).

Accuracy in Models and Terrain Variables

Wide discrepancies in accuracy of predictive forest models for vegetation mapping have been found to be site-specific depending on the methods used. Commonly used methods include kriging, co-kriging, mosaic diagrams, and linear regression. Bolstad et al. (1998) used kriging and co-kriging methods to create predictive models. Kriging and co-kriging uses weights on measured values to derive predictions for unmeasured areas, and have been found to yield significantly different results, and had a higher rate of error overall than the linear regression and mosaic diagram methods. Mosaic diagrams use nominal or ordinal scales to plot terrain variables and expected vegetation in order to summarize the relationship between the two (Bolstad *et al.*, 1998). Mosaic diagram and linear regression methods were found to be similar to each other with regards to accuracy. A separate study in the Andes Mountains based entirely on a logistic regression model also showed high levels of accuracy using terrain variables. The researchers were able to achieve 84% accuracy in the prediction of forest cover in the tree line zone, though the researchers noted that one variable, altitude, accounted for 80% accuracy when used as a predictor by itself (Bader and Ruijten, 2008). Frequency of terrain sampling can have a significant effect on the accuracy of the mapping as well (Bolstad *et al.*, 1998; Store and Jokimäki, 2003). Bolstad et al. (1998) also found that different DEM resolutions produced different prediction accuracies. For example, Bolstad et al. (1998) found that coarser resolution DEM data assignment of forest types noticeably reduced accuracy compared to finer resolution data. The coarser resolution data had higher misidentification rates of cove and xeric oak-pine types as the mixed deciduous forest type (Bolstad *et al.*, 1998).   Smith *et al.*, 2008 when examining avian habitat relationships showed that for finer scale habitat structures (such as topographic changes within a single stand) a higher resolution of digital data is beneficial. Furthermore, it also concluded that habitat models for forested landscapes using more detailed data, i.e., stand level, will be more accurate than those exclusively using landscape level data (Smith *et al.*, 2008).

Terrain based modeling is also influenced by the selection of algorithms used to calculate the terrain variables and the error introduced through the use of them. In the add-on to the ArcGIS software platform, DEM surface tools there are three different algorithms available to users comparing different slope algorithms (Jones, 1998; ESRI, 2011; Jenness, 2012). The three algorithms available are the 4-cell method, Horn’s method, and the Sharpnack and Akins method (Jenness, 2012). All of these methods use a 3x3 pixel moving window to calculate the slope value for the center pixel in the window. The 4-cell method has been found to be consistently ranked better based on higher root mean squared error in previous studies (Morrison, 1974; Hodgson, 1995). The 4-cell method uses the differences in the elevation from the four cells (pixels) surrounding the center cell to calculate slope from north-south and east-west gradients. Previous literature has found this method to provide the closest approximation of the actual slope. The 4-cell method describes an area approximately 1.6 times the area of the original cell versus the other methods which use the all of the points in the 3x3 window which describes an area approximately twice the area of the original cell (Morrison, 1974; Hodgson, 1995; Jones, 1998; Jenness, 2012).

Significant relationships between terrain shape, or curvature, and elevation have been observed in previous research (McNab, 1991; Odom and McNab, 2000; Narayanaraj *et al.*, 2010) as well, although many of these studies note that individual species responded differently. Spatial co-variation decreases rapidly as distance between sampling points increases particularly with ridge and cove species which greatly hindered these two methods (Bolstad *et al.*, 1998). While elevation is directly derived from the DEM, calculation of curvature can also introduce error and inaccuracy of the model output. Curvature is related to terrain shape in that both describe the concavity or convexity of a site on a local and is ideal for assessing the impacts the micro-topography has on flora and fauna.

2.4 Existing Habitat Models of *G.s. coloratus*

Currently there are only cursory, descriptive habitat models for the CNFS or Virginia northern flying squirrel (*Glaucomys sabrinus fuscus,* VNFS). Existing habitat models for the northern flying squirrel are site specific, and cannot be accurately generalized to each current recovery areas. One existing study conducted by Hackett and Pagels (2003) in southwestern Virginia in the Mount Rogers area investigated whether CNFS den sites were associated with second (60-80 year old) and old growth (150-180 year old) montane boreal forest consisting of northern hardwoods (primarily yellow birch and American beech), and red spruce. Through quantification of all non-herbaceous vegetation above ground level, slope, aspect, distance to the nearest mature red spruce (diameter at breast height > 10 cm), and radio tracking CNFS, the study showed that almost all squirrels used at least two different den sites with a larger proportion of these sites being located in larger, older, and taller trees than surrounding trees that were available for nesting. The data also suggested that in this part of its range CNFS is not limited to old growth forest habitat types provided that second growth stands contain some older, decadent trees or is close proximity to those conditions (Hackett and Pagels, 2003). Based on these findings, the study indicates that features critical to the species' survival (i.e., microclimate and substrate to provide fungi that make a large proportion of the diet of CNFS, etc.) must be present in order for the species to inhabit diverse areas (Hackett and Pagels, 2003).

Odom et al. (2001) developed a habitat model for the VNFS in similar habitat conditions in the Allegheny Mountain portion of the central Appalachians in West Virginia using GIS to delineate potential occupancy probabilities. Wilcoxon signed rank tests revealed distance to conifer and elevation were significant and related to squirrel presence or absence. They used proximity to previously placed VNFS nest boxes (squirrels presence/absence for the dependent variable), and conifer (red spruce-eastern hemlock *Tsuga canadensis*) and non-conifer forest types to classify vegetation cover from satellite imagery in a logistic regression. Elevation and distance to conifer were found to be statistically significant in predicting squirrel presence or absence. The interaction between elevation and distance to conifer variable were not significant in the predictive model, and the model predicted nearly the entire area of study as potential habitat (Odom *et al.*, 2001). This effect was largely attributed to current nest box locations in the study area collectively not encompassing a wide enough range of conditions to accurately provide habitat thresholds of presence or absence VNFS leading the researchers to hypothesize that this species may actually inhabit a much larger area of the landscape than previously thought (Odom *et al.*, 2001). Ford et al. (2004) and Menzel et al. (2004) also found significant correlations in West Virginia for VNFS to conifer forests also using a logistic regression approach, though Menzel et al. (2004) improved it further using stand-level conifer data not previously used. In combination, these VNFS studies and other studies on CNFS by Weigl et al (1999), Hackett and Pagels (2003), and Payne et al (1989) are thought of as coarse preliminary models in that their research served as a baseline for more spatially explicit predictive models.

McGrath and Patch (2003) used a similar method as Odom et al. (2001) to model the presence or absence of CNFS in the Balsam Mountains of western North Carolina. McGrath and Patch (2003) developed a community classification model using terrain attributes and GIS. Combining red spruce and northern hardwood as predicted presence and the combination of northern red oak and red spruce as predicted absence, their model was unable to predict whether or not CNFS would be present or not. Instead, they determined that their model was relatively accurate in predicting presence but was not able to predict where CNFS would not occur (McGrath and Patch, 2003), the opposite outcome of Odom et al. (2001) for VNFS. However, the researchers did note that in all cases where their model predicted absence but were found were most like the result of the presence of a microhabitat community that differed from the surrounding plant community. Therefore, their model could be used to determine an approximate distribution throughout their study area or at least identify areas for future nest box surveys (McGrath and Patch, 2003). This follows the trend of previous studies in that it identifies what is thought to be “good” habitat but cannot eliminate areas that would likely be less favorable habitat (Odom *et al.*, 2001; Ford *et al.*, 2004).

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Chapter 3

Developing a topographic model to predict the northern hardwood forest type in Carolina Northern Flying Squirrel (*Glaucomys sabrinus coloratus*) recovery areas of the Southern Appalachians

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*To be submitted to the Journal of Forest Ecology and Management

Abstract:

The northern hardwood forest type is a critical habitat component for the endangered Carolina northern flying squirrel (CNFS; *Glaucomys sabrinus coloratus*) for denning sites and corridor habitats between montane conifer patches where the squirrel forages. This study examined terrain data, and patterns of occurrence for the northern hardwood forest type in the recovery areas of CNFS in western North Carolina and southwestern Virginia with the purpose of creating a more robust predictive model of this forest type for spatial delineation. We recorded overstory species composition as well as terrain variables at 338 points throughout the study area in order to quantitatively define the northern hardwood forest type. This data was used in conjunction with digital terrain data for creation of the predictive model. Terrain variables we examined to differentiate northern hardwoods from other forest types included elevation, aspect, slope gradient, curvature, and landform index. We used an information-theoretic approach to assess seven models based on existing literature and a global model. Our results indicate that on a regional, multi-state scale, elevation, aspect, and landform index (LFI) of an area are significant predictors of the presence of the northern hardwood forest type in the southern Appalachians. Our **Elevation + LFI** model was able to correctly predict northern hardwood presence and was our best approximating model based on lowest AICc score. It correctly predicted northern hardwood presence at 78.20% of our sample points observed to be northern hardwoods. We then used this model to create a predictive map of the distribution of the northern hardwood forest type in CNFS recovery areas.

3.1.1 Introduction

The Blue Ridge portion of the southern Appalachians, extending from northern Georgia to central Virginia (Simon *et al.*, 2005) have been labeled a “biodiversity hotspot” due to the unique ecosystems and number of imperiled species that occur here (Stein, 2001). Natural and anthropogenic disturbance history has significantly altered the landscape and continues to impact the habitat of endangered species such as the Carolina Northern Flying Squirrel (CNFS, *Glaucomys sabrinus coloratus*) that rely on the montane northern hardwood and red spruce (*Picea rubens*)-Fraser fir (*Abies fraseri*) forests for denning sites and foraging (Weigl *et al.*, 1999; Ford *et al.*, 2004; Weigl, 2007).

In the southern Appalachians, high elevation forest communities above 1300m have been subjected to varying degrees of disturbance over the last 200 years. Disturbance to these areas began with Native Americans and early European pioneers clearing land for settlements and pasture and more recently at the turn of the 20th century during the industrial logging boom (Odom and McNab, 2000; Ford *et al.*, 2004). The extent and type of clear cutting harvests during this time were important determinants for shaping high-elevation forests that occur in the region presently. In mid- to high- elevations, subsequent wildfires or in some cases intentional burning that often followed these clear cutting harvests of northern hardwoods favored heliophytic tree species, such as oak (*Quercus spp.*). In disturbed areas where red spruce-Fraser fir were cut and burned, stump sprouting and wind dispersed seeds allowed northern hardwoods to increase in mixed forests and make significant inroads into formally pure red spruce-Fraser fir stands (Nowacki and Abrams, 2008). Current theories are that oaks then regenerated throughout much of the areas that were previously occupied by northern hardwoods on more xeric slopes and northern hardwoods claimed sites once occupied by red spruce and Fraser fir in moderately mesic high elevation areas (Ford *et al.*, 2004). Currently, many high elevation oak stands appear to be in a transition state towards one dominated by northern hardwoods as shade tolerant species advance and become established in the understory; natural regeneration by oak species becomes much more difficult without continued intermediate disturbance from fire, for example.

Also impacting the high elevation forests of the southern Appalachians has been the introduction of the invasive pest balsam woody adelgid (*Adelges picea*) and beech bark disease. Balsam woody adelgid has caused significant mortality among Fraser fir at the higher limits of northern hardwood distribution. Beech bark disease has caused significant mortality among the American beech (*Fagus grandifolia*) in the southern Appalachians (McNab *et al.*, 1999; Simon *et al.*, 2005; McNab, 2010). The mortality of Fraser fir and beech trees can lead to the formation of gaps which allows for the woody shrubs such as blackberry (*Rubus canadensis*) to capture the gap and ultimately keeps succession arrested or on hold (Gandhi and Herms, 2010). Additionally, the southern Appalachians are known to be an area of heavy atmospheric acid deposition in the eastern United States (Shaver *et al.*, 1994).

The natural and anthropogenic disturbances to both the northern hardwood forests and other forest types in the study area have also severely impacted several animal species that occupy the northern hardwood forests and adjacent forests. Two such species are the CNFS and the southern flying squirrel (*Glaucomys volans*). These species frequently use the large cavities found in many of the older specimens in northern hardwood stands as nesting areas. Degradation of these forests limits the available nesting areas to CNFS, thus leading to more interactions between CNFS and the southern flying squirrel (Weigl, 1978). The CNFS is limited to isolated high-elevation areas along the Appalachian crest in western North Carolina and eastern Tennessee and southwestern Virginia, where nine populations are believed to exist (U. S. Fish and Wildlife Service, 1990; Weigl *et al.*, 1999; Boynton and Kelly, 1999 (Updated in 2007); McGrath and Patch, 2003) whereas the southern flying squirrel is relatively common throughout much of the southeastern United States (Weigl, 1969).

Disturbance events have allowed for the expansion of mast bearing species such as the northern red oak (*Quercus rubra*) to expand into higher elevation areas providing a high-energy food source allowing the more austral southern flying squirrel to survive in these more thermically difficult environments and allowed it to become locally synoptic with CNFS (Weigl, 1969, 1978; Menzel *et al.*, 2004). Existing studies have also found that southern flying squirrels, despite their smaller size, are much more aggressive than CNFS in den-site competition, often displacing extant CNFS in localized areas (Weigl, 1978; Ford *et al.*, 2004; Menzel *et al.*, 2004; Menzel *et al.*, 2006). Moreover, southern flying squirrels are chronic hosts of an intestinal nematode (*Stongyloides robustus*) that is often lethal to CNFS (Weigl 2007). Occurrence of *S. robustus* at higher elevations is believed to have contributed to further reductions in CNFS populations (Weigl, 1969, 1978; Pauli *et al.*, 2004; Krichbaum *et al.*, 2010).

Previous studies of CNFS indicate that the red spruce-Fraser fir forest serve as foraging areas attributed in part to the presumed higher abundance of mycorrhizal fungi that makes up a significant portion of CNFS diet and serve as drey (twig or leaf nest) sites on a limited basis (Payne *et al.*, 1989; Weigl *et al.*, 1999; Loeb *et al.*, 2000; Bird and McCleneghan, 2005). The northern hardwood species of these second growth forests, most commonly yellow birch (*Betula alleghaniensis*) or American beech (*Fagus grandifolia*), provide nesting sites for CNFS in the form of large hollows and cavities as well as food cache sites, latrines, and natal sites (Weigl, 1978; Weigl *et al.*, 1999; Hackett and Pagels, 2003). Weigl (2007) and Meyer et al. (2005) found that these sites also had substantial ground cover and closed canopies that provide a degree of protection from predators as well as quantities of wet, decaying wood that support the truffles, and lichens, that make up a large portion of CNFS diet. Additionally, northern hardwoods can be relatively poor habitat for the competing southern flying squirrel and can serve has habitat corridors linking red spruce-Fraser fir patches that may constitute the preferred foraging habitat (Menzel et al. 2006).

The isolation of CNFS and current threats to its habitat have prompted the creation of the recovery plan, developed by the Northern Flying Squirrel Recovery Team in conjunction with the United States Fish and Wildlife Service (USFWS) for both CNFS and the Virginia northern flying squirrel (VNFS, *Glaucomys sabrinus fuscus*) in 1990. The goals of the recovery plan are to determine the exact distribution of the two subspecies, protect areas with suitable habitat, explore the ecology of the two subspecies, and test their response anthropogenic disturbances (U. S. Fish and Wildlife Service, 1990). An improved understanding of the distribution of northern hardwoods in relation to CNFS recovery areas (Figure 1) will contribute to those goals.

3.1.2 Predictive Habitat Modeling

Using indirect gradients such as terrain variables for the creation of predictive models for forest types such as northern hardwoods is effective because of the positive correlation that usually occurs along species' spatial distributions on the landscape and terrain variables (Guisan and Zimmermann, 2000). Digital elevation model (DEM) derived topographic variables are ideal for predictive modeling of vegetation and habitat through the use of Geographical Information Systems (GIS) at a regional scales and they can often be generated with minimal loss in precision of the topographic measurements (Horsch, 2003; Petersen and Stringham, 2008). This type of modeling has also been shown to aide in identification of areas that can be incorporated into a managed forest or reserve system for conservation of a species of concern (Rotenberry *et al.*, 2006). Previous studies that created models central and southern Appalachian forests have been small in scope, limited to specific mountain ranges, or watersheds (Odom *et al.*, 2001; McGrath and Patch, 2003). Simon et al. (2005) used topographic variables in addition to geological and soil fertility data in their first approximation to classify ecological zones of the southern Appalachians using GIS and were able to achieve greater than 90% accuracy for their red spruce-Fraser fir and shortleaf pine (*Pinus echinata*)-oak health zones. However, a lack of overlap among the predictions existed in their final classification map is an issue from a management standpoint. Realistically, it would be improbable to be able to sample every area that possibly might be habitat for CNFS, or survey areas suitable for forest restoration or enhancement, i.e., increase the component of red spruce in current northern hardwood stands. Furthermore, a more precise model of the northern red oak forest types, northern hardwood forests, and their ecotone would allow forest managers to more appropriately use prescribed burning to accomplish burning goals without harming fire sensitive northern hardwood or red spruce-Fraser fir regeneration. Lastly, a predictive model would help facilitate a better understanding the impact of climate change in these areas.

The objectives of our study were to define the northern hardwood forest type and determine if the geographic distribution of northern hardwood forest types can be accurately determined from digital terrain modeling in and adjacent to CNFS recovery areas using GIS. To meet the objectives, this study used a decision tree approach for initial classification based on similar stand composition and species abundance within those stands as were used in previous studies (McNab 1996, Simon et al. 2005, Yoke and Rennie 1996). We examined presence or absence of northern hardwoods at 338 points at high elevations from extreme southwestern North Carolina and into southwestern Virginia using an information-theoretic approach (Burnham and Anderson, 2002). We hypothesized based on previous studies that elevation, aspect, slope, curvature, and landform index (LFI) would contribute to the predictive model (Bolstad *et al.*, 1998; Daniels *et al.*, 1999; Odom and McNab, 2000; North Carolina Wildlife Resources Commission, 2005; Nowacki and Wendt, 2009).

3.2 Methods

3.2.1 Study Areas

During the summer of 2012 and January of 2013, we sampled vegetation and terrain characteristics at 338 points which made up 113 3-point belt transects across 11 study areas in western North Carolina, eastern Tennessee, and southwestern Virginia (Figure 3.1). Nine sites within North Carolina and/or adjacent portions of Tennessee along the border shared with North Carolina and the Grayson Highlands area of southwestern Virginia contained known populations of CNFS; (Payne *et al.*, 1989; Reynolds *et al.*, 1999; Weigl, 2007). Additionally, we sampled two areas with northern hardwood forests where CNFS have not been documented—the Standing Indian and Wayah Bald massifs. The sample points fell within the Blue Ridge Parkway National Park (BRPNP), Pisgah, Nantahala or Cherokee National Forest, or on lands owned by the Eastern Band of Cherokee Indians. These areas receive on average 114 centimeters at lower elevations to more than 200 centimeters on the higher peaks of precipitation annually, distributed relatively evenly throughout the year (occurring as snow and ice during the winter months and rain in the summer months). Temperatures are widely variable throughout the year due to the effects of elevation and aspect, and average approximately 2.2°C in January and approximately 23°C in July (Shanks, 1954; McNab, 1996; Simon *et al.*, 2005). Typically the first frost occurs in early October, and the last frost in early May, with 130 frost free days on average (National Climatic Data, 2012). Soils in the study area tend to fall in frigid temperature regime and be acidic with deep organic layers and can vary from boulder-fields to mineral soils of considerable depth (Cain, 1931; Daniels *et al.*, 1999; Loeb *et al.*, 2000).

