Potential Silvicultural Effects on Bald Eagle Nesting Substrate and Economic Yields at a Navy Installation in the Chesapeake Bay: An Approach Using the Forest Vegetation Simulator and Mahalanobis Distance

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ABSTRACT

In the interest of maintaining lands to fully support the military mission, Department of Defense (DOD) installations must manage competing objectives under constraints related to mission operations, regulation and compliance requirements, and budget reductions. Silviculture offers promise for ecosystem management while providing financial means through the sale of forest products. This study used forest inventory and bald eagle nest site data to investigate the potential effects of silviculture on bald eagle nesting habitat at Naval Support Facility Indian Head. Mahalanobis distance was used to define and classify preferred nesting substrate. Silviculture was simulated using the Forest Vegetation Simulator (FVS) to assess forest nesting substrate, economic yields and the tradeoffs between these two objectives. An alternative substrate model based on cumulative distribution functions (CDFs) and Boolean logic allowed evaluation of the strengths and weaknesses of the Mahalanobis distance method.

The Mahalanobis distance model provided greater relative fit to the sample of nest sites compared to the CDF model but had lower discriminating power between presence and absence data. Simulation results indicate that top performing silvicultural treatments resulted in greater substrate availability compared to no-action over equal time periods. Uneven-age management was shown as the best system for providing nesting substrate as well as favorable economic yields in hardwood stands. Results also stress the importance of thinning in providing future nesting substrate and maintaining preferred substrate late in the rotation. Economic and habitat tradeoffs varied by treatment, suggesting that optimum prescriptions could be identified to provide for both objectives and minimize tradeoffs.

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Chapter 1: Introduction

The Department of Defense (DOD) manages over 28 million acres in the U.S. and its territories on military facilities and installations. Installations are typically located in rural areas with adequate undeveloped land for ordnance safety arcs, training and maneuvering, airfield safety, clearance and buffer zones, and minimized encroachment pressures from outside community development (Schrack 1984). As a result of this large and diverse land base, DOD installations face the responsibility of balancing their primary objective, the military mission, with a multitude of other natural resource issues. Examples of the interrelated and often competing objectives DOD natural resources managers must consider include: management of rare, threatened, and endangered (RTE) species, protection of biological diversity, forest stewardship and protection, invasive species management, consumptive and non-consumptive outdoor recreation, protection of real property investment, soil and water conservation, among others. From a forest management perspective, such a multitude of objectives presents increased constraints on the implementation of silvicultural operations.

For many installations, revenue generation from commercial forestry is not a major resource management priority. In the early 1990's, DOD natural resource management experienced a shift from multiple use management to an ecosystem management approach. In 1994, DOD established its first policy for ecosystem management which focused on maintaining biodiversity and ecological processes not just within installation borders but at a broader local and regional scale. In 1995, the Interagency Ecosystem Management Task Force called for all federal agencies to adopt an ecosystem approach to management. In this same year a dialogue on management of biodiversity helped facilitate the development of policy guidance for managing biodiversity in concert with the military mission. The policy guidelines became part of DOD Instruction 4715.3 of 1996 on the Environmental Conservation Program, which explicitly stated the use of an ecosystem approach to natural resource management (Benton et al. 2008). With reduced focus on commodity production and an emphasis on ecosystem management and biodiversity, there may be a greater tendency toward a "hands-off" approach to forest management on installations with modest forest holdings rather than an active use of silvicultural operations to achieve ecological objectives.

In times of budget reductions, funding for non-compliance natural resources management projects (e.g., invasive species control, wildlife management, etc.) ranks low as a priority. Funding for forest management however, which can achieve both economic and ecosystem management objectives, has some degree of self-sufficiency thanks to the DOD Reimbursable Forestry Program (Sale of Certain Interests in Land; Logs. 10 USC 2665), enabled by congress in 1956. This program allows DOD to use proceeds from timber sales to reimburse installation forestry programs for their funding obligations. In the seven years following enactment of this law, the military land in forest use increased from 1.1 million ac to 1.5 million, and the revenue generated from forestry increased from $10.5 million to $26.7 million (Benton et. al. 2008). In 1981 the state entitlement program was created which required installations to distribute 25% of the revenue from timber sales to the state, which then distributes the money to the county where the installation is located. In 1984 the entitlement amount rose to 40%, allowing distribution of greater economic benefit to surrounding rural communities. Currently, surplus revenue after installation forestry program reimbursement and state entitlement goes into the DOD Forestry Reserve Account for must-fund forestry expenses, such as salaries of forestry employees in years of low timber sales. Funding in excess of the Reserve Account minimum balance of $4 million is returned to the U.S. Treasury (DOD 2002). In short, timber sales can provide economic benefits to the community and provide a means for accomplishing ecosystem management objectives on the installation when funding levels are otherwise inadequate.

Naval Support Facility Indian Head (NSFIH) is a naval installation located on the Potomac River in Charles County Maryland, approximately 30 miles south of Washington D.C. The primary objective of NSFIH is the military mission and the installation manages land and natural resources for zero loss in mission support capability. NSFIH has seen an increase in bald eagle use since 1989 due to a productive fishery with an abundant prey base, a large area of forested habitat with protections from habitat loss, and increasing development of areas surrounding the installation (Navy 2010). Bald eagle management is a compliance-based objective, meaning that zero net loss in installation capability to support its mission is achieved by planning and implementing management to minimize the accidental take of the federally protected eagles. As a result bald eagles have great potential to constrain land use, forestry, and mission operations.

This thesis focuses on the effects of silvicultural forest management on two installation objectives:

1) Ensuring no net loss of the military mission through management to ensure the capability of installation land for successful bald eagle nesting
2) Promoting forest stewardship and maintaining the value of the forest as an installation asset.

To ensure compliance, NSFIH has documented goals for continued eagle nesting capacity in its Bald Eagle Management Plan (BEMP) (Navy 2010). The objective for bald eagle management stated in the BEMP is to maintain the current level of eagle activity on the installation and protect existing nesting, foraging, and roosting habitat. Specifically, NSFIH attempts to maintain 8-10 bald eagle nests and 1 communal roost site per year, a number based on current nesting and roosting populations, availability of prey and the existing riparian habitat suitable for nest construction (Navy 2010).

In 2010, the installation's forest was inventoried and the NSFIH Forest Management Plan (FMP) was revised. As is required by agreement with the U.S. Fish and Wildlife Service (USFWS), this updated plan must consider bald eagle management in the development of commercial and non-commercial forest management goals (USFWS 2007). Forest management activities can have negative effects on the success of the bald eagle population. As is typical with actions that alter or manipulate habitat, a treatment designed to achieve a particular goal may negatively impact other natural resources. Scientific study of the effects of forest management and habitat manipulation on bald eagle nesting is limited. Destructive research methods to test the effects of forest harvesting on bald eagle nesting have generally not been attempted due to the bald eagle's protected status. Furthermore, the recovery of the bald eagle over the last quarter century has led to a decline in research dollars directed towards the species. Regardless, resource managers managing for bald eagles along with other objectives require tools and information to evaluate the impacts of silviculture on bald eagle habitat.

Objectives

The primary objective of this thesis was to evaluate potential silvicultural treatments on NSFIH in terms of their effect on bald eagle nesting substrate and economic benefit. Study goals are threefold:

1) To define the forest conditions on NSFIH of preferred bald eagle nesting substrate in a way that allows evaluation of available forest habitat in terms of nesting substrate suitability over time.

2) To use the definition developed in goal 1 to evaluate the effects of common silvicultural treatments on bald eagle nesting substrate over the course of a management rotation or given evaluation period.
3) To analyze the tradeoffs of potential silvicultural treatments with respect to maintaining and creating economic value in the forest and the provision of bald eagle nesting substrate.

Chapter 2: Literature Review

Introduction

Scientific attention towards the bald eagle closely follows the trend of species prosperity over the last century. As subject matter, the bald eagle was most prolific in the forestry and wildlife literature in the period between the late 1960's to the 1990s. Early in this period environmental legislation such as the Endangered Species Preservation Act of 1966, amended in 1973 to the Endangered Species Act (ESA), was introduced and the imperiled status of bald eagle populations across the country was recognized. Concern over the viability of the bald eagle was actually present earlier, however. By the first half of the 20th century, bald eagle populations had declined significantly from pre-colonial numbers as a result of habitat loss and harassment (e.g., shooting). This resulted in the passing of the Bald Eagle Protection Act of 1940.

Thanks to the ban of dichloro-diphenyl-trichlorethane (DDT) in 1972 and the protections enabled by the ESA, bald eagle populations began a recovery which eventually led to delisting from the federal endangered species list. Coinciding with that recovery was a reduction in scientific inquiry directed towards the bald eagle. Nevertheless, there is still concern over the status of the species. State and federal agencies continually monitor local, regional and national bald eagle populations in compliance with the existing legal protections of the Bald and Golden Eagle Protection Act of 1940 (BGEPA), the Migratory Bird Treaty Act (MBTA) and various state level protections. Under the National Environmental Policy Act (NEPA), federal land management planning requires the consideration of human impacts on the health and productivity of bald eagle populations.

Data on the habitat preferences of bald eagles for nesting, the impacts of disturbance, and the effects of forest management on bald eagles are useful to managers in maintenance and enhancement of habitat quality and in assessing the impacts of management activities on local and regional bald eagle populations. Studies of the effects of forest management on bald eagles are limited, likely due to the species' long-protected status and the difficulty of attributing reproductive success or habitat preference to one particular factor. Outside of clearcutting, the response of eagles to silvicultural treatments has not been thoroughly studied (Arnett et al. 2001). Anthony and Isaacs (1989) stated the importance to biologists and foresters of having quantitative data on the characteristics of individual nest trees and surrounding forest stands and information on the effects of such structure on nest occupancy and productivity. Arnett et al. (2001), who studied the relationships between nesting bald eagles and selective logging in Washington, called for further investigation in other regions. They noted that studies of the response of bald eagles to forest management are rare and limited to descriptive observational studies or retrospective analyses.

The following literature review provides background on the range and history of the bald eagle in North America, a review of the habitat requirements of nesting bald eagles at both a forest substrate and holistic level, a review of the current understanding of the relationship between forest management and bald eagle nesting, and finally an overview of several methods of habitat modeling.

Decline and Recovery

The bald eagle occurs widely across the North American continent with large breeding populations occurring in Canada, Alaska, Minnesota, Wisconsin, Michigan, Maine, Washington, Florida, and the Chesapeake Bay region. The shallow foraging areas of the Chesapeake Bay have historically been highly productive habitat for bald eagles, comparable to undeveloped Alaskan populations (Fraser et al. no date). It is estimated that in the late 18th century, population levels were between 25,000 and 75,000 individuals in the continental US and as many as 500,000 throughout North America (Guilfoyle et al. 2000). Between 1930 and 1970, the bald eagle population experienced a significant decline. Speculative estimates of 600-800 breeding pairs in 1936 dropped to 80-90 pairs in 1970 (Tyrrell 1936, Abbott 1978). The leading cause of the decline during this time period is believed to be environmental contaminants, especially organochlorine pesticides such as DDT and related compounds which were used widely in the 1950's and 60's to control mosquitos. These compounds persist and accumulate in the food chain and disrupt calcium metabolism in bald eagles resulting in egg shell thinning and a loss of reproductive success.

In 1967 the bald eagle was listed as endangered under the ESA. In 1972 DDT was banned in the US and bald eagle populations began to experience a recovery. The ESA, the ban on DDT, along with other beneficial legislation and collaborative recovery planning resulted in the Chesapeake Bay population meeting the threshold outlined in the Chesapeake Bay Bald Eagle

Recovery Plan for federal down-listing in 1988. Formal reclassification from endangered to threatened status occurred in 1995 in most of the lower 48 states. Delisting from federally threatened status was proposed in 1999, at which time the Chesapeake Bay supported nearly 600 occupied nesting territories, approaching pre-DDT levels (Millar 1999, Watts 1999). In 2006, it was estimated that the population had reached approximately 70% of carrying capacity (Watts et al. 2006). In 2007, the bald eagle was delisted from federally threatened status under the ESA.

The bald eagle continues to be protected under the BGEPA and the MBTA and populations continue to gain productivity. Recently, nest productivity has reached levels of 1.5 chicks per breeding attempt first reported by Tyrrell in 1936 (Watts et al. 2008). As to whether the rise in productivity has reached its peak, Watts et al. (2008) suggest that nesting densities have not reached high enough levels to reduce productivity rates but that saturation in carrying capacity could be reached in the near future. In summary, the Chesapeake Bay bald eagle population has recovered significantly over the last 30 to 40 years and continues to support high productivity.

Management of threats to the population will play an important role in continued recovery. Habitat loss from shoreline development is the most significant long-term threat to Chesapeake Bay bald eagle populations (Watts et al. 1994). Management strategies to protect suitable habitat, along with the bald eagle's ability to adapt to increased human development, will likely determine the impact of increasing development pressures on population growth. Recent studies have suggested that bald eagles are adapting to humans and maintaining productivity in increasingly developed areas (Millsap et al. 2004, Watts 2006). Watts (2006) looked at the amount of impervious surface within nest buffer zones and concluded that nests with the highest amounts of impervious surface were at least as productive as other pairs in the population. Millsap et al. (2004) found that the location of the nest relative to urban development in Florida had no influence on productivity and fledgling survivorship.