Mature, second-growth high elevation forests that show evidence of both natural and human-induced disturbance factors over much of the last century characterize most of the study areas. There are some old growth stands that have naturally developed, however, a large portion of the study area are mature second growth stands following early 20th century harvesting (Whittaker, 1956; Oliver and Larson, 1996; Spies, 2004). Many of the second growth northern hardwood stands in the study area are a result of stump sprouting, seeding and advanced regeneration in areas where northern hardwoods previously occurred or areas that, prior to disturbance, were red spruce-Fraser fir or a mixed red spruce-Fraser fir and northern hardwood stand that is now dominated by northern hardwoods (Oliver and Larson, 1996; Vandermast, 2005; Rentch *et al.*, 2010). These second growth forests can provide denning, and to a lesser extent, foraging habitat for CNFS if sufficient cavities exist and conditions are suitable for hypogeal fungi (i.e., downed coarse wood debris, moist micro-sites). Simon et al. (2005) and Ulrey (199) classified the northern hardwood forest type in the southern Appalachians as being composed of four ecological subgroups: boulder fields, beech gap and slopes, rich cove, and northern hardwood in their studies of the ecological zones of the southern Appalachians (Ulrey, 1999; Simon *et al.*, 2005). These subgroups are described as primary overstory species being American beech, yellow birch, and red maple with cherry spp. (*Prunus serotina*), basswood (*Tilia americana*), and other maple species frequently found in these areas as well (Whittaker, 1956; Ulrey, 1999; Odom and McNab, 2000; Simon *et al.*, 2005). Northern red oak is often described as being part of an overall northern hardwood ecological group, but for this study it was classified as an individual group as these areas more frequently serve as habitat for the southern flying squirrel (Odom *et al.*, 2001; Smith, 2007).

Using a method to validate DEM-based models similar to the approach of Odom and McNab (2000), we used ESRI's ArcMap (2011) to randomly select sampling points in clipped USGS DEMs (Evans, 2012). These sampling points would serve as center points on 200m belt transects with sampling points placed at 0m, 100m, and 200m. This was done in order to maximize the topographic effects on the data based on our previous knowledge of the study area terrain. For accessibility, we generated study points that were within 1000m of the Blue Ridge Parkway itself, U.S. Forest Service roads (USFS) or public trails. An excess of points were originally generated to allow for the elimination of points in the field, which were placed in non-forested areas (e.g. grassy balds or ericaceous heath) or occurred in areas where sampling was prohibited by the National Park Service (NPS) or USFS (McNab and Odom, 2012; Young, 2012) and to stratify sampling points based on study area.

The number of points per study area was proportional based on total acreage above 1200m for each area. Sampling rates ranged between 0.2% for the larger mountains to 3% on the smaller mountains of area above 1200m in the study region. Sampling points in the 8 of the 11 study areas met the following criteria: elevation > 1219m, less than 1km to red spruce-Fraser fir forests as identified by the southeastern gap analysis land cover data (SEGAP), association with CNFS recovery areas, and accessibility. We selected sample points in the remaining 3 study areas, including one with documented CNFS populations, meeting the elevation criteria and where northern hardwood were known to occur but were not near any substantial red spruce-Fraser fir stands. The elevation criteria was based on the lowest recorded elevation of CNFS capture in the study area (U.S. Fish and Wildlife Service, 1990) and also represents the transition from mid elevation forest types to high-elevation forest types (McNab and Odom, 2012). Proximity to red spruce-Fraser fir forests, as identified by SEGAP, was important because previous research has shown that these conifer types are highly correlated with the presence of the mycorrhizal fungi that makes up a large portion of the diet of CNFS (Loeb *et al.*, 2000; Ford *et al.*, 2004).

We used a handheld Trimble GeoXT© GPS unit to navigate to the randomly generated study points that were generated from the DEMs. At each sampling point, we tallied the total number of stems for each tree species using a basal area prism with a factor of 10 to identify dominant species and generalize stand composition. The basal factor of 10 eliminated smaller stems from the tally to avoid understory and sub-canopy species from misclassification (U.S. Forest Service, 2008). We characterized each study point as ridgeline, shoulder, or cove, and assigned a slope position (low, medium, or high) to describe each point's location and topography in relation to the surrounding landscape (McNab, 1993). Elevation, slope, and aspect measurements were collected at each study point in the field using the GPS, compass, and clinometers following methods similar to those used by McNab et al. (1999) for comparison of those derived from the DEMs. Elevation was recorded from the GPS unit held approximately 1m off the ground. Aspect was measured in the direction of the steepest downward slope, and slope was recorded from the sampling point to the edge of the visible plot in the same direction. We noted dominant understory species to aid in identifying transitions from one forest type to another. We also looked for any evidence of past disturbances such as logging or establishment of USFS roads that would have impacted stand composition or recruitment by overstory species. Finally, we assigned forest type for each plot assigned based on dominant overstory species composition based on stem count observed through the prism. Categories of forest types included: northern hardwood (yellow birch, American beech, red maple, sugar maple, mountain maple *Acer spicatum,* and yellow buckeye), red spruce-Fraser fir, high elevation northern red oak (dominated by northern red oak with an element of American beech), and montane pine (composed mostly of table mountain pine (*Pinus pungens*) with pitch pine (*Pinus rigida*) present at some locations). Definitions and descriptions (Figure 3.2) of these forest types follow several previous studies in addition to a decision tree (Figure 3.3) created for continuity throughout the study on the decision of forest type; we acknowledged that some species overlap may occur between forest types due to the large variation in terrain conditions and geographic extent of the study area (e.g. (Whittaker, 1956; Callaway *et al.*, 1987; Bolstad *et al.*, 1998; Ulrey, 1999; Odom and McNab, 2000; Simon *et al.*, 2005)).

3.2.2 Deriving Terrain Variables

USGS-produced 1/3 arc-second (10 meter) digital elevation models (USGS National Elevation Dataset, NED)(Evans, 2012), were downloaded for each study area and used to derive terrain variables (elevation, slope, aspect, landform index [LFI], and curvature). Elevation, aspect, slope, and surface curvature have been shown to significantly influence forest stand composition (Bolstad *et al.*, 1998; Horsch, 2003) and we used the DEM Surface Tools add-on to ArcMap (Jenness, 2012) to derive them from the DEMs. We calculated slope using the 4-cell method in DEM Surface Tools rather than the 3x3 search array that ArcMap's Spatial Analyst (Horn's Method) uses. The 4-cell method has been found to be consistently ranked better based on higher root mean squared error in previous studies (Morrison, 1974; Hodgson, 1995). The 4-cell method uses the differences in the elevation from the four cells (pixels) surrounding the center cell to calculate slope from north-south and east-west gradients. Previous literature has found this method to provide the closest approximation of the actual slope. The 4-cell method describes an area approximately 1.6 times the area of the original cell versus the other methods which use the all of the points in the 3x3 window which describes an area approximately twice the area of the original cell (Morrison, 1974; Hodgson, 1995; Jones, 1998; Jenness, 2012). We derived Curvature values using an algorithm identified by Moore et al. (1991) as a way to describe hydrological catchment areas. Jenness' DEM Surface tools multiply the values by negative 1 and then by 100 to maintain consistency with the values calculated by the ArcGIS software package (Jenness, 2012). This method was a way to identify the concavity and convexity of the landscape with a numerical value, with convex surfaces having positive values and concave surfaces having negative values. Curvature differs from LFI in that it uses a 3x3 cell moving window versus the 1000m radius circle used by LFI. This allows for examination of the effects of concavity or convexity on a local scale LFI use the focal mean of the 1000m radius circle on a DEM subtracted from a pixel's value from a DEM. The resulting valueshows how exposed or protected a site is in regards to the surrounding landscape. Once these values were calculated for the study area, we overlaid a vector point file of actual sample point locations and we extracted terrain variable values for each sample point were then extracted. We then exported this digital data as a spreadsheet for statistical analysis.

3.2.3 Statistical Analysis

We used correlation analysis to examine multi-collinearity and redundancy among variables and eliminated those variables with a correlation coefficient greater than 0.8 and proceeded with the variable we believed to be most beneficial to analysis based on existing literature— a technique shown to limit bias in analysis during model creation (Graham, 2003). For the binary logistic regression, we coded sample points as northern hardwood forest (1) and all other forest types (0). We then examined the presence or absence of the northern hardwood forest type through a series of stepwise logistic regression equations using the derived terrain variables and the latitudinal gradient. In addition to the main effects, all interactions among variables, as well as quadratic effects of individual variables, were examined. The quadratic effects of a variable allow for examination of a nonlinear relationship between a predictor variable and a response (Vittinghoff, 2012). The mixed stepwise regression allowed for the addition and removal of variables, using a p-value threshold of 0.25 to enter or remove a variable (Sall *et al*., 2007). This allowed us to remove insignificant variables while keeping significant variables.

We created a series of six models to examine presence or absence of the northern hardwood forest type based on previous predictive models and theories relating to the effects of topography on forest types plus a global model that included all of the variables from the models. In addition to topographic effects, we included our northing coordinate for each sample point in each of the models to investigate if latitude was a significant predictor. We based our models on the existing literature (McNab, 1989; Yoke and Rennie, 1996; Bolstad *et al.*, 1998; Daniels *et al.*, 1999; Odom and McNab, 2000; North Carolina Wildlife Resources Commission, 2005; Nowacki and Wendt, 2009) and expanded them to include the quadratic effects of each variable in addition to the main effects and interactions. The models we constructed based on inclusion of the following variables: 1) **Elevation** (Nowacki and Wendt, 2009), 2) **Elevation and LFI** (Odom and McNab, 2000), 3) **Elevation and Aspect** (Daniels *et al.*, 1999), 4) **Elevation and Curvature** (McNab, 1989; Bolstad *et al.*, 1998), 5) **Slope and LFI** (Yoke and Rennie, 1996), 6) **Elevation, Aspect and Slope** (North Carolina Wildlife Resources Commission, 2005), and 7) **Global** using all parameters. We monitored the Akaike information criteria corrected for small sample sizes (AICc) to avoid over fitting of the model to the dataset (Akaike, 1987). We also generated receiver operating curves for each model and the AUC (area under the curve) was examined for accuracy. We then ranked all of the models based on their respective AICc scores.

To determine the best approximating or data fitting model, we ranked all of the models based on AICc scores and used the model with lowest AICc score as the best approximating model (Burnham and Anderson, 1998).

In order to examine how well the predictive models performed, we used a jackknife procedure to compute the specificity and sensitivity of the models. The jackknife procedure compares a model's estimated values against measured values by resampling the data minus 1 data point from the measured data. Specificity is defined as the percent correct classified of non-northern hardwood forest types points and sensitivity is defined as the percent correctly classified of northern hardwood forest type points (Sall *et al.*, 2007). We then took the best performing model and created a predictive map produced using the study area terrain rasters and then overlaid the sample point shape file using ArcGIS (ESRI, 2011). A 70 percent probability cutoff was used to determine predicted northern hardwood or other, as we felt this provided the best agreement between the predicted and observed values of the calibration set (Fielding and Bell, 1997; Guisan and Zimmermann, 2000). Predicted forest type was then extracted to each of the 338 sample points, and we compared these predicted values to observed values to examine model performance.

3. 3Results

3.3.1 Model Selection and Prediction Accuracy

We sampled 338 points in the southern Appalachians of western North Carolina, adjoining areas of eastern Tennessee, and in southwest Virginia across a wide range of terrain (Table 3.1). Of the 338 sites we sampled, 179 were the northern hardwood forest type and the remaining 159 sites were composed of the high elevation northern red oak forest type (n = 80), the red spruce-Fraser fir forest type (n = 73), or the montane pine community (n = 6). The northern hardwood forest type was found more often in sheltered areas at higher elevations than either the high elevation northern red oak forest type or montane pine communities, but at lower elevations than the red spruce-Fraser fir forest type based on the terrain variables we examined. Among the terrain variables, the amount of overlap in aspect across all of the forest types was more than nominally expected, while the lack of overlap in elevation between forest types was less than we expected (Table 3.2 and Figures 3.4, 3.5, 3.6).

Our model containing **Elevation + LFI**, the latitude variable, and all interactions between the variables was shown to be the best approximating model for the overall study area (Table 3.3). **Elevation +LFI** indicated that the predicted occurrence of the northern hardwood forest type was positively correlated with quadratic effects elevation, and negatively the interaction of elevation and LFI and the quadratic effects of the latitudinal variable (Table 3.4). Empirically there was some support for the **Elevation + Aspect** model since it was within approximately 11 AICc units of the **Elevation + LFI** model (Table 3.3) Sensitivity for the remaining models and the **Global** model ranged from 49.72-81.56%. Specificity for the remaining models and the **Global** model ranged from 40.88-73.58%. Out of all of the terrain variables we examined, the quadratic effect of elevation (elevation-mean*elevation-mean) and the latitudinal variable was statistically significant ($p < 0.05$) across all of models. Our R^2 were similar to previous studies using terrain based modeling (. None of the main effects were significant in our models and only the main effects of aspect and curvature were significant in the **Global** model.

3.4.0 Discussion and Conclusions

3.4.1 Discussion

Use of GIS in forest management practices gives foresters and ecologist a tool to potentially understand remote and isolated habitat areas that would otherwise be labor intensive and difficult to access. Such tools are especially important for species such as CNFS where forest management decisions will play a crucial role in the future of species. Previous studies have indicated that through the use of digital terrain data and GIS, most physiographic regions can be modeled with some degree of accuracy (McCombs, 1997; Bolstad *et al.*, 1998; Odom and McNab, 2000; Narayanaraj *et al.*, 2010).

Our models show, based on the varying success of the models, that a perceptible relationship exists between the northern hardwood forest type and the variables we examined. Our **Elevation + LFI** model was the best model for the study area as a whole. We used the **Elevation + LFI** model to produce a predictive map of the northern hardwood forest type with a high level of confidence for the study area as whole (Figure 3.6). On our predictive map we subjectively classified areas as having a high probability (>70%), moderate probability (50-70%), and low probability (<50%) of northern hardwood presence. Using the combination of existing forestry data, land cover data from satellite imagery analysis, and our predictive map of northern hardwoods, would allow for a second step of pruning our incorrect classifications using these data. The combination of predicted northern hardwood distribution and existing land cover data will make it possible to identify and put into practice management policies that will help conserve areas such as recovery areas for CNFS.

Our best model, **Elevation + LFI**, supports the current thought that elevation plays a key role, as does the level of shelteredness of a point in determining the presence or absence of the northern hardwood forest type (McNab, 1989; Yoke and Rennie, 1996; Ulrey, 1999; McGrath and Patch, 2003; Flanigan, 2010; McNab, 2010). The significance of the quadratic effects of the elevation variable suggests that it is not a linear relationship but is also influenced by other attributes of a specific site such as LFI. Previous studies have also indicated the role of an elevational gradient in combination with other site factors on stand development in the southern Appalachians (Cain, 1931; Braun, 1950; McNab, 1991; Ulrey, 1999; Simon *et al.*, 2005).

Our results also show that there was significant overlap in the values of several of the terrain variables we examined between the northern hardwood forest type and the combined forest type of red spruce-Fraser fir, high elevation northern red oak, and montane pine community. The overlap in elevation values can be partly explained by the combining of the northern red oak forest type and the spruce-fir forest type into the northern hardwood absence response. This is because the northern hardwood forest type has a higher mean elevation than the northern red oak forest type, but lower than the red spruce-Fraser fir forest type. Additionally, the overlap in the other terrain variables is likely due to the wide variation in terrain occupied by all the forest types examined. It also supports our hypothesis, and that of others that as elevation increases, aspect plays a smaller role in determination of forest type (Daniels *et al.*, 1999). Although the best approximating models varied by region, the resulting maps appear to follow the trend of northern hardwoods occupying more sheltered areas below ridgelines and away from exposed shoulder areas based on field observations (Ulrey, 1999; Simon *et al.*, 2005). The model's accuracy was congruent with accuracy rates for other vegetation models in the study area, which range from less than 50% (Bolstad *et al.*, 1998) to 86% (Odom and McNab, 2000). Inclusion of additional variables such as a soil related variable or factoring in disturbance history would have likely increased our model's accuracy.

The variance in significance among predictors between the models on the overall study area also shows the complexity of the effects of latitude, terrain, site quality, and disturbance patterns on stand composition. Terrain, site quality, and disturbance patterns are directly related to stand development in the southern Appalachians. Logging operations that gradually moved from selective cutting of large trees to harvesting of almost all trees with the invention of the portable sawmill (Frothingham, 1931) and other disturbances such as farming and livestock raising lead to burning and clearing of large areas of forest in the southern Appalachians (Odom and McNab, 2000; Vandermast, 2005). These disturbances lead to soil nutrient leaching, fires, and erosion events on steeper slopes that degraded site quality and which has typically allowed species such as oak to capture a site (Cain, 1931; Oliver and Larson, 1996). In much of the southern Appalachians these disturbance events led to stand replacement or conversion events. One example would be red spruce-Fraser fir forests where northern hardwood species are common understory components but a disturbance event, such as harvesting and burning, would allow northern hardwoods to capture the site. Major disturbance events would give a competitive advantage to the fast growing northern hardwood species over the slower growing conifer trees on mesic slopes but conversely might favor oak species on more xeric or exposed slopes (Harmon *et al.*, 1984; Oliver and Larson, 1996; Taverna *et al.*, 2005).

The acreage of the northern hardwood forest type in the southern Appalachians is likely to increase as this forest type begins to reclaim areas previously occupied by oak communities along with predicted declines in the areas occupied by red spruce and Fraser fir due to climate change. Further studies have also shown that climate change and atmospheric deposition continue to threaten the red spruce-Fraser fir forests of the southern Appalachians likely resulting in the northern hardwood forests encroaching further into areas they once occupied (Bruck and Robarge, 1988; Nowacki and Wendt, 2009; Rentch *et al.*, 2010). Fire suppression that began in the 1940's and lasted through 1980's allowed for conditions to favor mesophytic species commonly associated with the northern hardwood forest type such as American beech, birch, and maple (Fowler and Konopik, 2007; Nowacki and Abrams, 2008). The high elevation northern red oak forests that were previously supported by fire regimes are now primarily regenerating on the more xeric or exposed mid-elevation slopes thereby allowing for expansion of the northern hardwoods overall (Fowler and Konopik, 2007). Our findings show that the expansion of the northern hardwood forest may indicate a larger amount of suitable habitat for the CNFS than previously thought.

3.4.2 Conclusion

How the expansion of the northern hardwood areas and decline of other forest types impacts species such as CNFS and southern flying squirrels is not yet known. Previous research has indicated that presence and distribution of mycorrhizal fungi that makes up a large portion of CNFS diet may have more of an impact over the species distribution than the presence of northern hardwoods. By using our predictive maps in combination with additional variables such as proximity to red spruce- Fraser fir where southern flying squirrels have less of a competitive advantage may better delineate areas for conservation. However the expansion of the northern hardwoods with American beech expansion into the red spruce-Fraser fir forests may also prove beneficial to the hard mast dependent *G. volans* as oak species will remain a fixture in these areas (Odom *et al.*, 2001; Ford *et al.*, 2004; Menzel *et al.*, 2004; Ford, 2012), further showing the importance of using such models to manage and make the necessary policy decisions in regards to development of a more specific habitat map for CNFS. Additionally, maps produced using these models could be used in combination with existing data to prioritize for spruce restoration, and reintroduction of fire to appropriate areas in the southern Appalachians.

The use of these models could have significant implications in management practices when used in combination with known areas of red spruce and Fraser fir. A more specific habitat management and conservation plan could be developed for CNFS with available resources channeled to a more focused area. It also increases the likelihood that this species may occupy a larger portion of the landscape than previously suspected and raises the possibility of the existence of a larger population of this species and that recovery efforts may be more successful than previously thought. However with the current threats to the high elevation ecosystems it will be crucial to continue to gather on site data for much of this area. Further analysis and inclusion of additional variables would be needed to increase the predictive power of the models examined due to the influence of the variability of points occupied by the northern hardwood forest type.