Nesting Substrate

Bald eagle nesting habitat has been studied in Alaska (Corr 1974), California (Leman 1980), Maryland (Andrew and Mosher 1982), Minnesota (Juenemann 1973, Fraser 1981), Maine (Todd 1979, Livingston et al. 1990), Florida (McEwan and Hirth 1979, Cornutt and Robertson 1994, Wood et al. 1989), Oregon (Anthony and Isaacs 1989), Washington (Grubb 1976), the Greater Yellowstone Ecosystem (Swenson et al. 1986), Saskatchewan and Manitoba (Whitfield et al

1974), New Brunswick (Stocek and Pearce 1981), and other areas. Regional differences in habitat occur and account for wide variability in nesting substrate by location. Bald Eagles will nest in trees, rocky cliffs, in the tops of shrubs, on artificial substrate such as osprey platforms and transmission lines, and where there is nothing else available, on open ground (Grubb 1980, Guinn 2004, Navy 2010).

A nesting site, or nesting territory, is defined as the area containing one or multiple nests used by a breeding pair of eagles (Snow 1973, Livingston et al. 1990). Chrest (1964) reported up to five nests occurring in one nesting territory. Breeding eagles typically use the same nest year after year, but will move to an alternate nest if the first nest is destroyed or due to the presence of parasites. Strong bonds between breeding pairs and fidelity towards a specific nest site will cause pairs to use a nest site even after the initially selected habitat has been altered (Newton 1979). Anthony and Isaacs (1989) suspect that in some cases breeding pairs will continue to use an altered nest site until a member of the pair dies. Herrick (1924) reported a nest in Ohio was used for 34 years before the tree eventually blew down. Average nest longevity has been reported to be 9 years (Mattsson and Grewe 1976).

In the Chesapeake Bay region, trees of adequate size and strength to support a nest are typically chosen as nesting substrate. Tree species is less important than the size and structure of the tree (McEwan and Hirth 1979); however, some tree species are more suitable for nesting because of their inherent size and structural characteristics. Beyond the individual nest tree, the structure of the surrounding forest can impact the preference for a particular nesting site. McEwan and Hirth (1979) believed that the apparent preference for certain habitat types over others was a result of selection for a particular type of nest tree rather than the floral composition of these communities. Similarly, in Oregon, Anthony and Isaacs (1989) reported that structure appears to be more important than species composition, which was variable across the observed nesting sites. In Maryland, Andrew and Mosher (1982) found that 70% of nest trees were in coniferous trees, with loblolly pine dominating that category. Most studies have shown that the breeding pair will usually nest in a live tree, although adjacent snags are used for perching (Herrick 1924, Gerrard et al. 1975, Swenson et al. 1986, Anthony and Isaacs 1989, Wood et al. 1989, Livingston et al. 1990).

Eagles typically prefer to nest in trees with dominant canopy positions, often considerably larger than trees in the surrounding stand. These trees have been termed “supercanopy” trees or “superdominants” (Fraser 1981, Stalmaster 1987, Anthony and Isaacs 1989). Anthony and Isaacs (1989) found that 65% of nest trees were dominant and 35% were co-dominant. They also found that nest trees in each forest type were larger in diameter at breast height (DBH), taller than other trees in the surrounding stand, and usually old-growth individuals. In a study of nest trees in Minnesota, Guinn (2004) reported an average DBH of 51.6 cm (20.3 in.) and a height of 24 meters (78.7 feet), compared to average stand DBH and height of 31.4 cm (12.4 inches) and 18.6 meters (60.9 feet), respectively. Andrew and Mosher (1982) found an average DBH of 62 cm (24 inches) out of 70 nest sites in the Chesapeake Bay. Of 19 nests in southern pines measured in Florida, DBH averaged 57.9 cm (22.8 inches), and nest tree height averaged 26.3 meters (86.3 feet) (McEwan and Hirth 1979). Stalmaster (1987) found that nest trees averaged 29 meters (95.1 feet) in height while the surrounding trees averaged 24 meters (78.7 feet).

It is important to note that between diameter and height, the difference in diameter between nest trees and the available surrounding forest is often the more significant variable. Cornutt and Robertson (1994) found that nest trees were taller at only 2 of 12 sites; Wood et al. (1989) on only 19 of 98 sites. Guinn (2004) found only 65 of 120 (54.2%) nest trees were taller than trees within 100 m., whereas diameter of the nest tree was found be larger than stand trees at 97 of 120 sites (80.1%). The greater importance of diameter is understandable because tree height growth will typically reach a maximum at maturity, while diameter growth will continue to increase. Furthermore, diameter and basal area are highly correlated with crown size and crown width (Dawkins 1963).

While tree height is not as significant as diameter, tree prominence is still believed to be an important factor in nest tree preference. Studies show that nest trees are found in more open habitat, closer to forest edges, or have some form of canopy discontinuity around the nest tree. Some suggest this trend is due to the large size of the bald eagle and its reduced ability to maneuver through closed canopies (Gerrard et al. 1975, Grubb 1976, Todd 1979, McEwan and Hirth 1979, Andrew and Mosher 1982). Andrew and Mosher (1982) found that nest sites were more regularly in open habitat and closer to forest edge than sites selected at random. They found that 53% of the nest sites had some form of habitat discontinuity within 100m of the nest tree. In addition to proximity to water, they believed that open, mature forest was one of the most important factors in nest site selection. Anthony and Isaacs (1989) found that most nest trees (61%, n=181) were located on the top quarter of slopes, further suggesting the role of prominent positioning in selection of the nest tree. McEwan and Hirth (1979) found that suitable nest trees were usually dominant trees or were located along ecotones or in open fields and pastures. Guinn (2004) found that nests were located closer to terrestrial edges than sites selected at random, often within 20 m (65.6 ft.) of an opening. In the Chippewa National Forest in Minnesota, Fraser (1981) found that nests were often located higher than the surrounding trees or the nest tree was situated at a habitat edge. Wood et al. (1989) found that over 90% of nests across all the regions they sampled in Florida were located within 229 m (751 ft.) of an edge or were lone trees in open habitat.

Holistic Habitat Requirements

The suitability of habitat for nesting does not end with the characteristics of the nest tree or the structure of the surrounding forest. While all ecological factors at play in determining suitability can never be fully understood, a holistic picture of nesting habitat depends largely on factors including available nesting substrate, foraging habitat, roosting habitat, nest territory density, and human disturbance relationships. Essential forest components also include perch trees used for foraging and other activities. Perching habitat is located adjacent to shoreline where prey can be easily sighted and is usually in easily accessible live or dead trees (Buehler et al. 1992, Chandler et al. 1995). Roosting habitat is used by immature eagles as well as adult eagles outside of the breeding season.

A prerequisite to nest site selection is good foraging habitat with a consistent food supply (Anderson 1985). The diet of the bald eagle is primarily water based, so nest sites are typically within close proximity to water. Proximity varies regionally and is assumed to reflect the availability of suitable nesting sites (Corr 1974, Gerrard et al. 1975, McEwan and Hirth 1979). Distances from the nest to foraging areas have been reported as far as 7.2 km (4.5 mi.), but most often nests are located less than 3 km (1.9 mi.) from water. Livingston et al. (1990) found that 107 of 115 nests (93%) were within 1 km (0.62 mi.) of a major body of water. Fraser et al. (1985) found that the mean distance of nests to the shoreline was less than 1 km. Guinn (2004) found a mean distance to water in Minnesota of 159.28 m (522.6 ft.) and nest sites were much closer to water than random sites, even when all random sites were chosen within 1 km of water. In Alaska, Corr (1974) found a mean distance to water of 329 m (1079.4 ft.). Gerrard et al (1975) found a mean of 201 m (659.4 ft.) in northern Saskatchewan and Manitoba. In Florida, active nest sites averaged 1.06 km (0.66 mi.) from water while all nests were located within 3 km (1.9 mi.) of permanent bodies of water larger than 10 ha (24.7 ac) (McEwan and Hirth 1979). In Oregon, Anthony and Isaacs (1989) found that all nest trees were within 7.2 km (4.5 mi.) of permanent bodies of water and 84% were within 1.6 km (0.99 mi.) of water.

It has been suggested that eagles nest further from shoreline where high levels of human disturbance are present (Lehman 1980, Fraser et al. 1985). Grubb (1976) found that successful nests in Washington were farther away from human activities than unsuccessful nests. The variability in proximity to water does not appear to be an effect of optimizing foraging activities. Productivity studies have shown no significant relationship between the number of fledged young and the distance to open water, suggesting that even the longest observed distances to water are optimal (Gerrard et al 1975, Andrew and Mosher 1982). McEwan and Hirth (1979) also found that proximity to water was not correlated to reproductive success in Florida.

Variability is also evident in the degree to which breeding eagles will tolerate human disturbance and successfully reproduce. Young (1980) observed an apparent adjustment in the timing of nesting activities at nest sites with heavy public use in the vicinity. Newman et al. (1977) describes what appears to be an adaptation to human disturbance in highly developed areas, where nest occurrence increased in areas of significant development and public recreational use. The most probable explanation for tolerance of disturbance from high levels of human activity is the availability of food. Tolerance to disturbance is greater where food availability is higher (Stalmaster 1987). Gende et al. (1998) found higher nest density in developed areas near Juneau, AK compared to undeveloped areas in close proximity to clearcut logging, due to in part to the suspected greater food abundance at the more developed site.

In a study of noise disturbances from weapons testing at Aberdeen Proving Grounds in Maryland, Brown et al. (1999) found that most eagles did not show any activity in response to weapons testing noise, the most frequent activity was a head turn. Roosting eagles, who showed more activity after noise than nesting eagles, exhibited no difference in activity at times with noise compared with times without noise. Sound intensity levels had no effect on frequency of activity versus no activity. Nest success and productivity at Aberdeen Proving grounds was not different from nest success and productivity in adjacent areas of Maryland.

Stalmaster and Kaiser (1997) studied the impact of military activities on wintering bald eagles on a military installation in Washington State. Military activities included firing of artillery, mortar shelling, automatic and small arms fire, explosive ordnance disposal, frequent helicopter flights along major waterways, motorized and non-motorized boat traffic, winter training exercises, and public recreational use. They found that disturbance from military activities was not disruptive enough to prevent high eagle use of the area and attributed the high use to habituation to the disturbance and the greater importance of the food and habitat available in the area.

Forest Management and Bald Eagle Nesting Habitat

Timber harvesting and bald eagle management are widely viewed as competing land uses (Anderson 1985) and few examples exist of managers using manipulative silvicultural techniques to create, maintain, or enhance nesting habitat. Forest management involving timber harvesting generally results in habitat alteration and often benefits one particular species at the expense of another.

Negative Impacts

Past studies have shown that the disturbances created by logging have caused nest desertion, abandonment, or relocation (Welchsler 1971, Juenemann 1973, Thelander 1973). Welchsler (1971) reported that logging within ¼ mile of a nest may cause desertion of the nest site. Where nest site fidelity may prevent nest desertion, productivity may still be reduced due to the proximity of logging operations. In Oregon, Anthony and Isaacs (1989) found a negative correlation between proximity to clearcuts and main logging roads and bald eagle productivity.

One consensus emerges from the literature: clearcutting is the most detrimental operation to nesting habitat (Anthony and Isaacs 1989, Gende et al. 1998). Clear-cutting has been implicated in reduced nesting densities and productivity in some areas (Anthony and Isaacs 1989, Gende et al. 1998, Hodges et al.1984) and clearcutting of roosting areas has been identified as a threat to the population as a whole (Hansen 1987). Gende et al. (1998) found that inter-nest distances increased with proximity to clearcuts. Most directly, clearcutting results in an absence of trees for replacement or alternate nesting sites and perching habitat. Corr (1974) suggested clear-cutting in Alaska would not completely eliminate bald eagle nesting as long as a substantial fringe of shoreline timber was not cut. Nesting habitat models for Maine developed by discriminant analysis of various habitat variables suggest that eagle nests are negatively associated with timber harvests, most notably clearcuts (Livingston et al. 1990).

Aside from clearcutting, or regeneration system type, inadequate rotation lengths may have a negative impact on nesting habitat. The preference shown for large diameter, prominent trees, generally indicates a dependence on long enough rotations for such trees to develop. During development of their nesting model for the Chesapeake Bay, Watts et al. (1994) found that random sites had comparatively more area in intermediate age forest and active nest sites contained significantly more mature forest. However, they also found that active and random sites were not significantly different with respect to land area in clearcut and young forests. In general they found that active nest sites in the Chesapeake Bay watershed, compared to random points, were surrounded by comparatively more forest cover, less agricultural land, and less urban development.