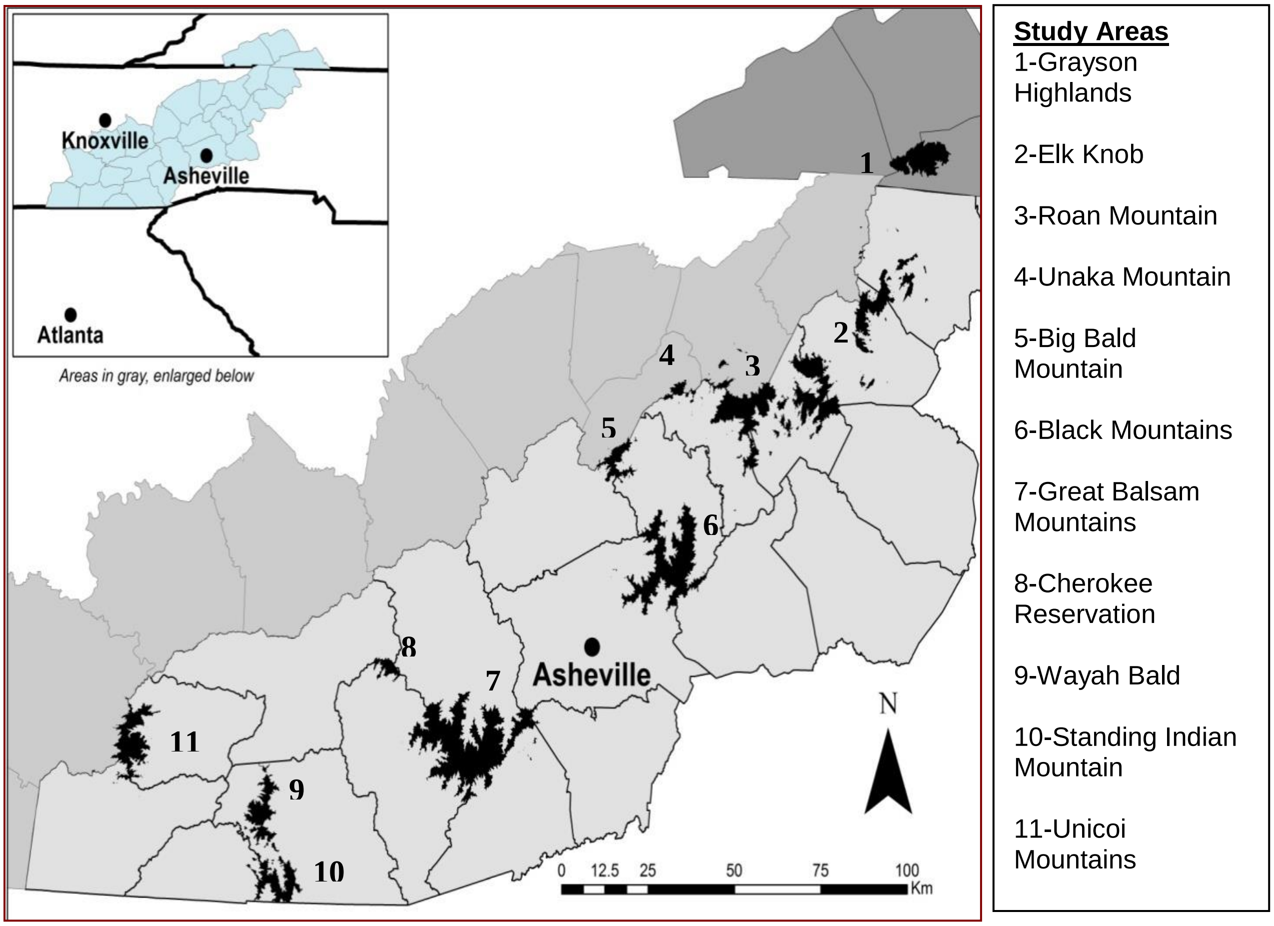

Figure 3.1. Map of counties of Western North Carolina, eastern Tennessee, and southwestern Virginia showing mountain areas that composed the study area that were sampled between June 2012 and January 2013. All of these ranges are believed to have populations of CNFS with the exception of the Wayah Bald (9) and Standing Indian Mountain (10).

Figure 3.2: Examples of three basic forest types of the southern Appalachians found in the study areas that were sampled between June 2012 and January 2013. From Left: red spruce-Fraser fir, Center: high elevation northern red oak, Right: northern hardwood.

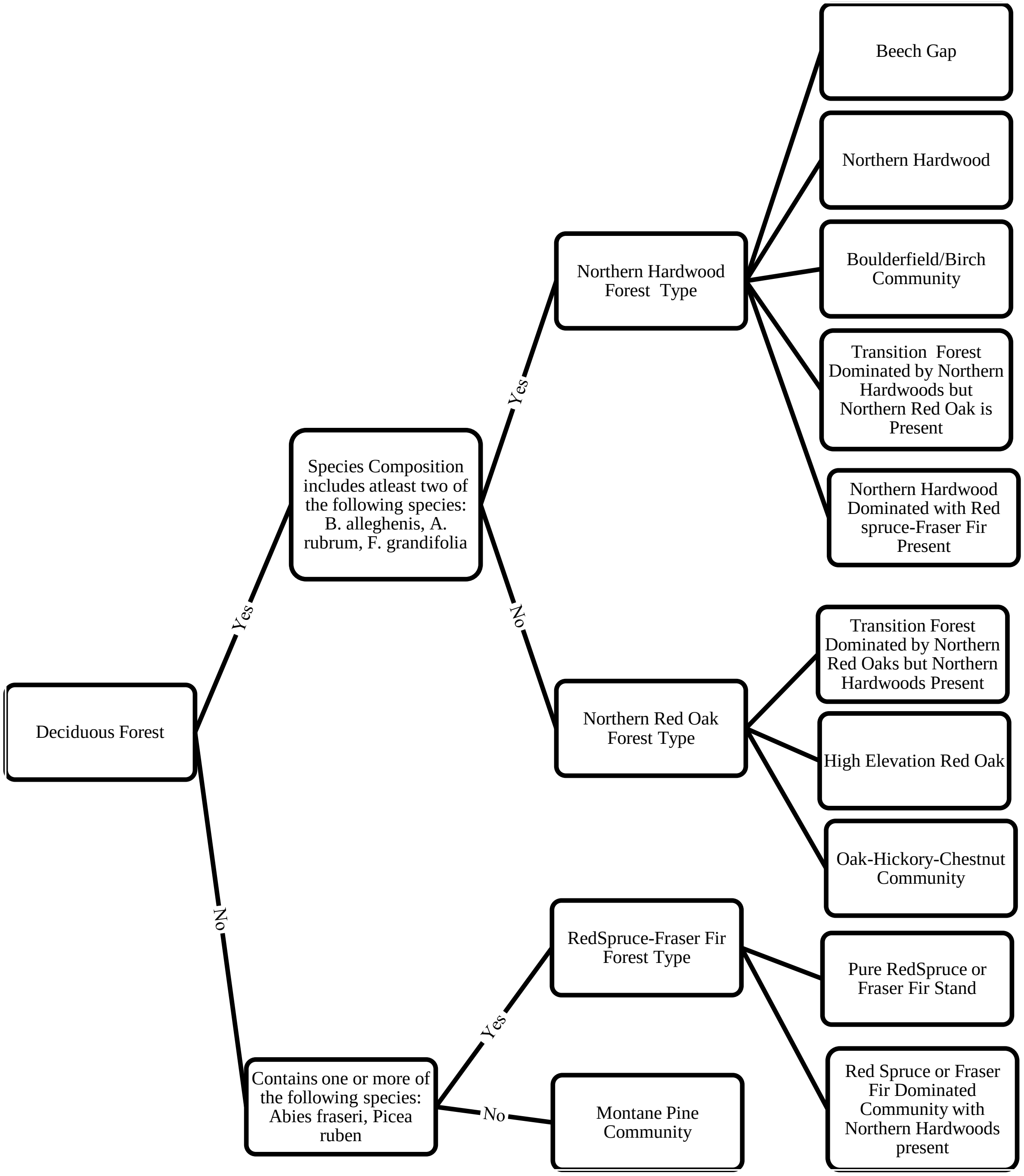

Figure 3.3. Decision Tree used to classify forest types observed in the study area. Species composition for each forest type was based on existing literature on vegetation communities occurring in the study area that were sampled between June 2012 and January 2013.

	N	Elevation (m)	Aspect[A]	Slope[B]	Curvature[C]	LFI[D]
Northern Region						
Grayson Highlands, VA	23	1394.48 - 1726.72	60.91 - 353.23	6.03 - 55.32	-1.55 - 0.53	-16.49 - 121.10
Roan Mountain, NC/TN	42	1255.30 - 1904.50	0.24 - 345.10	10.61 - 69.81	-1.88 - 2.63	-105.18 - 177.00
Elk Knob, NC	12	1373.13 - 16.38.66	17.30 - 34.76	3.00 - 50.27	-1.67 - 2.40	30.85 - 198.73
Unaka Mountain, NC/TN	9	1284.52 - 1506.87	151.42 - 325.98	12.10 - 57.81	-0.34 - 1.50	6.84 - 96.94
Big Bald Mountain, NC/TN	12	1580.59 - 1630.12	100.48 - 317.95	25.09 - 54.67	-0.71 - 0.85	86.49 - 114.36
Central Region						
Black Mountains, NC	54	1404.77 - 1833.97	22.82 - 354.34	7.24 - 79.84	-2.33 - 7.84	14.82 - 216.24
Great Balsam Mountains, NC	90	1318.94 - 1907.04	1.99 - 358.50	9.93 - 76.81	-2.87 - 4.6	-67.23 - 149.70
Southern Region						
Unicoi Mountains, NC/TN	30	1228.76 - 1676.32	6.31 - 344.24	9.89 - 103.83	-6.54 - 10.74	-57.79 - 125.01
Standing Indian, NC	15	1221.30 - 1513.17	18.31 - 352.07	0.00 - 57.47	-3.19 - 3.06	-79.31 - 66.37
Wayah Bald, NC	15	1376.98 - 1584.64	15.63 - 355.88	9.67 - 50.66	-2.39 - 3.51	47.63 - 136.80
Cherokee Reservation, NC	36	1330.69 - 1640.04	7.38 - 352.44	13.31 - 60.72	-11.49 - 8.06	-42.39 - 166.32
Overall	338	1221.30 - 1907.04	0.24 - 358.50	0.00 - 103.83	-11.49 -10.74	-105.18 -216.24

Table 3.1: Continuous terrain variables for the study area characterized by region and individual study sites that were sampled between June 2012 and January 2013.

[A] Aspect was recorded in degrees azimuth

[B] Slope was recorded in percent change

[C] Curvature describes the concavity or convexity of a site based on a 30m x 30m window with concave sites having negative values and convex sites having positive values

[D] LFI provides an index of concavity or convexity of a given pixel in regard to the surrounding landscape using a 1000m radius circle

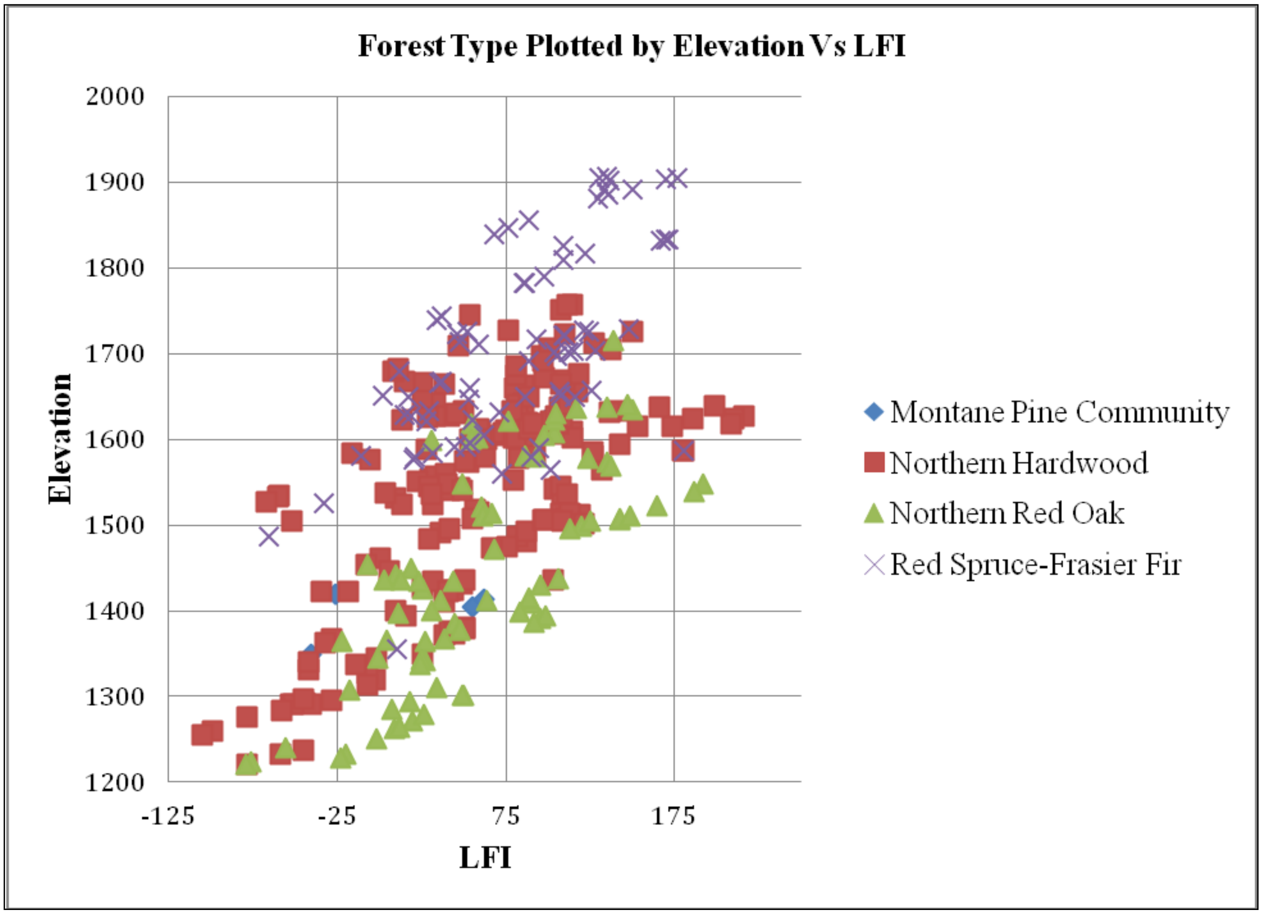

Figure 3.4. Forest types sampled plotted by Elevation on the Y-axis and LFI on the X-axis. Each point represents an individual sample point that was sampled between June 2012 and January 2013. This graph shows slight gradient occurring between forest types, with spruce and Fraser fir occupying the highest elevations, and Northern Red Oak and Northern Hardwoods occupying the lower elevations.

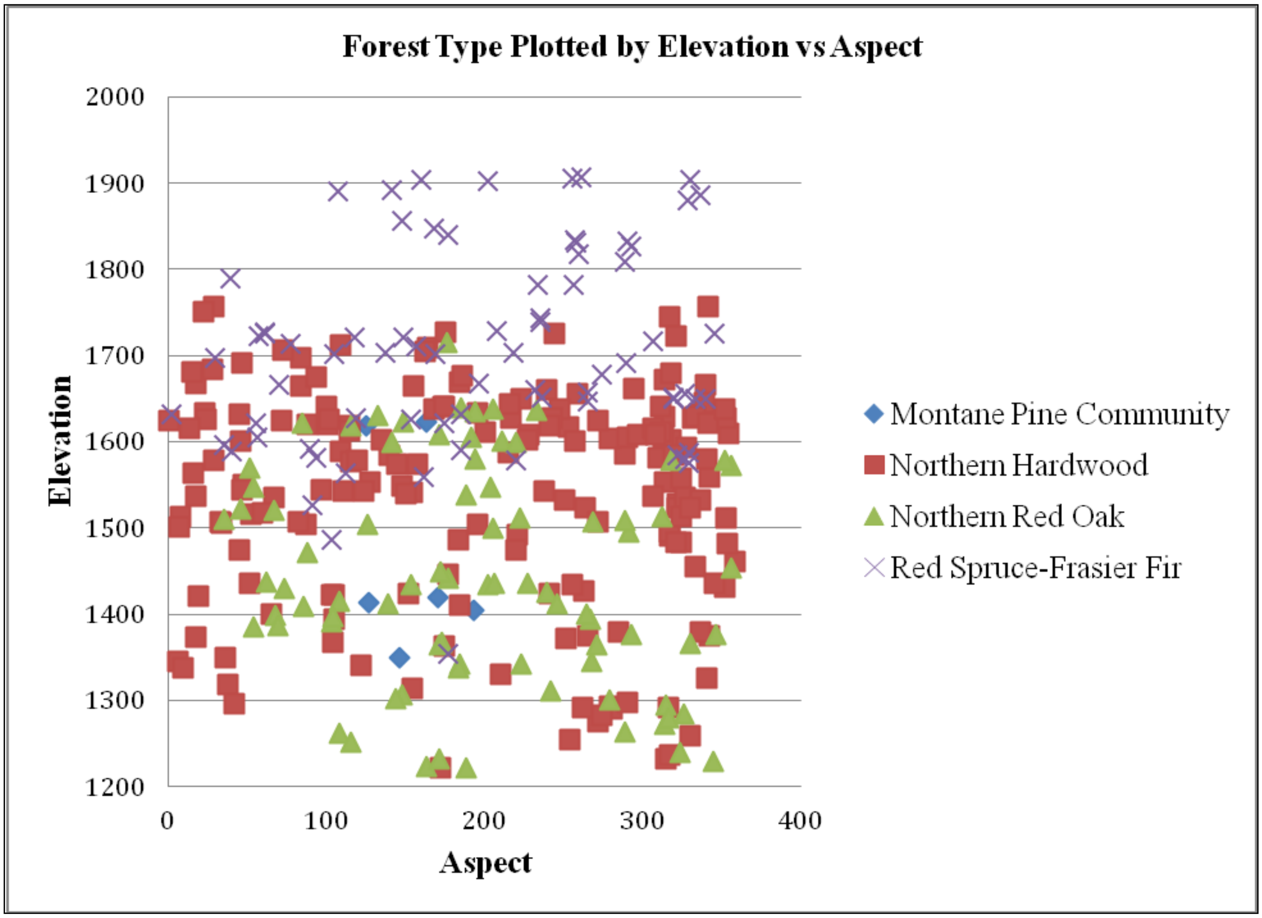

Figure 3.5. Forest types sampled plotted by Elevation on the Y-axis and Aspect on the X-axis. Each point represents an individual sample point that was sampled between June 2012 and January 2013. This graph shows the overlap occurring between forest types in the study area in regards to aspect.

Descriptive Statistics

	Northern Hardwood Forest Type Present Sample Points		Northern Hardwood Forest Type Absent^A Sample Points		Digital Elevation Model of Study Area	
Variable	Mean ± SD	Range	Mean ± SD	Range	Mean ± SD	Range
Elevation (m)	1538.09 ± 125.26	1221-1756.54	1564.33 ± 177.34	1221.3 - 1907.04	1393.07 ± 141.99	1214.20-2036.70
Aspect (°)	198.08 ± 63.80	0.24 - 358.50	194.93 ± 91.35	1.98 - 355.88	183.69 ± 102.44	-1- 359.99
Slope (%)	35.50 ± 14.82	0.00 - 79.84	35.18 ± 14.92	0.00 - 103.828	43.54 ± 18.45	0 – 300.86
Curvature	0.25 ± 1.81	-8.17 - 8.06	0.60 ± 2.05	-11.49 - 10.74	0.004 ± 1.88	-75.08 – 53.29
LFI	59.02 ± 63.80	-105.18 - 216.24	68.54 ± 56.26	-79.31 - 186.87	-5.47 ± 65.00	-239.42 – 278.58

[A] *Conifer, Northern Red Oak, and Montane Pine Forest Types were combined for the regression model*

Table 3.2. Descriptive Statistics for those sites where northern hardwood was observed present versus those sites as northern hardwood absent in addition to the entire study area. The table shows the wide range of terrain of those sites where northern hardwood was found present as well as those sites where it was absent that were sampled between June 2012 and January 2013.

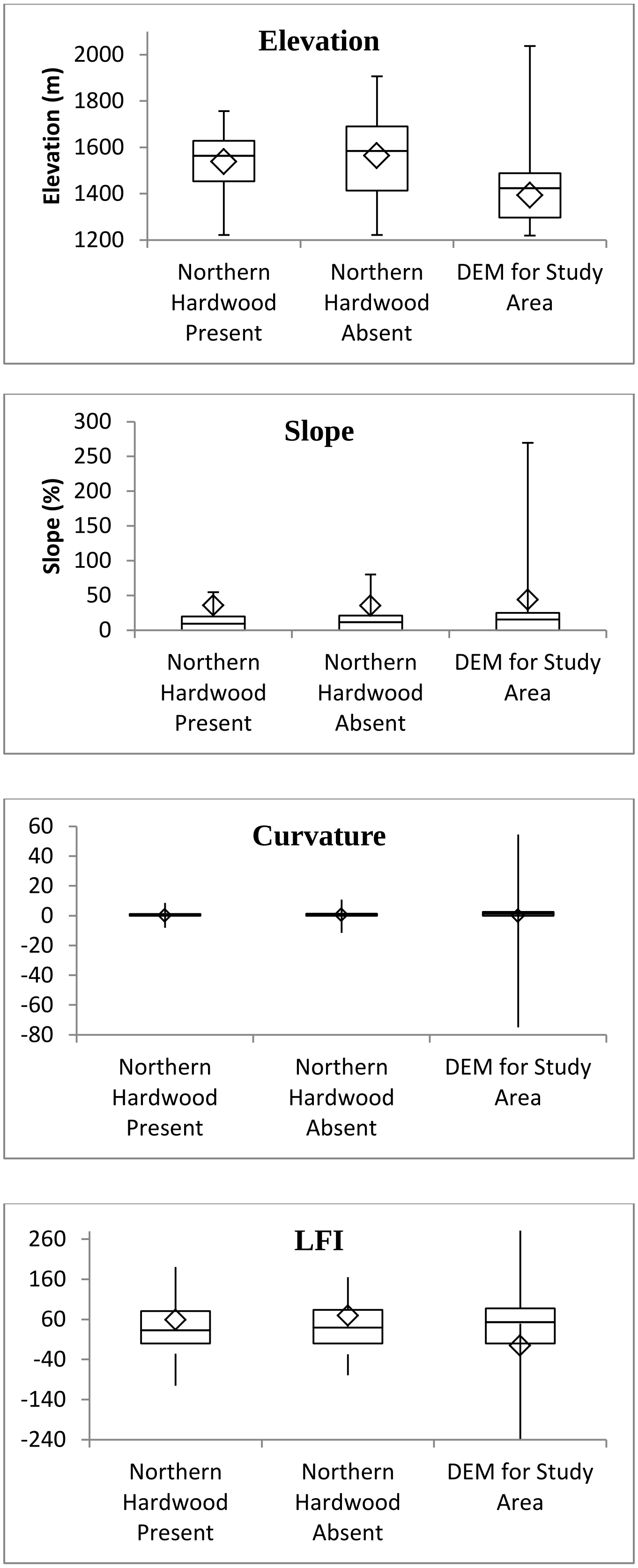

Figure 3.6 Box plots of terrain variable distributions for northern hardwood present sites versus northern hardwood absence sites that were absent that were sampled between June 2012 and January 2013. This shows the amount of overlap between sites with northern hardwood present versus those where northern hardwood was absent, plus the wide range of terrain that occurred in our study area as derived from DEMs.

Study Area Model Rankings based on AIC$_c$

Model	K[A]	AIC$_c$	ΔAIC$_c$[B]	R^2	SEN[C*]	SPEC[D*]	IPNH Presence[E*]	IPNH Absence[F*]	PCC[G*]
Elevation + LFI	8	418.99	0.00	0.15	78.20	52.20	47.79	21.78	65.98
Elevation + Aspect	8	430.13	11.14	0.13	67.59	63.52	36.48	32.40	66.68
Elevation+ Slope + Aspect	10	439.27	20.28	0.15	71.50	64.77	35.22	28.49	69.46
Elevation	6	440.88	21.89	0.08	75.98	40.88	59.12	24.02	59.47
Elevation + Curvature	8	442.23	23.24	0.10	75.98	45.91	54.09	24.02	61.83
Slope + LFI	6	468.05	49.06	0.04	49.72	63.52	36.48	50.27	56.21
Global	15	477.89	58.90	0.36	81.56	73.58	26.42	18.44	77.81

Table 3.3. Logistic regression models explaining the influence of terrain variables on the presence or absence of Northern Hardwoods in the study area (n=338) that was sampled between June 2012 and January 2013. Model rankings were based on Akaike's Information Criterion corrected for small sample size (AICc)

[A] Number of parameters + 1 in approximating model

[B] Difference between current model and best approximating model (minimum AIC$_c$)

[C] SEN is percent of correctly predicted NH presence at sites observed to be NH at 70% probability

[D] SPEC is percent of correctly predicted NH absences at sites observed to be other at 70% probability

[E] IPNH Presence is percent of incorrectly predicted NH presence at sites observed to be other at 70% probability

[F] IPNH Absence is percent of incorrectly predicted NH absence at sites observed to be NH at 70% probability

[G] Overall percent correctly classified

[*] Measures completed using jackknife procedure

Best approximating logistic model (**Elevation + LFI**) for predicting presence or absence of the northern hardwood forest type (N = 338)

Parameter	Estimate	Std. Error	ChiSquare	P>ChiSquare
Intercept	-1.36238	15.14307	0.01	0.9283
Northing	2.03644e-7	3.8683e-6	0.00	0.9580
Elevation	-0.00013	0.00119	0.01	0.9094
LFI	0.00426	0.00280	2.31	0.1286
(Elevation-1550.4)*(Elevation-1555.4)	6.02964e-5	1.0819e-5	31.06	<0.0001**
(Elevation-1550.4)*(LFI-64.4693)	-0.00012	0.00003	13.50	0.0002*
(Northing-3948504)* (Northing-3948504)	-1.444e-10	6.313e-11	5.23	0.0222*

*indicates significance at 0.05 level

**indicates significance at 0.001 level

Table 3.4. The best approximating logistic model (**Elevation + LFI**) explaining presence or absence of Northern Hardwoods in the study area (n=338).

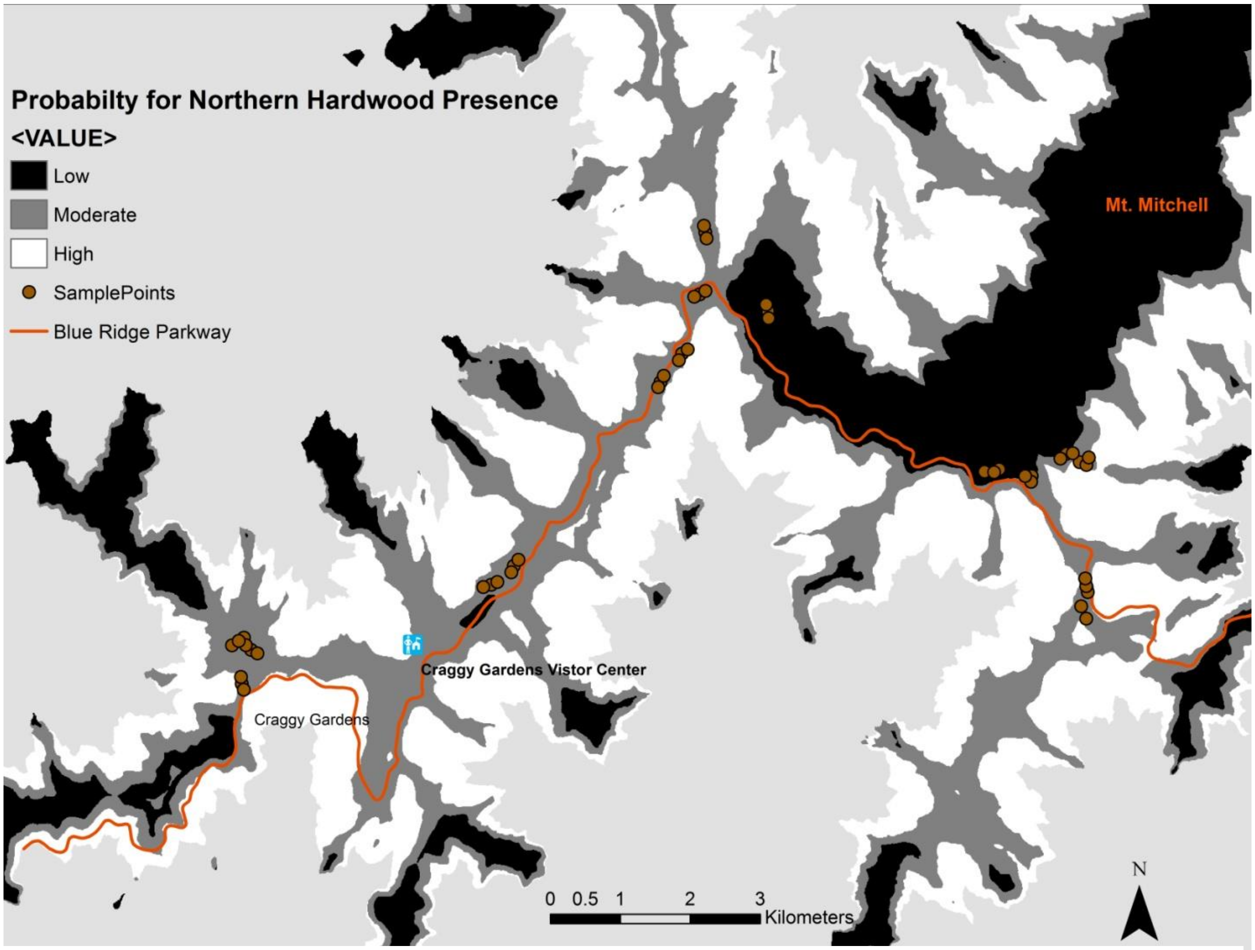

Figure 3.7 Predictive Map for the Black Mountains created using the **Elevation + LFI** model showing probabilities of northern hardwood forest presence, the Blue Ridge Parkway, and sampling points in the area that was sampled between June 2012 and January 2013. The Blue Ridge Parkway National Park's Craggy Gardens visitor center, Craggy Gardens mountain, and Mount Mitchell are shown for reference points.

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Chapter 4

Comparing Digital Terrain Variables to Field Measured Terrain Variables

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Abstract:

The resolution of digital terrain data has improved with new technology in recent years. When digital terrain data are used in spatial prediction, resolution can greatly affect the accuracy of predictive models. This study focused on augmenting existing research on Digital Elevation Models (DEM), which has become progressively more important for forest researchers, ecologists, and policy makers. We used data from 240 field sampling points in the mountains of western North Carolina and digital terrain data extracted from digital elevation models (DEM) with resolutions of 10 meters and of 30 centimeters to perform a comparative analysis of accuracies between field measured and DEM-derived terrain attributes. We compared three terrain variables widely used in terrain based ecological modeling and forestry applications: elevation, aspect, and slope. We used a paired t-test to examine individual measurements between the three data sets. Our results showed significant differences between field measurements and DEM derived measurements in elevation and slope both resolutions of DEM we used.

4.1.1 Introduction

Over the past two decades, use of Geographic Information Systems (GIS) has significantly changed the development of landscape-level predictive ecological modeling and other forestry related applications (Franklin, 1995). Moreover, linkages to newer and more advanced statistical analysis programs has allowed for extensive data mining and spatial trend analysis in the context of spatial modeling (Miller *et al.*, 2007). Spatially, the accuracy of ecological models largely depends on the vertical precision and cell resolution of the digital elevation models (DEM) used to produce the terrain datasets (Thompson *et al.*, 2001). Using indirect gradients such as those obtained from terrain variables for the creation of predictive ecological models is effective because of the positive correlation that usually occurs along both vegetation and animal species' spatial distributions on the landscape (Guisan and Zimmermann, 2000).

DEM-derived topographic variables are ideal for predictive modeling of vegetation and habitat because many environmental gradients are associated with topography, especially in mountainous areas (Odom and McNab, 2000). Topographic variables derived from DEMs can often be generated with minimal loss in precision of the topographic measurements through the use of GIS at regional scales (Horsch, 2003; Petersen and Stringham, 2008; Wang *et al.*, 2011). Thus, this type of predictive modeling has aided in identification of areas that can be incorporated into a managed forest or reserve system for conservation of a species of concern (Rotenberry *et al.*, 2006). There have been several studies that have quantified the relationship between vegetation and topographic variables in the southern Appalachians (McNab, 1991; McCombs, 1997; Boerner, 2006; McNab, 2010). The relationship between terrain and vegetation in the southern Appalachians is unique due to the diversity of vegetation communities and the wide variety of topographical conditions that occur there (Ulrey, 1999; Simon *et al.*, 2005). Such studies frequently integrate field vegetation data with readily available digital data, and use a GIS program to examine correlations between vegetation communities and land cover types (McGrath and Patch, 2003; Taverna *et al.*, 2005; Hall, 2008) through the analysis of contingency tables for model development of specific vegetation types (Horsch, 2003). Terrain variables that are derived from a DEM typically have moderate to high correlation with vegetation composition to the level that the spatial pattern of montane forest types can be explained and simulated to a large extent through the use of terrain variables alone (Bolstad *et al.*, 1998; Narayanaraj *et al.*, 2010).

DEM rasters of varying resolutions are widely available. They typically range in resolution from sub-meter LiDAR (Light Detection and Ranging) rasters with cell sizes of 30 centimeters x 30 centimeters to upwards of 30 x 30 meter cell sizes. With a wide array of data resolutions available in the public domain today it becomes up to the researcher to determine the appropriate resolution for their research goals. However, the choice of resolution should be carefully considered since resolution of data has been found to influence prediction accuracies (Bolstad *et al.*, 1998; Wang *et al.*, 2011).

Higher resolution data (≤ 30 meter cell size) is often used in forestry and ecological applications since courser resolution data may smooth or under estimate variation in terrain (Bolstad *et al.*, 1998; Flanigan, 2010; Irfan *et al.*, 2012). For example, Bolstad et al. (1998) and other studies have also found that higher resolution data resulted in higher accuracy in the predictive forest modeling using DEM derived terrain variables. Shoutis et al. (2010) found that 5m and 10m resolutions worked well for characterizing riparian vegetation in bottom areas of valleys where coarser resolutions smoothed out micro-topography that influences riparian vegetation, but noted that these resolutions can cause error when calculating hydrological variables. However, more research on the role of data resolution on prediction accuracies is needed (Bolstad *et al.*, 1998; Thompson *et al.,* 2001; Horsch, 2003).

Modeling the vegetation of the southern Appalachians has been extensively studied due to the strong relationship between topography and vegetation communities in this region (see (McNab, 1996; Bolstad *et al.*, 1998; Abella *et al.*, 2003; Copenheaver *et al.*, 2006; Nowacki and Wendt, 2009). The objective of this case study was to compare the values of field measured terrain variables to DEM derived variables from two resolutions (10m and 30cm) representative of northern hardwood forest in western North Carolina. Our case study was part of a larger project on modeling the distribution of northern hardwood forest in western North Carolina that are designated recovery areas for the endangered Carolina northern flying squirrel (CNFS) (U. S. Fish and Wildlife Service, 1990), and the datasets used here were obtained as part of this larger project. By examining three commonly used terrain variables (elevation, aspect, and slope), we hope to determine whether one resolution of DEM might better quantify a sample point's terrain attributes than another.

4.2 Methods

4.2.1 Study Areas and Field Data Collection

During the summer of 2012 and January of 2013, we sampled vegetation and terrain characteristics at 240 points which made up 80 3-point belt transects across 11 study areas in western North Carolina (Figure 4.1). The sample points fell within the Blue Ridge Parkway National Park (BRPNP), Pisgah, Nantahala or Cherokee National Forest, or on lands owned by the Eastern Band of Cherokee Indians. Terrain in the study area is characterized by steep slopes ranging from flat to near vertical and elevations that ranged from 1200m to over 2000m. These areas receive on average 114cm of precipitation annually at lower elevations to more than 200cm on the higher peaks, distributed relatively evenly throughout the year (occurring as snow and ice during the winter months and rain in the summer months). Temperatures are widely variable throughout the year due to the effects of elevation and aspect and average approximately 2.2°C in January and average approximately 23°C (Shanks, 1954; McNab, 1996; Simon *et al.*, 2005). Typically the first frost occurs in early October, and the last frost in early May, with 130 frost free days on average (National Climatic Data, 2012). Soils in the study area tend to fall in frigid temperature regime and be acidic with deep organic layers and can vary from boulder-fields to mineral soils of considerable depth (Cain, 1931; Daniels *et al.*, 1999; Loeb *et al.*, 2000).

We used ESRI's ArcMap (2011) to randomly select sampling points in clipped USGS DEMs (Evans, 2012) using a method similar to the approach of Odom and McNab (Odom and McNab, 2000) to validate DEM based models. The DEMs had been previously clipped to 1219m and above to encompass all areas that made up CNFS recovery areas. These randomly selected sample points would serve as center points on 200m belt transects that were parallel to the topography with sampling points placed at 0, 100, and 200 meters. We generated sample points that were within 1000m of the Blue Ridge Parkway itself, U.S. Forest Service USFS roads or public trails in order to facilitate access to the sample points. We initially generated an excess of points to allow for the elimination of points in the field which occurred in areas where we were prohibited from sampling by the National Park Service(NPS) or U.S. Forest Service (USFS) (McNab and Odom, 2012; Young, 2012) or could not be safely accessed.

The number of points per study area was proportional based on total area above 1200m and ranged between 0.2% for the larger mountains to 3% on the smaller mountains of area above 1200m in the study region. Sampling points in the 10 study areas were above elevation > 1219m covered all aspects and a variety of slopes. The elevation criteria was based on the lowest recorded elevation of CNFS capture in the study area (U. S. Fish and Wildlife Service, 1990) and also represents the transition from mid elevation forest types to high elevation forest types (McNab and Odom, 2012).

We used a handheld Trimble GeoXT© GPS unit to navigate to the study points that were generated from the DEMs. At each sampling point, we tallied the total number of stems for each tree species using a basal area prism with a factor of 10, to identify dominant species and generalize stand composition. The basal factor of 10 eliminated smaller stems from the tally to avoid understory and sub-canopy species from misclassification following the USFS timber management field book guidelines (2008). We characterized each study point as ridgeline, shoulder, or cove, and assigned a slope position (low, medium, or high) to described each a point's location and topography in relation to the surrounding landscape landform type (McNab, 1993). Elevation, slope, and aspect measurements were collected at each study point in the field using the GPS, compass, and clinometers following methods similar to those used by McNab et al. (1999) for comparison of those derived from the DEMs. Elevation was measured using Trimble GeoXT© GPS unit based on a minimum of 6 satellites to triangulate our position, and held at approximately waist level (~1m). Slope was measured using USFS timber management field book guidelines (2008) in which an observer measures slope percentage in the steepest downhill direction to the edge of a sampling plot. Aspect was measured in degrees azimuth in the steepest downhill direction.

4.2.2 Deriving Terrain Variables

We downloaded USGS-produced 1/3 arc-second (10 m) DEMs (USGS National Elevation Dataset, NED)(Evans, 2012), and North Carolina flood plain mapping project produced bare earth LiDAR DEMs for each study area. From each DEM we derived elevation, slope, and aspect. Slope and aspect were derived using DEM Surface Tools add-on to ArcMap Jenness (2012). We calculated slope and aspect using the 4-cell method in DEM Surface Tools---a method that calculates the slope and aspect based on the cells immediately to the north, south, east, and west of the central cell (Ritter, 1987; Jones, 1998; Jenness, 2012). Once these values were calculated for the study area, we overlaid a vector point file of actual sample point locations and we extracted the three terrain variable values for each sample point. We then exported this digital data as a spreadsheet for statistical analysis.

4.2.3 Statistical Analysis

We exported the spreadsheet containing the field measured data, the 10m DEM derived data, and the 30cm LiDAR DEM derived data to SAS Institute's JMP 10 Pro statistical software (2012). First we tested the data for normality and then used the matched pair platform for analysis. The matched pair analysis performs a direct comparison between each point between two data sets using a Tukey mean-difference plot and a paired t-test (Sall *et al.*, 2007). The Tukey mean-difference graph plots the difference of the two different data sets on the y-axis against the mean of the two responses on the x-axis. The paired t-test tests the hypothesis that the mean difference between the pairs of data is equal to zero, and that the data follows a normal distribution (Sheskin, 2011). The t-test calculates the difference between each pair of data, in our study there are three such pairs: Field vs. 10m, Field vs. LiDAR, and 10m vs. LiDAR. The standard error and the mean of the differences between each data set are then calculated and used to generate a test statistic, which indicates whether there is a significant difference between data sets (Townend, 2002).