Anthony and Isaacs (1989) noted that nest trees were larger in DBH than the minimum specification used for management of old-growth forest in the pacific northwest regional forest plans. They showed that bald eagles were using trees for nesting that were larger and older than those produced under short rotation (80-100 yr.) systems. Wood et al. (1989) reported on 28 nests in the Ocala National Forest region of Florida where 18 of the 28 nests had clearcuts within the primary protection zone. In these areas, where rotations are between 30-100 years, eagle nests were found in trees with smaller diameters, characteristic of young pine plantations. Eagles were also found nesting in lone trees on agricultural land. While nesting was continued on this available habitat, smaller diameter trees lack the strength and stability of larger trees and lone trees run greater risk of being hit by lightning (Wood et al. 1989).

The negative effects related to human disturbances created during logging can be temporary. Wood et al. (1989) suggested that continuous, year-round disturbances associated with development may have greater impact on eagle populations than periodic disturbances such as logging implemented outside of the breeding season. McEwan and Hirth (1979) noted that while timber cutting could be a highly disturbing activity for nesting eagles, harvest activities are relatively infrequent. They suggested that a nesting population of bald eagles is compatible with an active timber industry and that forest operations can enhance eagle nesting habitats.

Opportunities for Habitat Manipulation

While potential negative impacts of timber harvesting have been highlighted, there have also been many recommendations, though not widely implemented, for the use for timber harvesting to improve bald eagle habitat. Outside of the creation of artificial structures (Grubb 1995), increasing natural nest site availability can be accomplished by manipulating forest habitat through silvicultural treatments. Some suggest that judicious application outside of the nesting season of silvicultural practices (e.g., thinning, selection harvesting, prescribed burning, regeneration harvests, etc.) can enhance nest and roost-site habitat (Burke 1983, Anderson 1985, Chester et al. 1990, DellaSala et al. 1998).

Anderson (1985) and Arnett et al. (2001) provided two detailed looks at the coexistence of commercial forest management and bald eagle nesting on forest industry land. In Oregon, Anderson (1985) described nest successes and failures existing alongside commercial forest harvesting, and highlighted the variability in productivity and tolerance of disturbance. The study concluded that nesting success is highly variable even in the absence of forest management and that eagle nesting activity continues alongside forest management when activities are planned and implemented outside of critical periods of breeding.

Arnett et al. (2001) presented another case study of the results of forest management on industry land in Washington. In this situation, high stocking of trees, drought, reduced tree vigor due to competition, and increased fire, insect, and pathogen risks, posed threats to both commercial forestry and bald eagle habitat. Managers devised a plan with the objectives of improving forest health and commodity production and improving or maintaining nesting habitat and success. Prescriptions involved marking and releasing all nest trees and potential nest trees (>=50 cm/19.7 in. DBH), plus future replacement trees >35cm (13.8 in.). Understory fuels were also removed around leave trees. The remainder of the forest as thinned to a target of about 250 trees/ha (618 trees/ac), favoring ponderosa pine and Douglas fir due to their preferred structural characteristics for nesting sites (Anthony and Isaacs 1989).

The residual stand had 153-753 trees/ha (378-1860 trees/ac) across a range of diameters 10 - 110 cm (4 - 43 in.) DBH. Over 21 years nest productivity and occupancy was surveyed at the study area and compared to reference areas nearby. It was found that across both study and reference areas mean site occupancy increased during the post-treatment period. Relative to the reference areas, nest site occupancy at the study area was significantly higher post-treatment than pre-treatment. Productivity was lower at the study area pre-treatment compared to reference sites, but the increase in productivity post-treatment was higher at the study area than at the reference sites.

Habitat Management Recommendations:

In the interest of maintaining the holistic nesting habitat requirements, perch and roosting habitat must be provided for. Live trees are generally preferred over snags as nest trees (Andrew and Mosher 1982), however it is recommended that snags be preserved or created for winter roost trees and perch trees near shorelines (Stalmaster and Newman 1979, Glinski et al. 1983, Keister and Anthony 1983). Chester et al. (1990) suggested that silvicultural treatments, such as seed-tree regeneration cuts and thinning, be used to create and maintain roost habitat in pine stands while perch tree management may only require maintenance of large trees along the shoreline by conservation of mature loblolly pines and snags of at least 20in. DBH.

Manipulating forest structure for eagle benefit should focus on creating prominence in suitable nesting trees and providing future nesting substrate. McEwan and Hirth (1979) suggested creating dominant trees by releasing large trees from competition and creating a clear flight path. Where no existing large trees exist, young trees should be set aside to grow into dominant trees for future nest sites. While eagles will nest in sparse forest cover, Anthony and Isaacs (1989) recommend denser and more structurally diverse stands to provide visual buffering from human disturbances. They recommended uneven age and multiple species management to produce the variable structure, species composition and tree size found around nests in Oregon. The minimum nest tree and forest stand requirements suggested by Anthony and Isaacs in Oregon necessitate uneven-age (UEA) management to provide the recommended tree height distribution. In the Douglas fir type, the recommended nest tree DBH is 2.6 times the average forest stand DBH, 2 times the average stand DBH in mixed conifer, and 2.2 times average stand DBH in ponderosa pine. Douglas fir crown closure is 55%, 30% for mixed conifer, and 30% for ponderosa pine.

McEwan and Hirth (1979) suggested that nest trees may be highly likely to die due to their advanced age as well as the potential of lightning strikes due to prominence. Alternate nesting trees should be provided for both future nesting and additional habitat (McEwan and Hirth 1979, Anderson 1985). Promoting future replacement of nest trees should be fostered through prescriptions which involve thinning smaller trees underneath the dominant overstory canopy (DellaSala et al. 1998, Arnett et al. 2001). Anthony and Isaacs (1989) suggest that where undesirable tree species dominate the understory, precommercial thinning of young trees may be necessary to manage for desirable future nest trees.

Management Guidelines

To a large extent the impact of timber harvesting on nesting habitat and success depends on the method of logging and timing of operations. The literature suggests that forest management can be implemented alongside bald eagle management in accordance with proper planning in the nature and timing of operations and it seems reasonable to conclude that silviculture can be integrated with bald eagle management on the same area.

Restricting activities during the times when breeding eagles are most sensitive to disturbance is one of the most effective ways to mitigate conflicts between forest operations and bald eagle nesting success. Forest management activities should take place after young have fledged and before the start of the next nesting season (McEwan and Hirth 1979).

Identify Used Habitats

The regional variability in substrate and other habitat conditions requires a site specific approach to formulating management guidelines. Anderson (1985) noted variability of habitat conditions and levels of human disturbance at nest sites and suggested the ineffectiveness of preparing a specific prescription that would apply to all eagle nesting habitat.

Due to the variability in nesting substrate and habitat preferences it is important for managers to know the factors influencing habitat preference in their specific area. Site specific factors such as level of tolerance to disturbance and development, topography, and ecological characteristics such as the type of foraging habitat and forest cover affect which areas are used has habitat.