4.3 Results

Descriptive statistics of the three data sets show statistically significant ($p < 0.001$) differences between the pairs of means of each dataset (Table 4.1). Additionally, the values from each of the datasets for all three variables are normally distributed, with the exception of a small number of outliers that occurred in each of the datasets slope measurements (Figure 4.2) Our results indicated that field measured elevation values and 10m DEM elevation values were significantly different (M (mean difference) = 7.336, SE (standard error) = 1.03333), t (239) = 7.099668, $p < |t| = 0.001$ (Figure 4.3). Our results also showed there was a significant difference between the field measured elevation values and LiDAR 30cm DEM elevation values

(M = 7.36442, SE = 0.74001), t (239) = 9.951809, $p < |t| = 0.001$ (Figure 4.3). Additionally, our results show that slope values were significantly different between the field measured values and the LiDAR 30cm DEM values (M = 5.5584, SE = 0.64854), t (239) = 8.570576, $p < |t| = 0.001$ (Figure 4.5). The difference between our field measured slope values and the 10m DEM slope values was also significant (M = 5.44883, SE = 0.76204), t (239) = 7.150343, $p < |t| = 0.001$ (Figures 4.5). There were two different points with exceptionally large disparities in elevation values between the field measurements and DEM derived measurements. One point from the 10m DEM differed from the field measured elevation by more than 150m, and a different point from the LiDAR DEM differed from the field measurements by more than 100m. We found no significant difference between the values for field-measured and DEM-derived aspect (Figure 4.4).

4.4 Discussion

The effects of terrain on site characteristics such as soil quality, temperature, and moisture levels has been widely studied, especially in the southern Appalachian mountains (McNab, 1996; Bolstad *et al.*, 1998; Abella *et al.*, 2003; Boerner, 2006; McNab, 2010). Differences between field measured terrain variables, and those derived from both resolutions of DEM were significant for elevation and slope at our study sites. Our field measured elevation values tended to be slightly higher than those derived from both of resolutions of DEM (Figure 4.3). While our field measured slope values were on average slightly higher than the DEM derived values, there was also substantial variation in the data (Figure 4.5. Our results suggest that using DEM-derived terrain variables for vegetation modeling may not always accurately characterize a site, as measured in the field, and the use of DEM-derived topographic variables alone may not be sufficient to quantify the relationship between vegetation communities and topographic conditions. DEM-derived terrain variables in conjunction with field data has been used successfully in the past to model vegetation communities (Franklin, 1995; Ulrey, 1999; Odom and McNab, 2000) and may be a preferred method. Our results also suggest that at the resolutions we examined there was statistically little difference between the 10m DEM and the 30cm LiDAR DEM derived terrain variables. This supports previous studies that indicate that there may be a minimum resolution threshold for deriving terrain related variables (Thompson *et al.*, 2001; Shoutis *et al.*, 2010). Shi et al (2012) had similar findings when comparing 1m and 5m LiDAR DEMs to field measurements in northern Vermont and found no significant differences between the two LiDAR DEMs. Miller et al. concluded that the resolution of DEM to be used for predictive modeling should be based on the ecological scale of the response data.

There are two potential causes for the disparities between the DEM datasets and the field data, DEM based error and field based error. First, a LiDAR sensor depends on light reflectance to accurately determine surface height, so areas with little vegetation cover tend to have a higher density of reflectance points, and thus a more accurate DEM (Hall, 2008). However, in areas with substantial vegetation cover fewer points reach the surface and thus can contribute to inaccuracies in elevation measurements (Anderson *et al.*, 2006). Errors based on field measurements are commonly associated with the setting up sampling plots (Wang *et al.*, 2011) and we used a visible plot in areas where the vegetation was often dense and the terrain highly variable which could have introduced error in our field measurements of slope. Additionally, we used Trimble GeoXT© GPS to record elevation which when used under optimal conditions is highly accurate. However with the dense canopy cover and rough terrain of our study area, it is likely that some error was introduced unintentionally. It should be noted that the maximum differences in elevation measurements appear to be DEM errors since other points on the same belt transects did not show wide disparities.

Future studies spatially modeling vegetation communities using DEM derived terrain variables will only increase as the availability of geospatial data increases (Davis *et al.*, 2007; Tirpak *et al.*, 2009). As resolution and precision of DEM increases, researchers and end-users of geo-spatial data will need to consider the limitations of these data sets. This is especially true in studies where the number of terrain variables calculated using algorithms in GIS increases and collection of field data decreases (McNab, 1991).

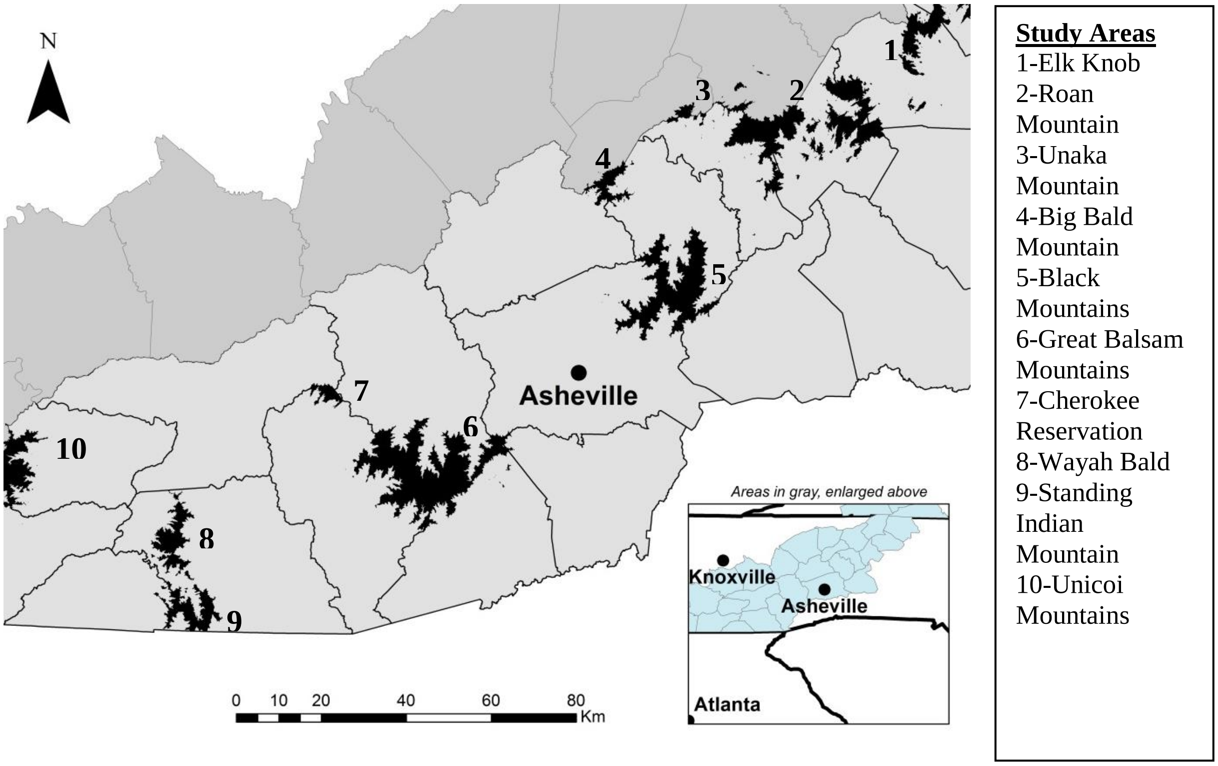


Figure 4.1. Map of counties of Western North Carolina, eastern Tennessee, and southwestern Virginia showing mountain areas that composed the study area. All of these ranges are believed to have populations of CNFS with the exception of the Wayah Bald (9) and Standing Indian Mountain (10).

Table 4.1. Descriptive statistics showing mean, standard deviation, and standard error of the mean differences for elevation, aspect, and slope values from field measurements that were collected between June 2012 and January 2013 and measurements derived from two resolutions of DEM (10m and 30cm LiDAR) for the study area in western North Carolina. *Indicates significance at < 0.001 level

Descriptive Statistics Terrain Attributes

Data Set	df	Mean Diff.	Std. Error	t-statistic	Prob > |t|
Elevation (m)					
Field Measured - 10m	239	7.33608	1.0333	7.099668	< 0.0001*
Field Measured - LiDAR	239	7.36442	0.7400	9.951809	< 0.0001*
LiDAR - 10m	239	-0.0283	0.7039	-0.04025	0.9679
Aspect (azimuth degrees)					
Field Measured - 10m	239	-5.4286	4.8011	-1.13069	0.2593
Field Measured - LiDAR	239	-3.3912	4.6504	-0.72922	0.4666
LiDAR - 10m	239	-2.0374	2.431	-0.8381	0.4028
Slope (percent)					
Field Measured - 10m	239	5.44883	0.76204	7.15034	< 0.0001*
Field Measured - LiDAR	239	5.5584	0.64854	8.57057	< 0.0001*
LiDAR - 10m	239	-0.1096	0.50443	-0.21722	0.8282

Figure 4.2. Difference plots of three measurements of elevation compared for western North Carolina that was sampled between June 2012 and January 2013. Top left, difference plot of field measured elevation and 10m DEM derived elevation measurements. Top right, difference plot of field measured elevation and 30cm LiDAR derived elevation measurements. Bottom, difference plot of 10m DEM derived elevation and 30cm LiDAR derived elevation measurements.

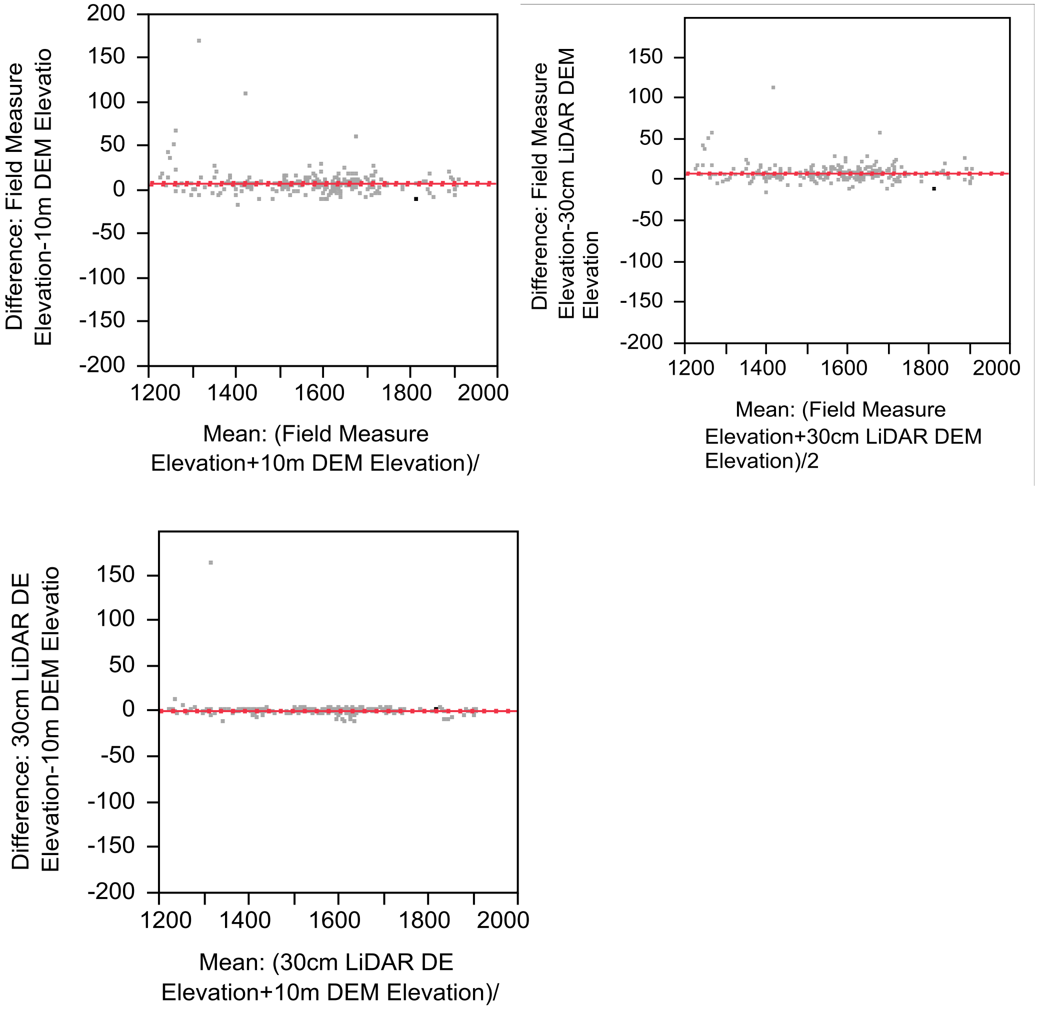


Figure 4.3. Difference plots of three measurements of aspect compared for western North Carolina that was sampled between June 2012 and January 2013. Starting at top left, comparison between field measured aspect and 10m DEM derived aspect. Top right, difference plot of field measured aspect and 30cm LiDAR DEM derived aspect measurements. Bottom, difference plot of 10m DEM derived aspect and 30cm LiDAR derived aspect.

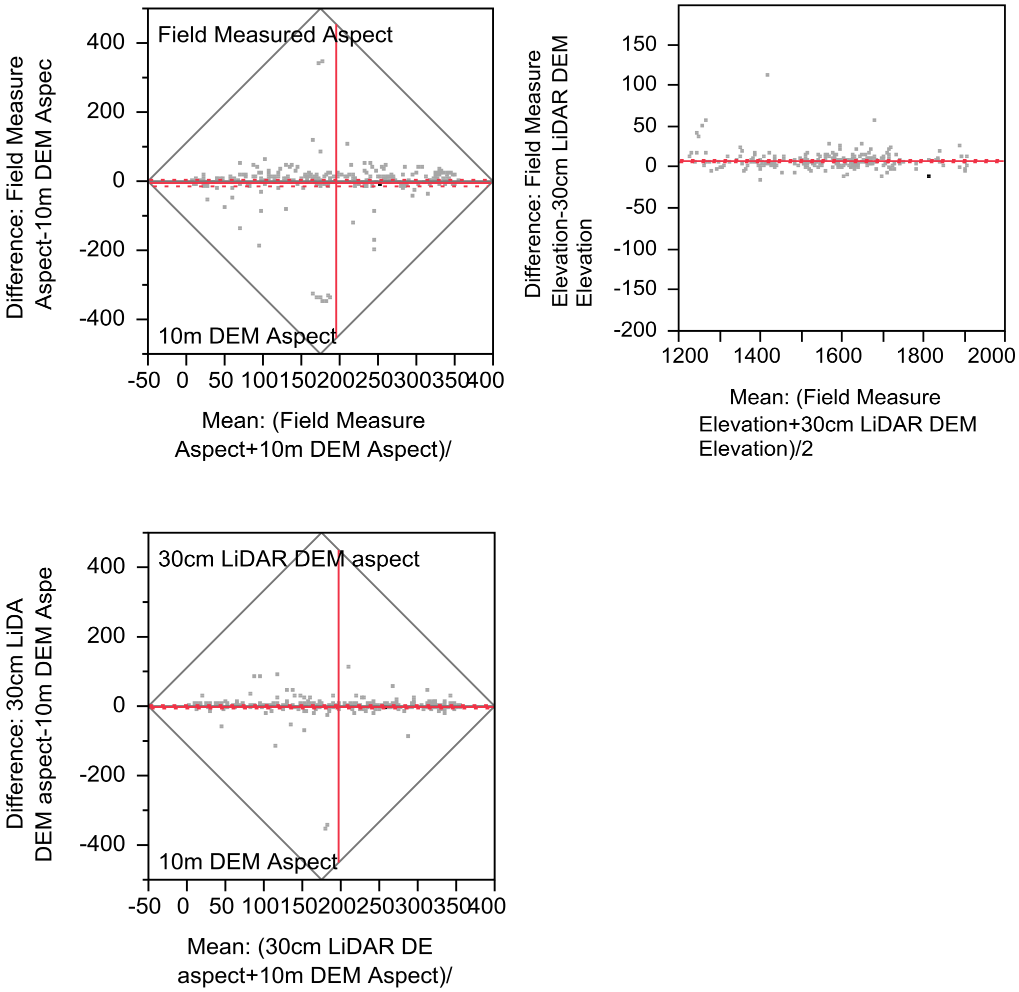
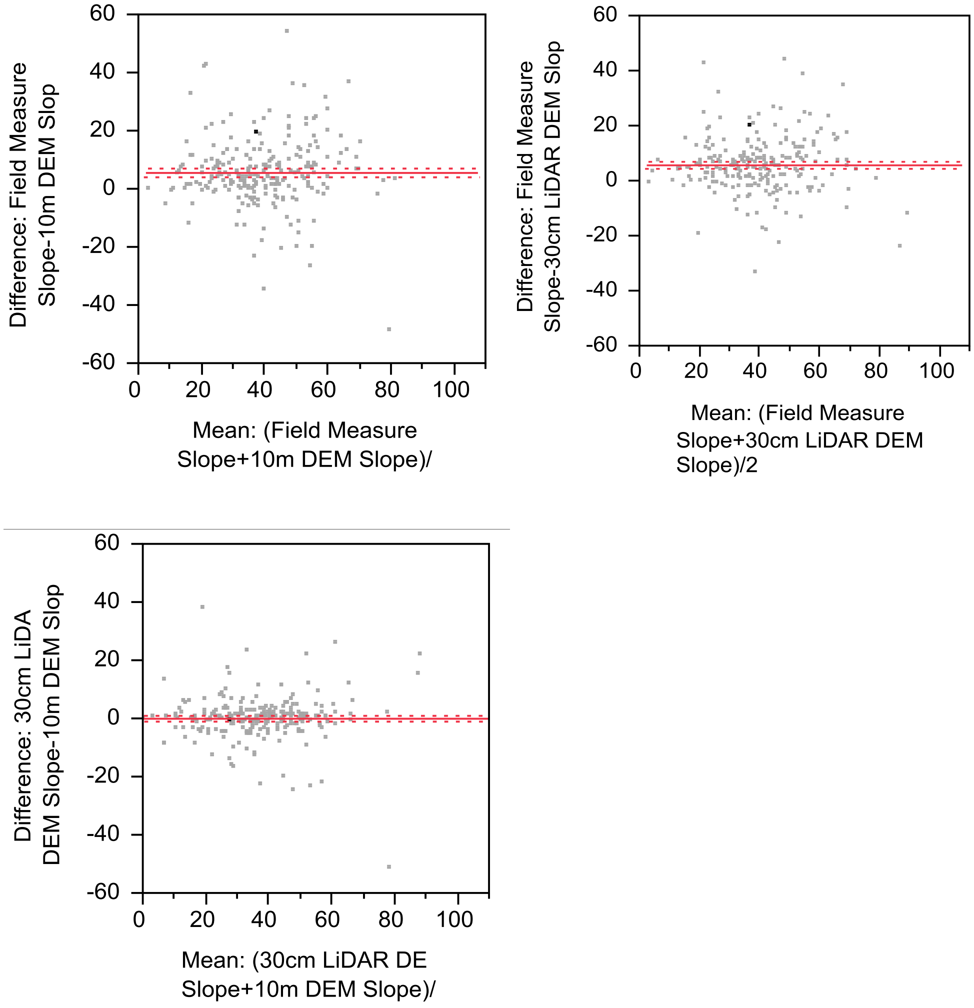


Figure 4.4. Difference plots of three measurements of slope compared. Starting at top left, comparison between slope measurements from 10m and 30cm LiDAR DEM derived measurements. Top right, difference plot of field measured slope and 10m DEM derived slope measurements. Bottom Right, difference plot of field measured slope and 30cm LiDAR derived slope measurements.



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5.0 Appendixes

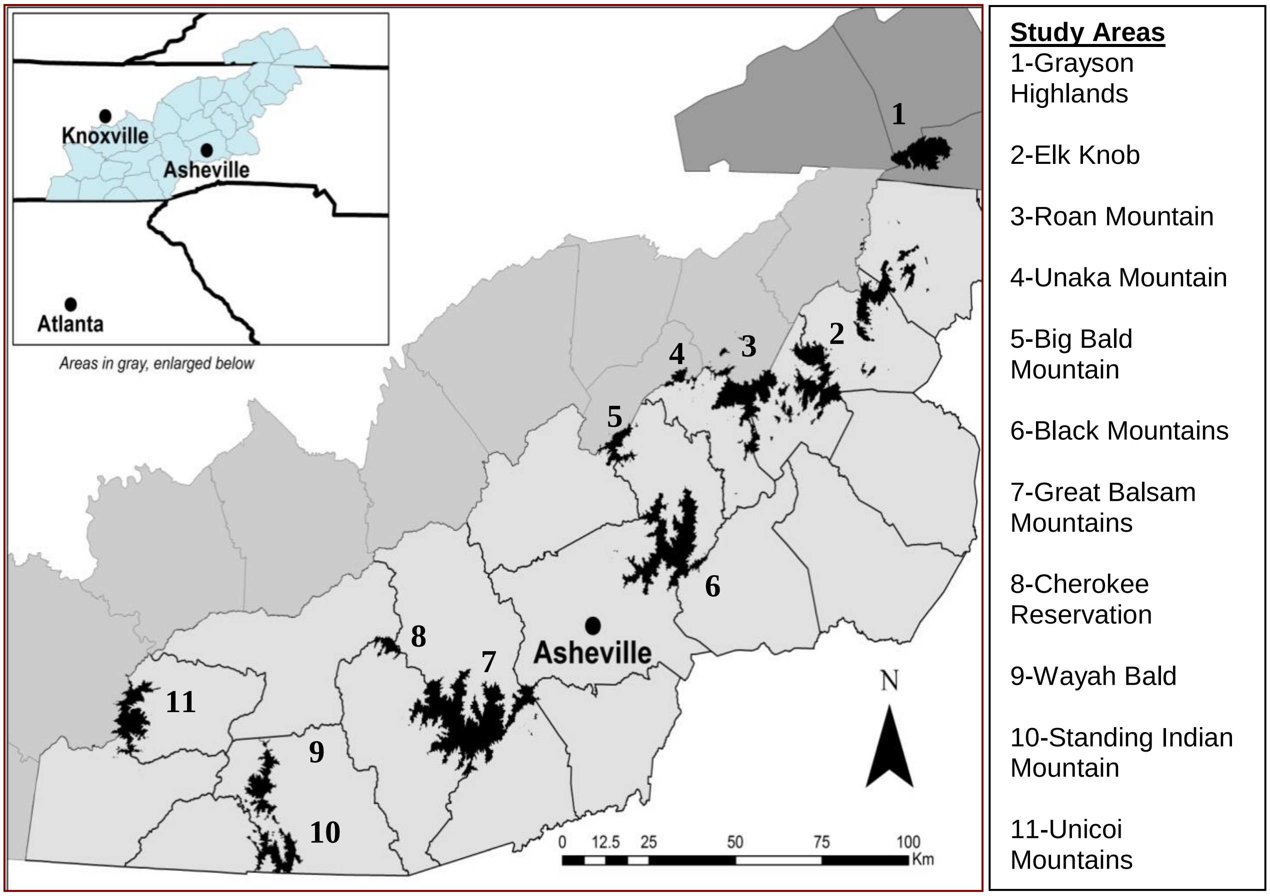


Figure 5.1. Map of counties of Western North Carolina, eastern Tennessee, and southwestern Virginia showing mountain areas that composed the study area. All of these ranges are believed to have populations of CNFS with the exception of the Wayah Bald (9) and Standing Indian Mountain (10).

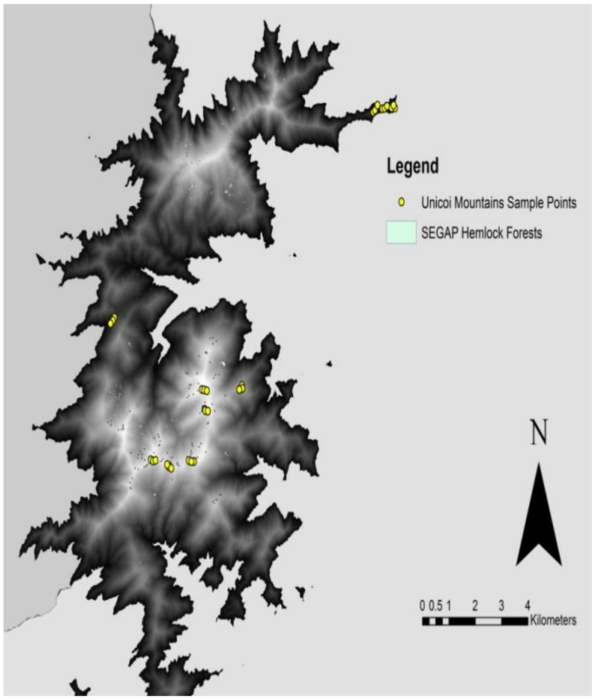


Figure 5.2. Map of Unicoi Mountains in southwest North Carolina showing sampling point locations, and areas identified by SEGAP as eastern hemlock forest that was sampled during July 2012.

Figure 5.3. Map of Standing Indian Mountain and Wayah Bald in southwest North Carolina showing sampling point locations, and areas identified by SEGAP as eastern hemlock forest that was sampled July 2012.

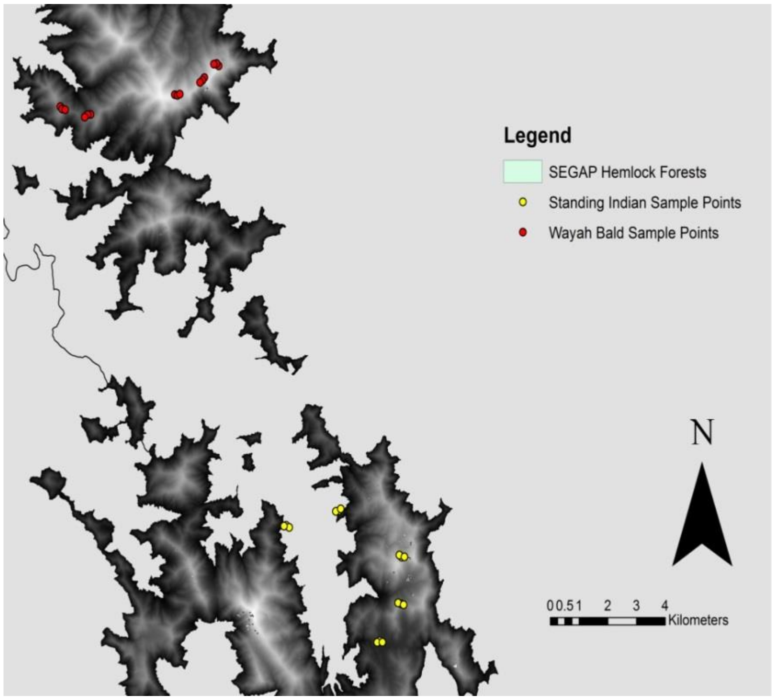


Figure 5.4. Map of high elevation areas of Eastern Band of Cherokee Indians reservation in southwest North Carolina showing sampling point locations, and areas identified by SEGAP as eastern hemlock forest and red spruce-Fraser fir forest that was sampled January 2013.

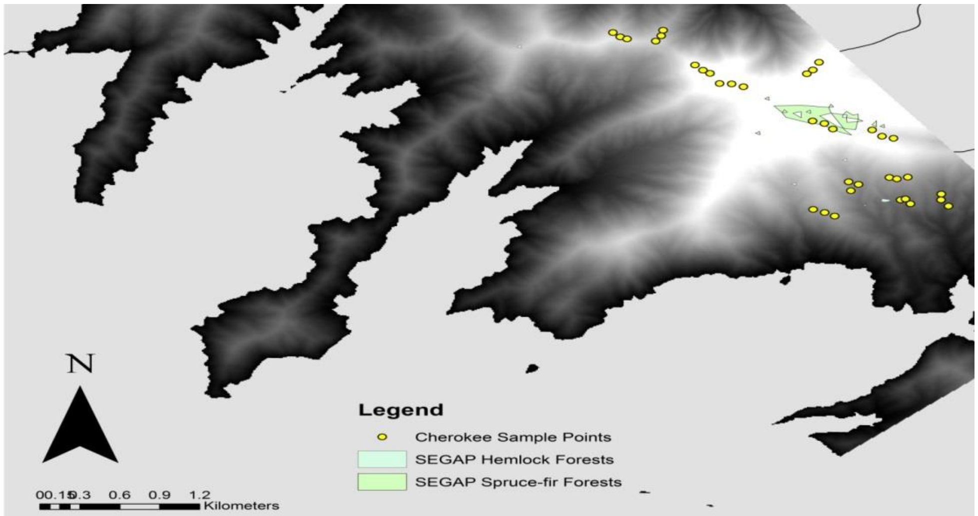


Figure 5.5. Map of Grayson Highlands area in southwest Virginia showing sampling point locations, and areas identified by SEGAP as red spruce-Fraser fir forest that was sampled September 2012

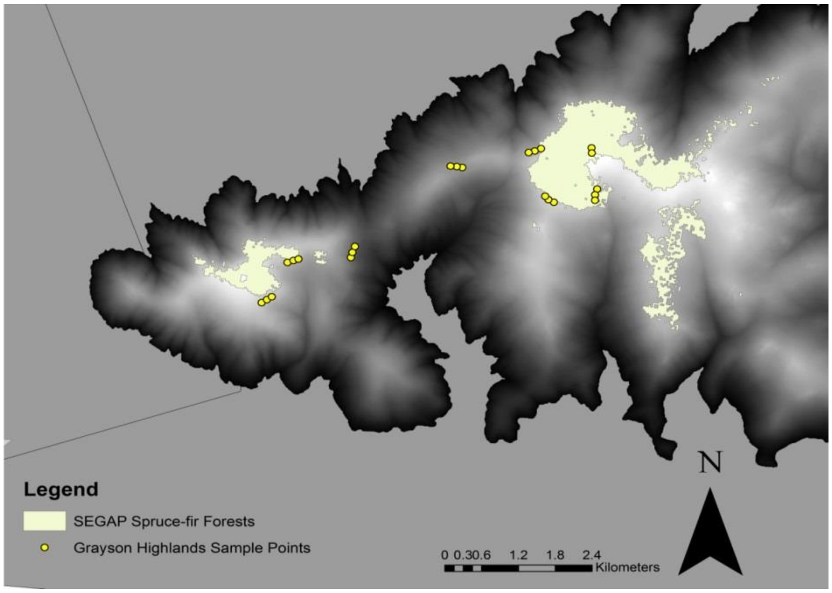
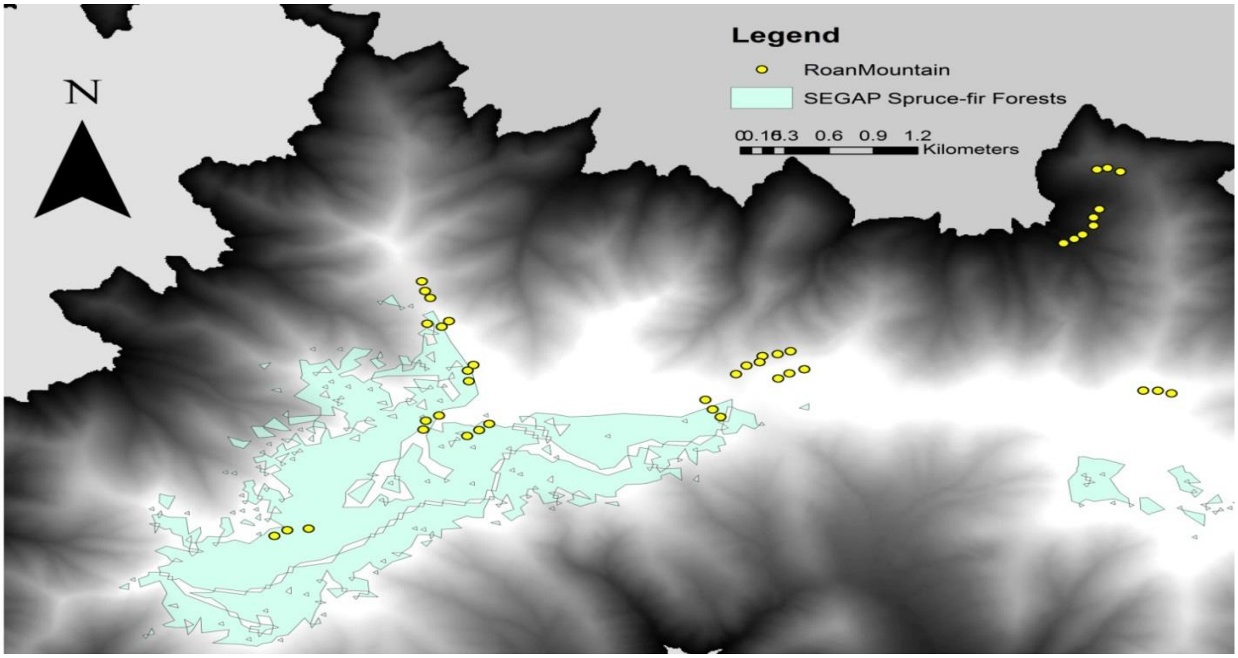


Figure 5.6. Map of Roan Mountain on the border of western North Carolina and eastern Tennessee showing sampling point locations, and areas identified by SEGAP as red spruce-Fraser fir forest that was sampled July 2012.



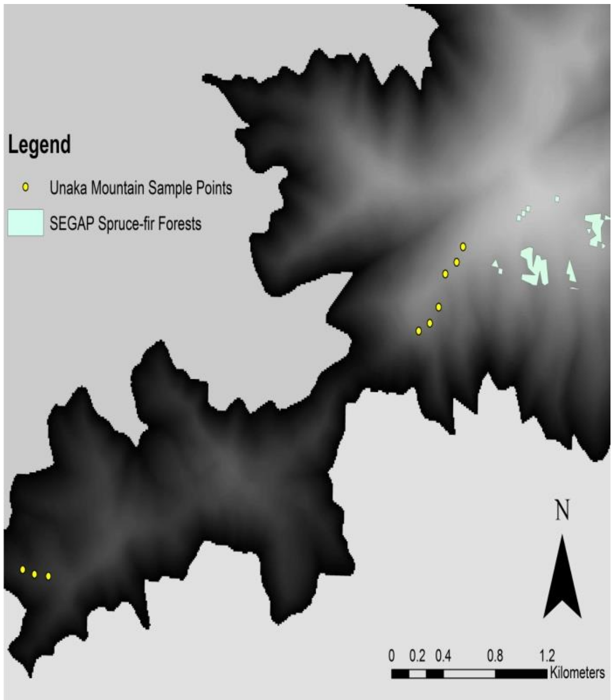


Figure 5.7. Map of Unaka Mountain on the border of western North Carolina and eastern Tennessee showing sampling point locations, and areas identified by SEGAP as red spruce-Fraser fir forest that was sampled July 2012.

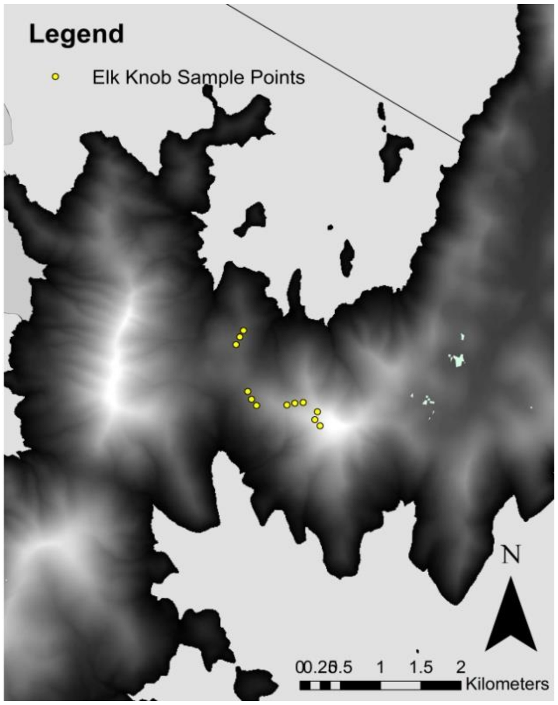


Figure 5.8. Map of Elk Knob in western North Carolina showing sampling point locations, and areas identified by SEGAP as red spruce-Fraser fir forest that was sampled August 2012.

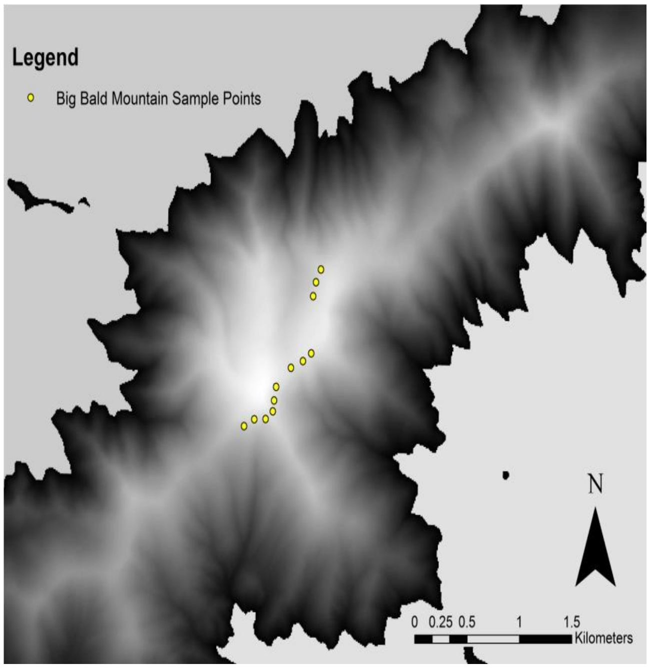


Figure 5.9. Map of Big Bald Mountain on the border of western North Carolina and eastern Tennessee showing sampling point locations that was sampled July 2012.

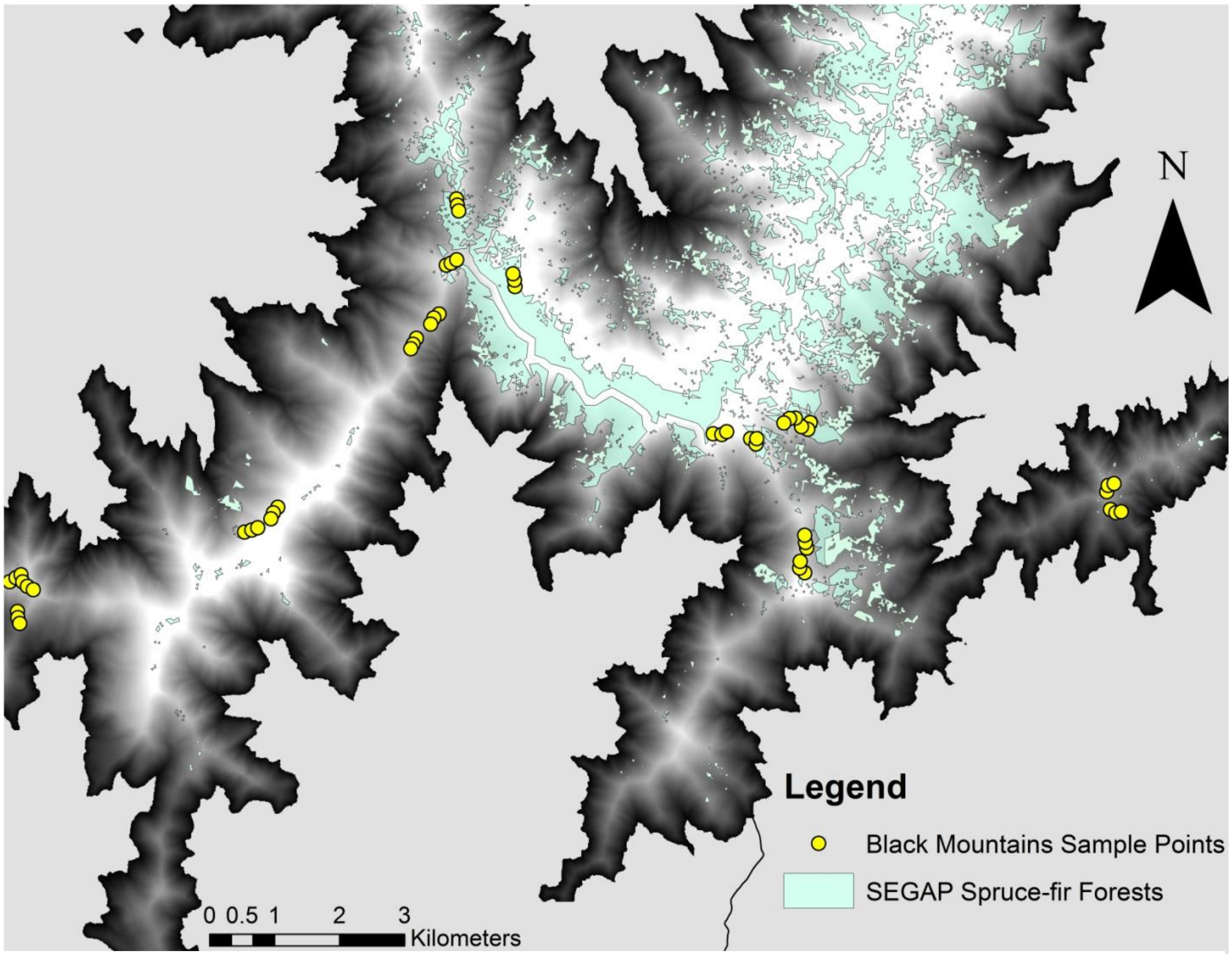


Figure 5.10. Map of the Black Mountains in western North Carolina showing sampling point locations, and areas identified by SEGAP as red spruce-Fraser fir forest that was sampled June 2012.