A top priority for management is to identify where and when bald eagles use habitat. Aerial surveys, ground based monitoring, and locally applicable habitat suitability models can be useful. Population monitoring through counts of breeding pairs and annual young produced are essential for managing for productivity. Knowledge of habitat preferences enables managers to focus efforts on areas that will reap the most benefit. Preference areas typically include locations within a limited distance from water and foraging habitat. For example, McEwan and Hirth (1979) suggested that there is no reason to create bald eagle habitat greater than 3 km from water. Guinn (2004) recommended the protection of large diameter trees within close (1 km) distance to water.

Nesting and Habitat Protection

Bald eagle protection policy is varied and multiple frameworks exist depending on the region. Over the history of bald eagle protection, policy guidelines and specifications have changed multiple times; however several key strategies have been consistently utilized including: nest tree protection, circular buffer zones, linear visual buffer strips, seasonal activity restrictions, preservation of large canopied trees, and restricted areas.

Protective Buffers

By federal law, a bald eagle nest and the tree/structure in which it is located cannot be removed as long as any portion of the nest remains in the tree/structure, regardless as to whether the nest is currently active or abandoned (USFWS and VDGIF 2001). Beyond the nest tree, the most common protective tool is a circular buffer, or series of concentric buffers, around existing nest trees and roosting sites. In Virginia, for instance, the recommended radius of the primary zone is 750 feet (229m), with the precise size of the zone depending on site conditions and the eagle's tolerance for human activity (USFWS and VDGIF 2001). In this first buffers zone it is recommended that all disturbances be prohibited. A second buffer zone extending beyond the first radius is often active only during the nesting season and gives further protection from disturbance with slightly less restriction. In the secondary buffer, limited timber harvesting may be possible.

Beyond the buffer zone

Many studies have noted the limitations of the buffer approach and its arbitrary sizes and as a result, buffer sizes have increased over the years. Anthony and Isaacs (1989) suggested that buffers are generally too small and can create "islands" of habitat within stands of young, even-age forests. Small isolated islands of nest buffers are susceptible to blowdown and have limited longevity. Maintaining a buffer of adequate size around nest trees also helps protect nests in areas with high windthrow hazard which could damage the nest or the entire nest tree (Anthony and Isaacs 1989).Gende et al. (1998) noted that the use of small buffer zones around the nest does little to provide for alternate nesting sites and perch habitat. Isaacs et al. (2005) showed that new nest trees are often outside of recommended buffer zones. They suggest that the long term consequence of nest tree selection outside of protected areas is important to consider, especially where nesting habitat is limited.

Linear buffer strips have been recommended to screen eagle nesting habitat from human disturbance (Stalmaster and Newman 1979). These strips do not need to completely surround the nest to reduce or eliminate line-of-sight (Juenemann 1973, Gerrard et al. 1975, Stalmaster and Newman 1979). They recommend that strips be 75-100 m (246-328 ft.) wide to adequately screen most disturbances. Andrew and Mosher (1982) suggested that buffer strips may effectively mitigate the disturbance effects of power plants, roads, logging, and recreation.

Bald Eagle Nesting Habitat Modeling

Bald eagle habitat has been described and quantified using many different modeling approaches. Much of the literature on bald eagle nesting has used statistical analysis to determine which habitat variables were important in describing selected sites. Fewer studies in the literature actually present a model in which measured variables can be input to derive a suitability rating. A limited number of such models exist for bald eagle nesting habitat and include models for Maine (Livingston et al. 1990), the Chesapeake Bay (Watts et al. 1994), the Great Lakes (Grubb et al. 2003), and the northern coterminous U.S. (Peterson 1986). These models either ignore forest structure or assess structure at a level too coarse for adequate assessment of silviculture.

Livingston et al. (1990) developed nesting habitat models for 4 habitat types in Maine including: inland river, inland lake, marine mainland, and marine island. This model used only three variables to describe forest nesting substrate: number of superdominant trees, length of forest edge, and area of land subjected to timber harvesting. Using discriminate function analysis, the variables which had the greatest classification power were entered into the final four models. Of the forest variables, length of forest edge was included in the inland river model and the marine island model. Number of superdominant trees and area of timber harvest were included in the lake model. River nest sites were found to be in areas being close to the shoreline of large rivers and having little forest edge. The lake model described nest sites as being positively associated with superdominant trees and negatively associated with areas of timber harvest, other disturbances, and distance to shoreline. The marine island model described nesting sites as being near openings, having little forest edge, and in waters classified as shallow.

Watts et al. (1994) used discriminant analysis to model suitable habitat in the Chesapeake Bay. Their model used variables of distance to nearest open channel, distance to nearest building, and distance to nearest secondary road, and produced a classification accuracy of 81.5%. The discriminant procedure found that forest variables which attempted to quantify the forest structure near to the nest did not score highly as discriminating variables and were therefore left out of the final model. They used the presence of forest as one indicator in a "quick and dirty" method of determining whether an area met the requirements to proceed with the final habitat suitability model.

Grubb et al. (2003) developed a Bayesian inference based pattern recognition (PATREC) model to classify bald eagle habitat along Great Lakes shoreline using six attributes: tree cover, proximity of human disturbance, type/amount of human disturbance, potential foraging habitat/shoreline irregularity, and suitable perch and nest trees. Peterson (1986) created a USFWS Habitat Suitability Index (HSI) model for breeding bald eagles in the northern coterminous U.S. The Peterson HSI model was developed as part of the USFWS Habitat Evaluation Procedure (HEP). HEP was developed for the evaluation of wildlife habitat for environmental impact assessments and project planning. As part of the HEP process, the HSI system was developed to determine the suitability of habitat for specific wildlife species (USFWS 1981). The early HSI system was based largely on review of the applicable literature, mostly relevant at a regional scale, and generally not based on statistical procedures. Forest substrate was addressed in the Peterson HSI model by evaluating the amount of mature, open canopy forest cover within 1.5 km of water. This model places optimum conditions for nesting in forest where mature timber exceeds 75% of the land area. The definition of mature timber is left up to the user of the model depending on the specific site; however, Peterson (1986) suggests the definition of mature timber as undisturbed, with uneven-aged structure and having a discontinuous canopy > 20 m (66 ft.) high. As mature forest cover declines from 75% of the evaluation area, suitability of this habitat component declines in a linear fashion. The Peterson HSI model also works under the following assumptions: mature forest stands within 1.5 km (0.93 mi.) of water "provide optimal nesting conditions regardless of stand composition" and "immature forest stands provide no nesting habitat".

All of these models attempt to use the most important and measurable variables to determine the suitability of an area as nesting habitat. Because of the greater importance of foraging habitat and disturbance in these broad regional models, micro-habitat forest variables were found to be unimportant discriminators of habitat quality. Not limited to what has been published for the bald eagle, a multitude of wildlife habitat modeling techniques exist to apply to modeling quality of forest nesting substrate, ranging from simplistic models based on general assumptions and current knowledge to more complex statistical models created from empirical data. Two particular methods were of interest to this study as a means of rating forest substrate using "presence" data: Mahalanobis distance and a Boolean logic model using cumulative distribution functions to determine adequate ranges of habitat variables. Presence data consist of measured habitat variables at sites where the species has been observed, or is known to use, and can be used to define the habitat used by a species. Presence data does not, however, define habitat that is not used because a species might use the habitat sampled even though its presence was not observed or known at the time of measurement (Dettmers and Bart 1999). For this reason, the habitat of highly mobile or elusive species can often only be described using presence data.

Mahalanobis Distance

Clark et al. (1993) used the Mahalanobis distance statistic to develop a model of black bear habitat. Mahalanobis distance is defined by the equation:

Equation 1: Mahalanobis Distance

$$d = (\underline{x} - \underline{\hat{u}})' \hat{\Sigma}^{-1} (\underline{x} - \underline{\hat{u}})$$

where $\underline{x}$ is a vector of habitat variables associated with each sample observation; $\underline{\hat{u}}$ is a mean vector of habitat characteristics estimated from the known habitat sample; and $\hat{\Sigma}$ is the estimated covariance matrix from the known habitat sample. Under this model, "optimum" habitat is defined as a multivariate vector of the means of the habitat variables measured from known habitat, $\underline{\hat{u}}$. The Mahalanobis statistic measures the "distance", or dissimilarity, of a multivariate mean of an observed sample plot, $\underline{x}$, to the multivariate mean of the optimum. Since it is a continuous measure, a threshold Mahalanobis distance value must be set which delineates good habitat from otherwise (Dettmers and Bart 1999).

Mahalanobis distance is considered well-suited to use with “presence” data. Clark et al. (1993) suggested that Mahalanobis distance could be used in evaluation of land management practices by using “what if” scenarios to optimize the effects on habitat. Knick and Dyer (1997) used the Mahalanobis statistic to rank cells in a GIS raster layer relative to the multivariate mean of habitat variables associated with black-tailed jackrabbits in Idaho. This technique enabled determination of the differences in spatial distribution of jackrabbit habitat by season and population phase.

The Mahalanobis distance statistic does not require equal variance-covariance matrices or equal group sizes, nor do assumptions of multivariate normality have to be met. Mahalanobis distance can be calculated for variables of any distribution, however, its properties are best known for normal data (Knick and Dyer 1997, Dettmers and Bart 1999)

Cumulative Distribution Function Approach with Boolean Logic

Dettmers and Bart (1999) presented an alternative to Mahalanobis distance for use with presence data by defining “good” habitat based on the cumulative distribution functions (CDF) of important habitat variables and Boolean operators. By graphing the CDF of the variables for presence observations alongside the distribution of the variable measurements for the random sample, they were able to identify the range of values for the variable which maximized the difference between the presence observations and random plots, given that a threshold percentage of presence observations were identified as good habitat. After the ideal ranges of habitat variables are determined from the comparison of the CDFs, a definition of habitat can be developed which joins the ranges using Boolean operators “*AND”* and *”OR”* to classify habitat as good or otherwise. An example of such a habitat definition is illustrated by the following statement, as provided in Dettmers and Bart (1999):

$$\left[\left(X_{1_L} < x_{1_i} < X_{1_U}\right) OR \left(X_{2_L} < x_{2_i} < X_{2_U}\right)\right] AND \left(X_{3_L} < x_{3_i} < X_{3_U}\right)$$

where x_{1_i}, x_{2_i}, and x_{3_i} are values for the variables 1, 2, and 3 for a sample observation, and X_{j_L} and X_{j_U} represent the lower and upper limits of ”good” habitat for variable j.

Suitability Threshold

In most analyses of eagle habitat it is important to determine habitat requirements or thresholds which are prerequisite to be considered for further analysis. This helps to focus efforts on areas which have potential to be used as habitat and avoid wasted effort on the analysis of areas which would never be considered for nesting. Summarizing many studies, bald eagle habitat suitability thresholds or requirements typically involve satisfying one, or several, of the following categories:

- Presence of forest, or a minimum % of the area forested
- Within a minimum distance of water (region dependent)
- Greater than a minimum distance from developed areas (roads, buildings)
- Greater than a minimum distance from disturbance (logging, development)
- Presence of a minimum tree diameter

Stratification of data

Another important step in modeling preferred habitat or habitat suitability is data stratification. In their description of nesting habitat in Maryland, Andrew and Mosher (1982) stratified pine and hardwood sites due to inherent differences in forest structure. Likewise, Livingston et al. (1990) created four separate habitat models for marine island, marine mainland, inland lake, and inland river. In their description of nesting habitat in Oregon, Anthony and Isaacs (1989) also separated nest sites into forest types of Douglas fir, mixed conifer, and ponderosa pine forest types for analysis and comparison. Data stratification groups observations with similar conditions, reduces the variability in the data due to mixing drastically different data, and thus allows for greater confidence in a habitat definition created from data averages. Generating one model of preferred habitat from data with wide variation can result in a model which broadly defines habitat and has reduced effectiveness at a smaller extent. Additionally, a coarse definition of habitat can fail to uncover patterns and unique characteristics of habitat specific to a particular data stratum.

Modeling Assumptions and Caveats

All models operate under assumptions which may not apply to all situations. Additionally there are caveats which should be understood about how a model was developed before management decisions can be evaluated using the model. The following concerns relating to modeling nesting habitat are discussed and include: description of nesting habitat using measurements from altered sites; inappropriate use of models in management planning, policy formation, and implementation; effects of scale and extent; and understanding model uncertainty.

As mentioned earlier, breeding pairs often display fidelity toward a nest site even after the conditions at that nest site have been altered. This can lead to a misrepresentation of the characteristics of eagle habitat where nest sites are measured years after they were initially selected. McEwan and Hirth (1979) recognized that it was impossible to identify the level of human activity at the time a nest was built and how this level of human activity may have affected nest site selection. Anthony and Isaacs (1989) also noted difficulty in knowing what habitat bald eagles may have originally selected versus what was tolerated for nesting, and recommended using unaltered nest sites as the model for guiding management actions.