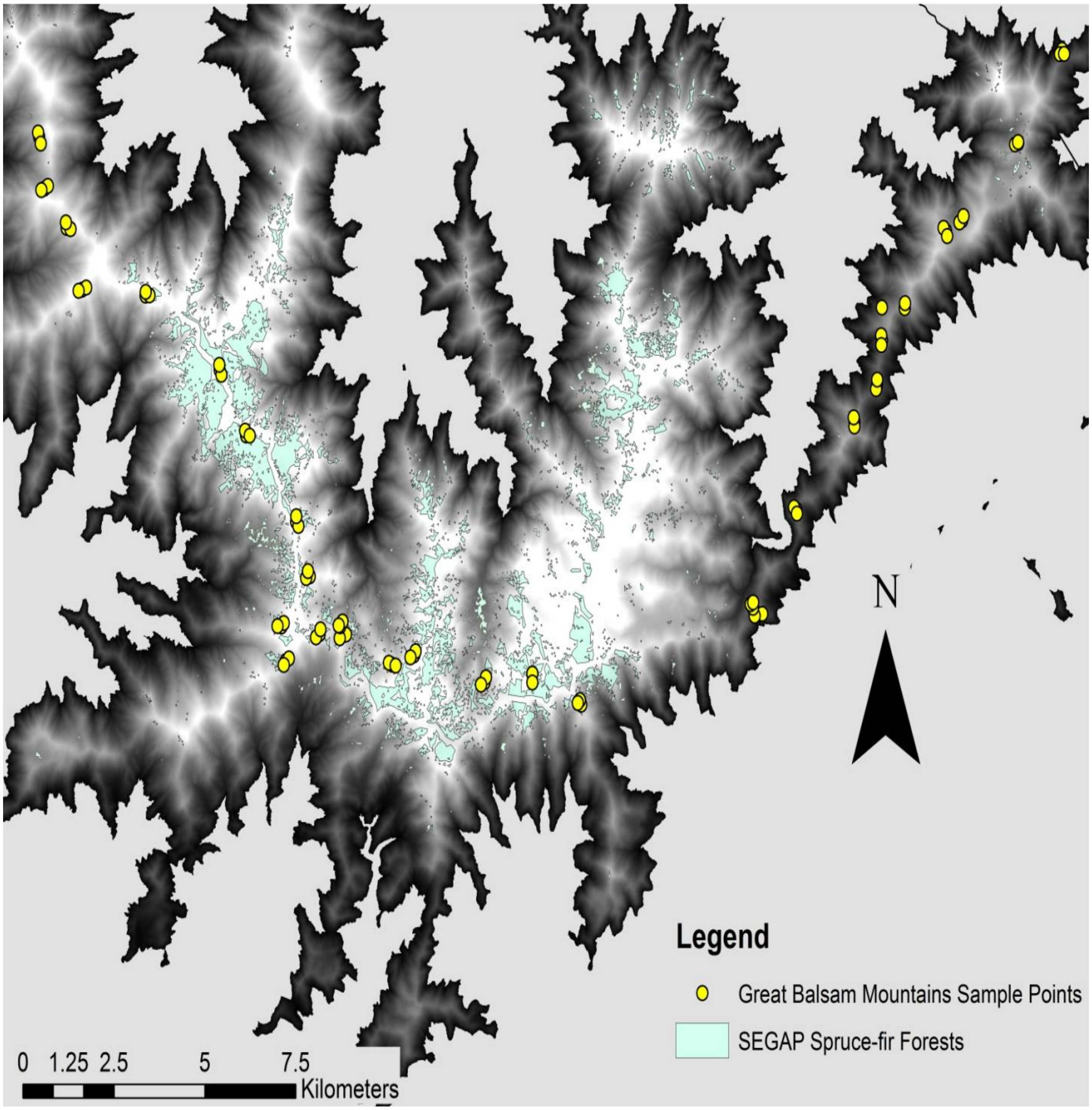


Figure 5.11. Map of the Great Balsam Mountains in western North Carolina showing sampling point locations, and areas identified by SEGAP as red spruce-Fraser fir forest that was sampled June 2012.

Figure 5.12. Field data sheet used for recording terrain and vegetation characteristics at sampling points.

Field Data Sheet	
Massif	
Transect Number	
Site	A, B, C
Easting	
Northing	
Elevation	Meters
Aspect	Degrees
Slope	Percent
Slope Position	(Lower 0-35) (Mid 35-70) (Upper 70) (Ridgeline =100, Bottom Area = 0)
TSI	
Landform Type	(Shoulder, Toe slope, Cove, etc)
LFI	
Species	(Name)
Number of Stems	Number of stems per species in visible prism plot
Basal Area Factor	
Dominant Overstory Species	Based on number of stems/total stems in visible plot
Dominant Understory Species	Based on observations
Forest Type	Northern Red Oak, Northern Hardwood, Spruce, or Transition Area (has characteristics of multiple types)
Forest Sub-Type	
Notes/Evidence of Past Disturbances	

Figure 5.13. Decision Tree used to classify forest types found observed in the study area during sampling between June 2012 and January 2013. Species composition for each forest type was based on existing literature on vegetation communities occurring in the study area.

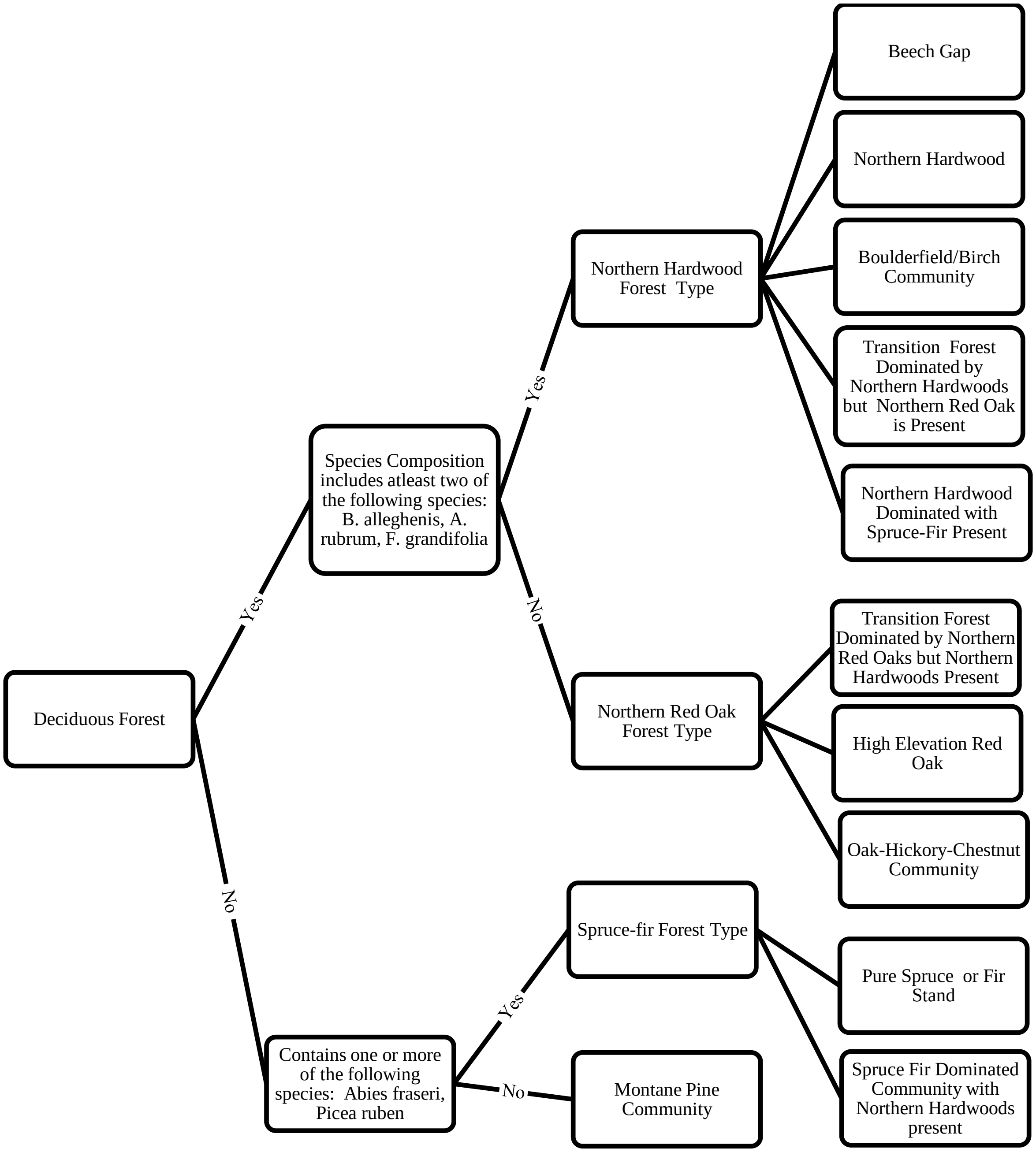


Figure 5.14. Model scripts used in ArcGIS raster calculator for prediction of northern hardwood presence or absence in western North Carolina.

Elevation + LFI

Exp(-1.36238 + (-0.000000203644 * "Northing") + (-0.00013 * "StudyArea_ele") + (0.00426 * "StudyArea_lfi") + (0.0000602964 * (("StudyArea_ele" - 1550.4) * ("StudyArea_ele" - 1550.4))) + (-0.0001283 * (("StudyArea_ele" - 1550.4) * ("StudyArea_lfi" - 63.4693))) + (-0.0000000001444 * (("Northing" -3948504) *("Northing" -3948504))))

Exp(-1.36238 + (-0.000000203644 * "Northing") + (-0.00013 * "StudyArea_ele") + (0.00426 * "StudyArea_lfi") + (0.0000602964 * (("StudyArea_ele" - 1550.4) * ("StudyArea_ele" - 1550.4))) + (-0.0001283 * (("StudyArea_ele" - 1550.4) * ("StudyArea_lfi" - 63.4693))) + (-0.0000000001444 * (("Northing" -3948504) *("Northing" -3948504))))

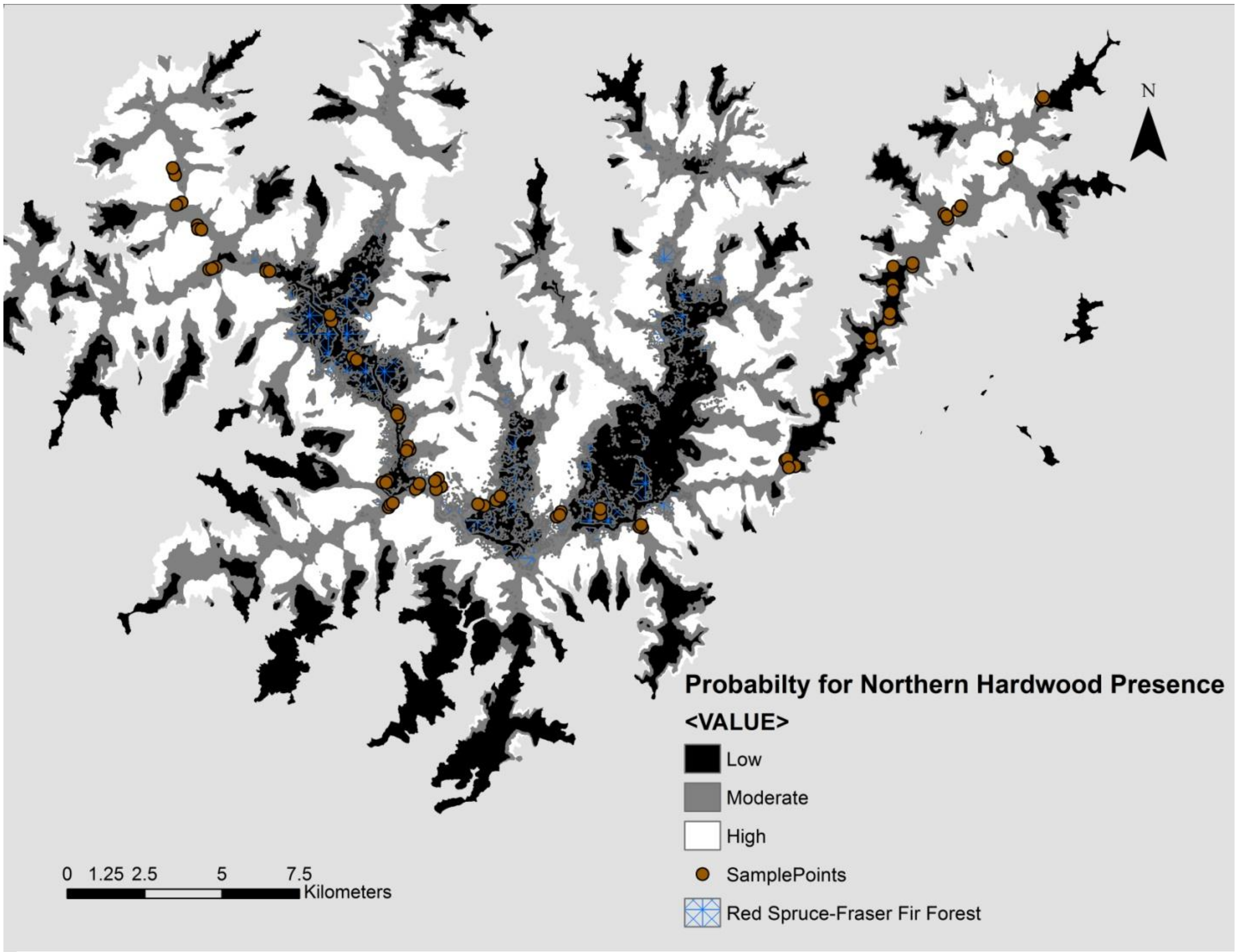


Figure 5.15. Probability map of the Great Balsam Mountains in western North Carolina showing probability of northern hardwood presence as predicted by the best approximating model, and sampling points used to fit the model.

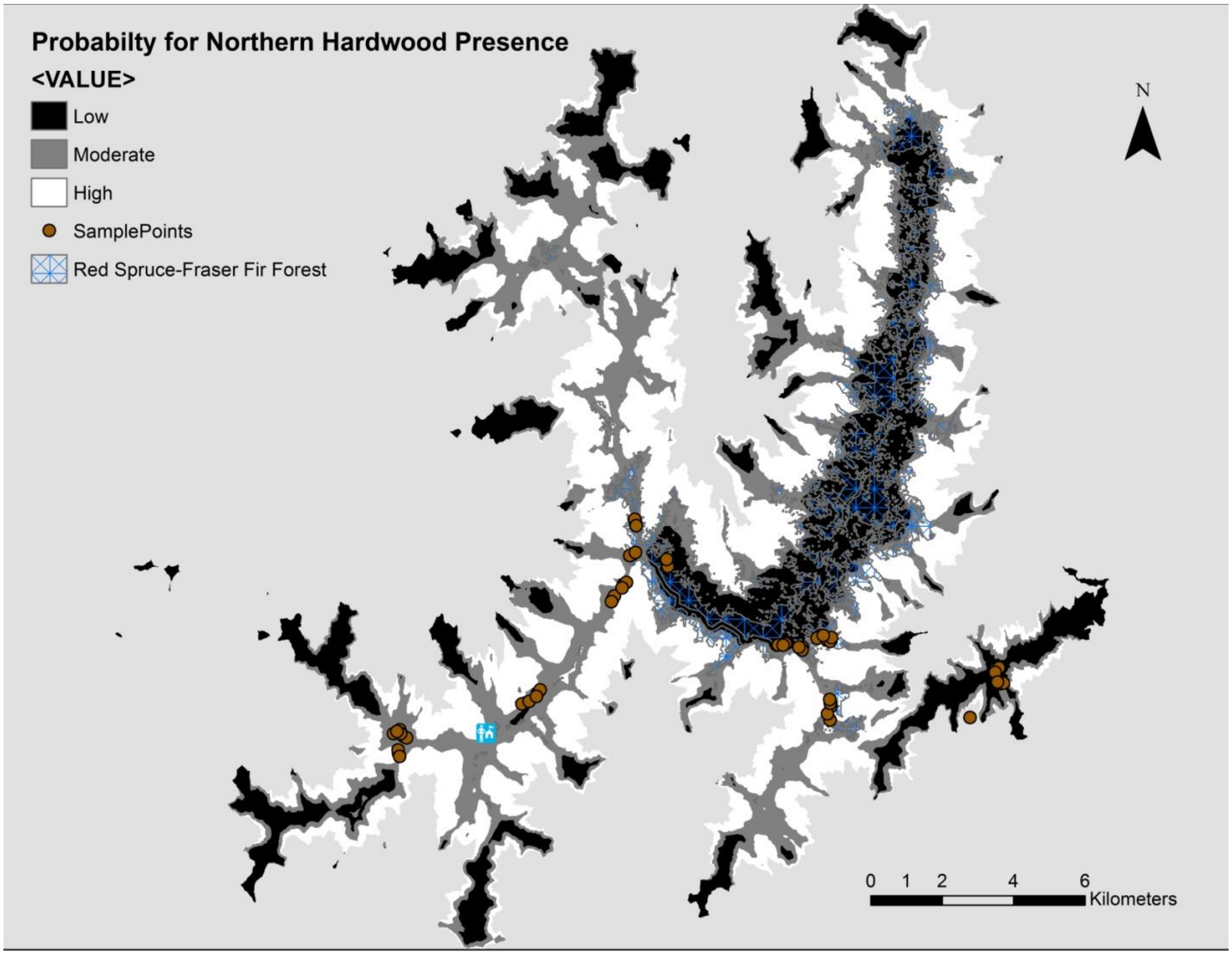


Figure 5.16. Probability map of the Black Mountains in western North Carolina showing the probability of northern hardwood presence as predicted by the best approximating model, and sampling points used to fit the model.

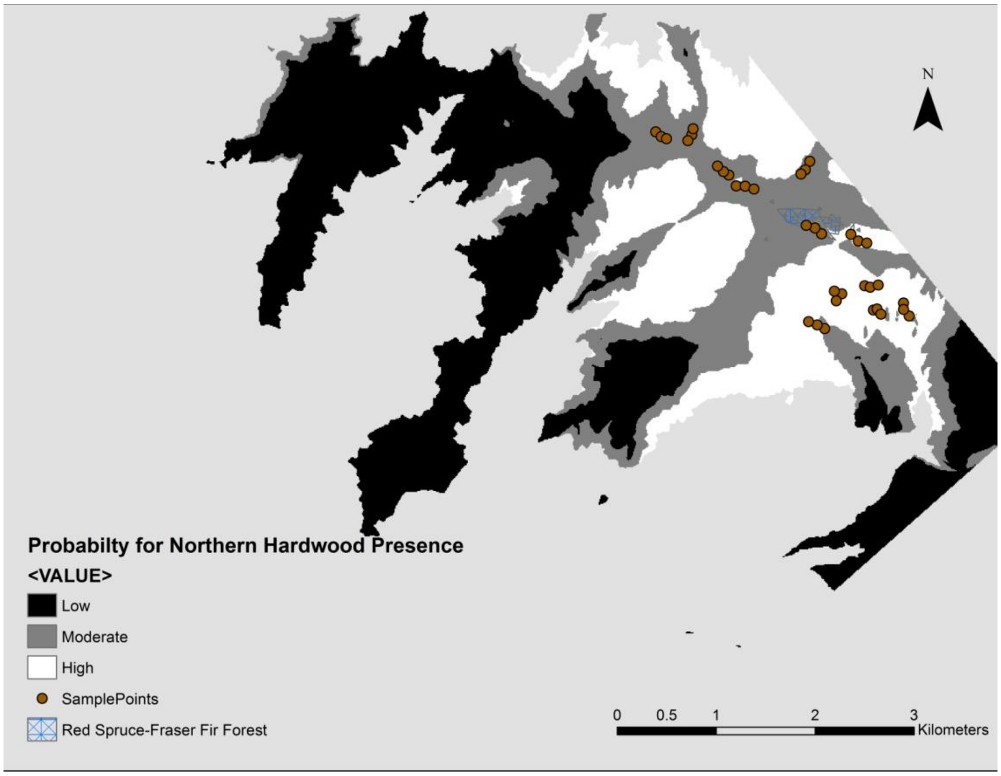


Figure 5.17. Probability map of the high elevation areas of the Eastern Band of Cherokee Indians Reservation in western North Carolina showing probability of northern hardwood presence as predicted by the best approximating model, and sampling points used to fit the model.

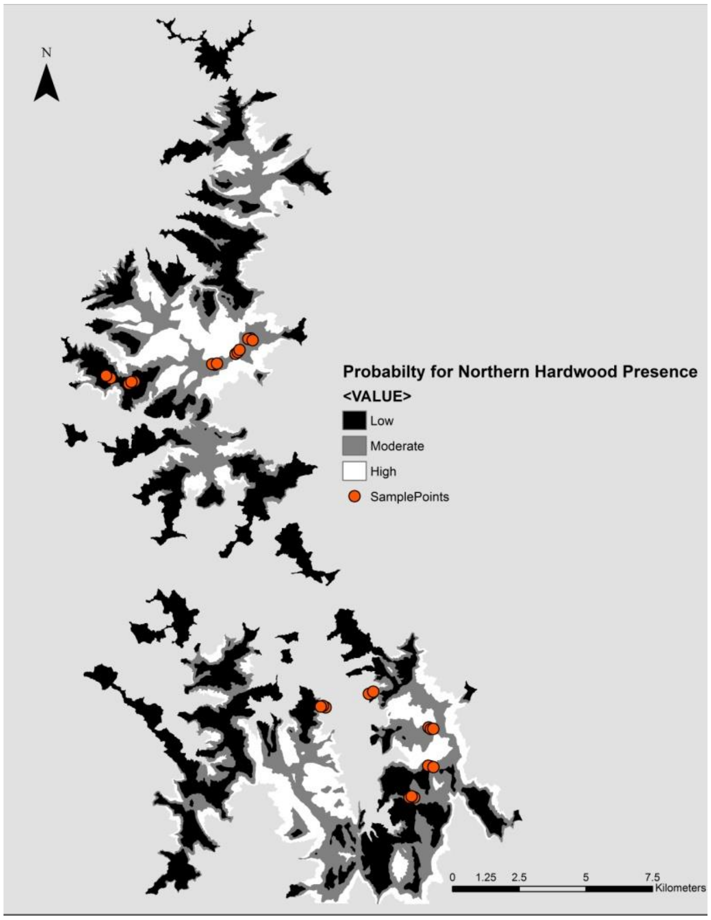


Figure 5.18. Probability map of Wayah Bald and Standing Indian Mountain in western North Carolina showing probability of northern hardwood presence as predicted by the best approximating model, and sampling points used to fit the model.

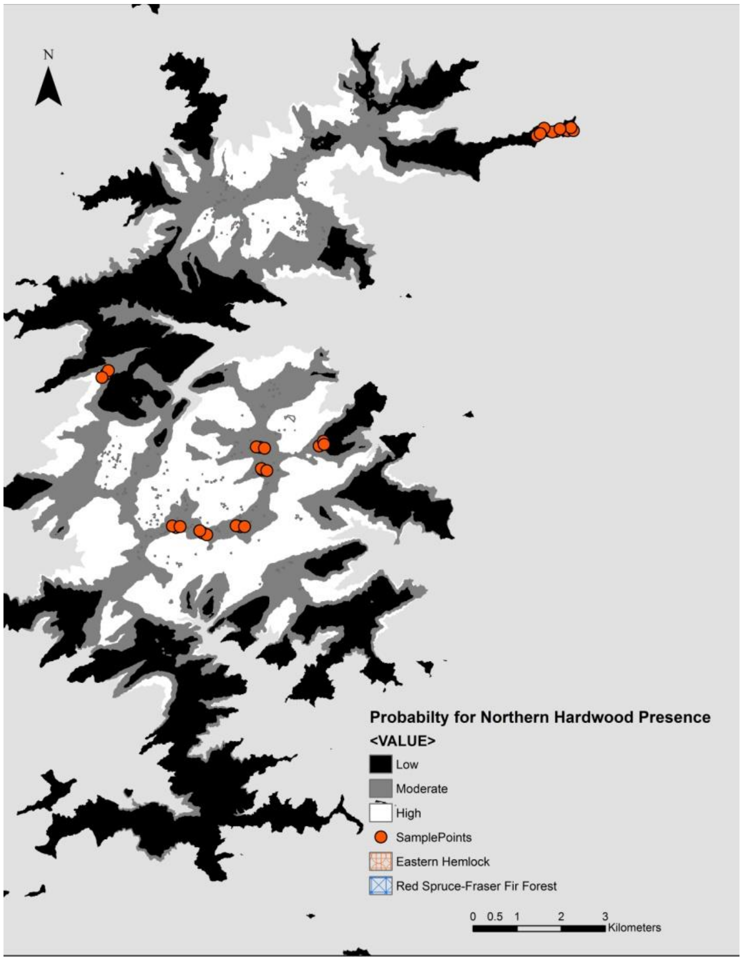
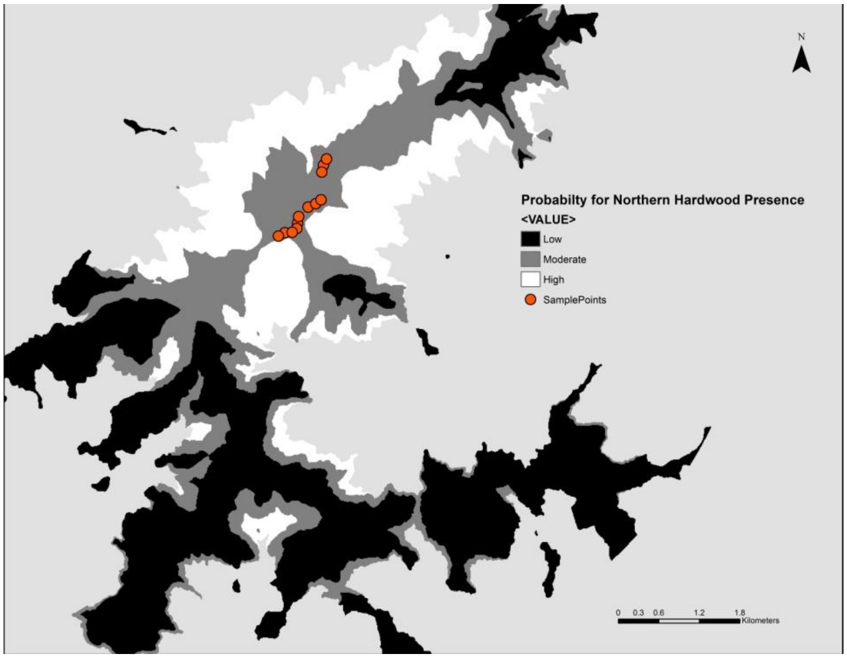


Figure 5.19. Probability map of Unicoi Mountains in western North Carolina showing probability of northern hardwood presence as predicted by the best approximating model, and sampling points used to fit the model.

Figure 5.20. Probability map of Big Bald Mountain western North Carolina showing probability of northern hardwood presence as predicted by the best approximating model, and sampling points used to fit the model.



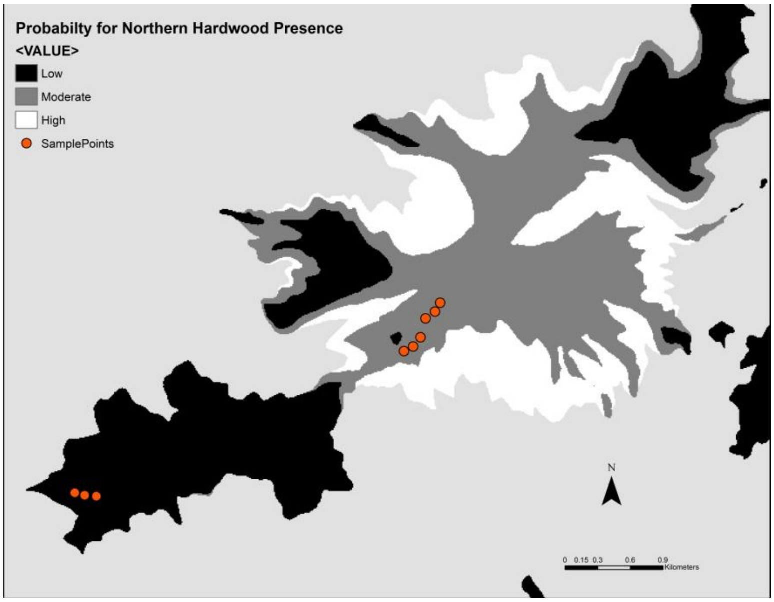


Figure 5.21. Probability map of Unaka Mountain in western North Carolina showing probability of northern hardwood presence as predicted by the best approximating model, and sampling points used to fit the model.

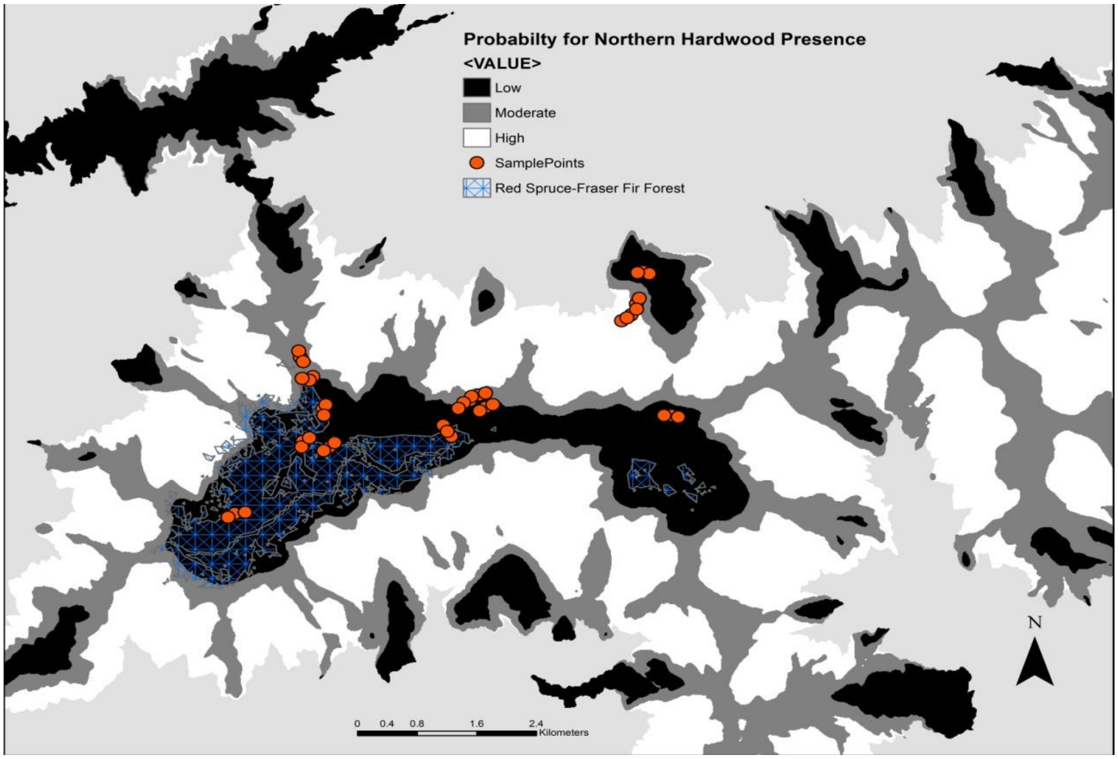


Figure 5.22. Probability map of Roan Mountain in western North Carolina showing probability of northern hardwood presence as predicted by the best approximating model, and sampling points used to fit the model.

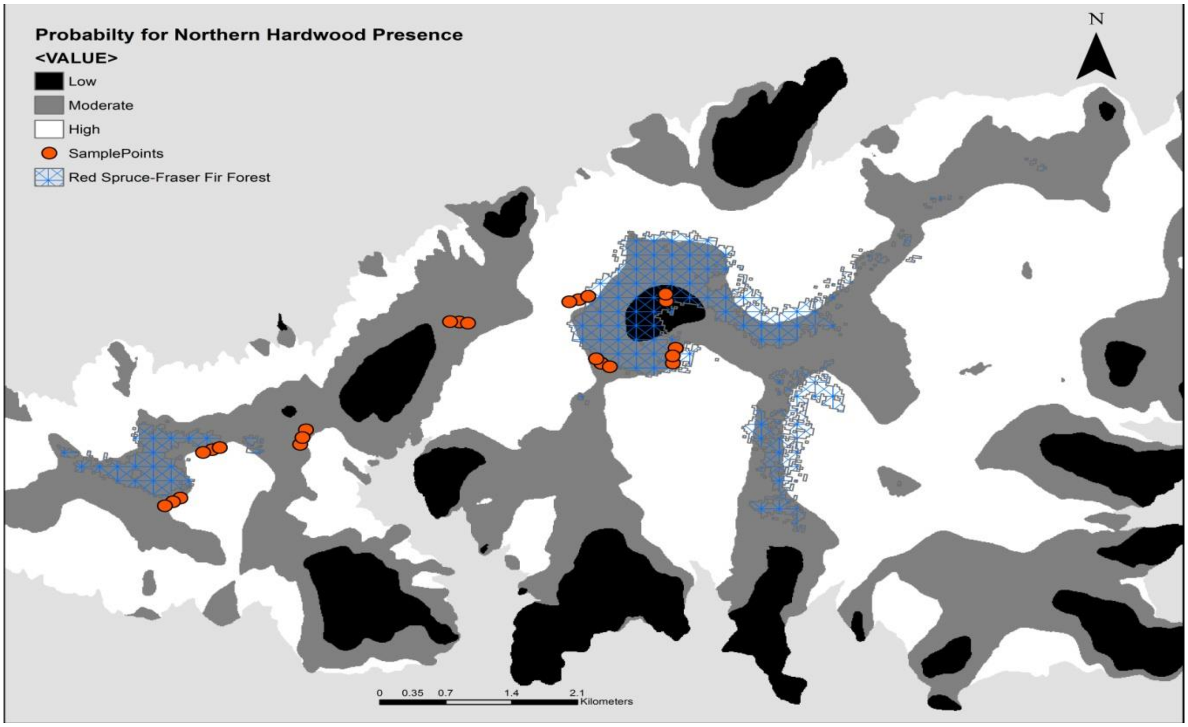


Figure 5.23. Probability map of the Grayson Highlands in southwestern Virginia showing probability of northern hardwood presence as predicted by the best approximating model, and sampling points used to fit the model.

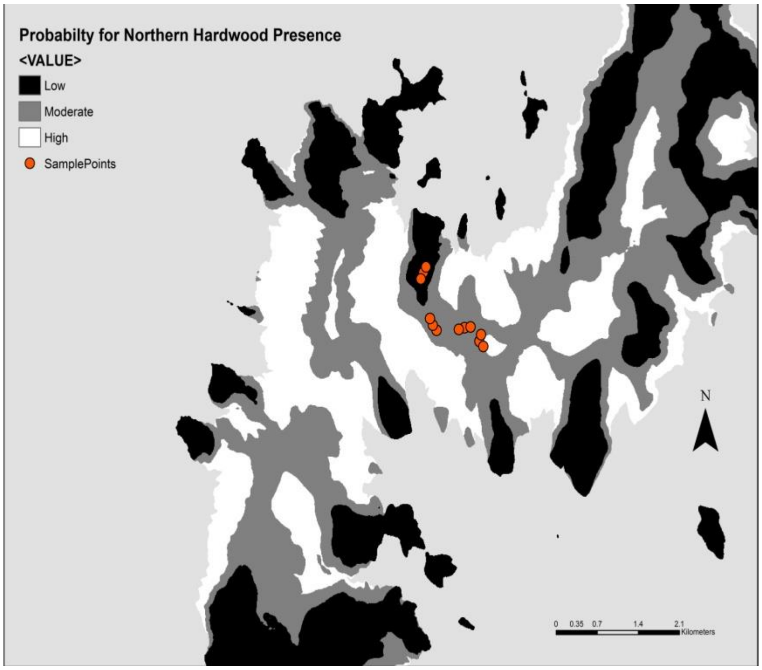


Figure 5.24. Probability map of Elk Knob in western North Carolina showing probability of northern hardwood presence as predicted by the best approximating model, and sampling points used to fit the model.

Figure 5.25. Examples of three basic forest types of the southern Appalachians. From Left to Right: red spruce-Fraser fir, northern red oak, and northern hardwood

Figure 5.26 Red spruce-Fraser fir forest with northern hardwoods present, subtype of red spruce-Fraser fir forest type

Figure 5.27 Northern hardwood forest with red spruce-Fraser fir present, subtype of northern hardwood forest type

Figure 5.28 Beech gap forest, subtype of northern hardwood forest type

Figure 5.29 Yellow birch boulder-field forest, subtype of the northern hardwood forest type

Figure 5.30 Northern hardwood forest with northern red oak present, subtype of northern hardwood forest type

Figure 5.31 High elevation northern red oak-hickory forest, subtype of northern red oak forest type

Figure 5.32 High elevation northern red oak forest with northern hardwoods present, subtype of northern red oak forest type

	N	CNFS	Elevation (m)	Aspect[A]	Slope[B]	Curvature[C]	LFI[D]
Northern Region							
Grayson Highlands, VA	23	Yes	1394.48 - 1726.72	60.91 - 353.23	6.03 - 55.32	-1.55 - 0.53	-16.49 - 121.10
Roan Mountain, NC/TN	42	Yes	1255.30 - 1904.50	0.24 - 345.10	10.61 - 69.81	-1.88 - 2.63	-105.18 - 177.00
Elk Knob, NC	12	Yes	1373.13 - 16.38.66	17.30 - 34.76	3.00 - 50.27	-1.67 - 2.40	30.85 - 198.73
Unaka Mountain, NC/TN	9	Yes	1284.52 - 1506.87	151.42 - 325.98	12.10 - 57.81	-0.34 - 1.50	6.84 - 96.94
Big Bald Mountain, NC/TN	12	Yes	1580.59 - 1630.12	100.48 - 317.95	25.09 - 54.67	-0.71 - 0.85	86.49 - 114.36
Central Region							
Black Mountains, NC	54	Yes	1404.77 - 1833.97	22.82 - 354.34	7.24 - 79.84	-2.33 - 7.84	14.82 - 216.24
Great Balsam Mountains, NC	90	Yes	1318.94 - 1907.04	1.99 - 358.50	9.93 - 76.81	-2.87 - 4.6	-67.23 - 149.70
Southern Region							
Unicoi Mountains, NC/TN	30	Yes	1228.76 - 1676.32	6.31 - 344.24	9.89 - 103.83	-6.54 - 10.74	-57.79 - 125.01
Standing Indian, NC	15	No	1221.30 - 1513.17	18.31 - 352.07	0.00 - 57.47	-3.19 - 3.06	-79.31 - 66.37
Wayah Bald, NC	15	No	1376.98 - 1584.64	15.63 - 355.88	9.67 - 50.66	-2.39 - 3.51	47.63 - 136.80
Cherokee Reservation, NC	36	Yes	1330.69 - 1640.04	7.38 - 352.44	13.31 - 60.72	-11.49 - 8.06	-42.39 - 166.32
Overall	338		1221.30 - 1907.04	0.24 - 358.50	0.00 - 103.83	-11.49 -10.74	-105.18 -216.24

Figure 5.33: Continuous terrain variables for the study area characterized by region and individual study sites that were sampled between June 2012 and January 2013.

[A] Aspect was recorded in degrees azimuth

[B] Slope was recorded in percent change

[C] Curvature describes the concavity or convexity of a site based on a 30m x 30m window with concave sites having negative values and convex sites having positive values

[D] LFI provides an index of concavity or convexity of a given pixel in regard to the surrounding landscape using a 1000m radius circle