Local extent and grain are important factors in the scale of analysis of habitat around a focal point (Thompson and McGarigal 2002). Extent is the coarsest level of the detail in the study and typically is represented as the study area, while grain is the finest level of resolution, or minimum mapping unit (MMU), such as the plot in field data or the cell in a raster GIS layer. If the scale of the analysis is too large, important small scale details that dictate habitat selection may be missed. Likewise, if the scale is too small, large scale landscape factors may be missed in the analysis.

Finally, models of natural systems are built upon assumptions and involve uncertainty due to natural variation. For example, forest development is greatly affected by regeneration, climatic and weather patterns, and site specific factors such as herbivory. Variability in these factors can result in very different results in stand development over time. Perhaps most of all, the simulation of regeneration over the course of a management regime greatly affects future stand conditions. In silviculture regeneration is one of the most challenging processes to influence and predict. Forest managers must use the best science in planning for natural regeneration and use adaptive management to achieve desired regeneration goals. In the case of simulating the responses to silviculture, management regimes were locked in to a given schedule of management actions. Similarly, regeneration was based on a mechanistic procedure of seed production proportional to canopy composition and greatly simplifies the ecological complexity inherent in natural regeneration in forests.

Chapter 3: Methods

Study Area

NSFIH is located in Charles County MD, approximately 30 miles south of Washington D.C, in the Coastal Plain physiographic province. The installation encompasses 3,314 ac with approximately 1648 ac of forestland. The land consists of three peninsulas, Cornwallis Neck, Stump Neck, and Bullitt Neck, with approximately 17 miles of shoreline on the tidewater of the Potomac River and its tributaries Mattawoman Creek and Chicamuxen Creek. NSFIH is approximately 80 river miles from the mouth of the Potomac and the confluence with the Chesapeake Bay. The terrain on NSFIH includes flat river terrace, rolling hills, and steep gullies and ravines. Elevations range from 0 to 130 feet above mean sea level. The majority of Mainside is generally flat with the steepest areas occurring along the shoreline or at drainage areas. Greater topographic variation occurs on Stump Neck with more rolling terrain with increased occurrence of steep gullies and ravines. The landscape on Bullitt Neck is flat to gently sloping with much of the low-lying land near the point of the peninsula and near the southern boundary mapped as wetland.

Forest cover varies by landscape position and includes: cove sites with bottomland hardwoods such as sweetgum, American beech, yellow poplar, and willow oak; mesic flats with seasonal wetlands dominated by willow oak, sweetgum, and red maple; rolling slopes and uplands dominated by mixed upland hardwoods such as white oak, southern red oak, hickory, sweetgum and yellow poplar, to dry uplands dominated by chestnut oak. Loblolly pine stands make up the smallest proportion of the forest and are primarily plantations, but some mixed pine/hardwood stands exist on the installation. 99.1% of the forest area is composed of deciduous forest with pine making up the remaining 0.9%.

NSFIH presents an interesting case study of bald eagle nesting due to its fragmented forests, moderately high levels of human activity and disturbance, and relatively dense bald eagle population. The forest on Cornwallis Neck is the most fragmented due to roads, buildings, and other infrastructure. Stump Neck, the second largest peninsula, is less developed with considerably more contiguous forest area. Bullitt Neck, the third peninsula, is the smallest of the three and is almost entirely forested except for a building used as a nature center. Terrestrial-based human disturbance is limited to low density residential housing, however forest harvesting has occurred on Bullitt Neck within the past 20 years. Military training is minimal on NSFIH and typical disturbances to nesting on land include explosive ordnance disposal, energetics testing, construction, and regular vehicle and pedestrian traffic. Typical water based disturbances result from recreational boating and fishing.

Data Collection

NSFIH Forest Inventory Sample

The NSFIH forest was inventoried from March to August 2010 as part of the installation's FMP update. The sampling method employed in the inventory was a stratified random sample which enables reduced error in estimating the overall population mean by estimating means from uniform strata with reduced variability and then combining means and errors (Avery and Burkhart 2002). Using ArcGIS (ESRI 2010), a 1 chain square grid of points was overlaid on a 2009 aerial photograph of the installation and the existing forest stands polygon layer. For each stratum, generally a pre-delineated stand polygon, a systematic random sample was established by selecting points from the grid at a uniform spacing which adequately covered the unique size and shape of each stand. The use of the regular grid of points resulted in a fairly regularly spaced sample when viewed at the scale of the entire NSFIH forest. The sampling unit used for overstory measurement was a 1/10th ac plot. Within the plot, all stems greater than or equal to 4.5 inches DBH were tallied by species, and data on merchantability, defect, quality of growing stock, live crown ratio, and canopy position was recorded. A total of 388 permanent forest inventory points were established available for analysis.

In addition to overstory plot data, increment core samples to estimate stand age and diameter growth data. In each large tree plot at least one increment core was sampled from a dominant or co-dominant tree. In some plots additional cores were sampled from sub-canopy trees in order to gather additional data on age and growth rates in subordinate crown classes. Increment cores were allowed to dry and then sanded to improve visibility of the growth rings. The age of the core was determined with the magnification aid of a dissecting microscope. The age of dominant and co-dominant trees enabled the calculation of site index (SI). SI was calculated using the curves and equations provided in Carmean et al. (1989). Age and radial growth was measured through the last full growing season, stopping at the beginning of the 2010 growing season. The radial growth of the last 10 years was measured using a digital caliper to the nearest hundredth of an inch and then doubled to derive an estimate of 10 year diameter growth (DG).

Presence Data

Preferred nesting substrate was sampled at a total of 13 known nesting sites on NSFIH, located with the assistance of natural resource staff. Using the nest tree as the plot center, a circular, 1/4 ac plot was established and all trees greater than 4.5 inches were tallied by species, measured for DBH, and classified by crown position using classes of dominant, codominant, intermediate, and overtopped. At the nest tree, total height and height to the base of the nest were also recorded. Eleven of these nest sites were in hardwood dominated stands; the remaining two sites were in pine dominated stands. Due to sample size, all known locations, including one inactive and two historical sites, were measured to gain all available information. Table 1 provides a listing of the nest sites measured, the year the nest was discovered (most likely the year the site was first selected), and the nest activity status as of 2010. Active nest sites are those sites occupied by eagles and which produced eggs during the last breeding season. Inactive nest sites are those which did not produce eggs by April 1st of the previous breeding season. Historical nests are those which have not produced eggs for the past three breeding seasons and may or may not still have an existing nest (Navy 2010).

The habitat component of interest in this analysis is the forest nesting substrate, the land area of NSFIH represents the extent, and the forest inventory plots and nest site plots represent the grain. While external factors such as proximity to foraging habitat, human disturbance, and presence of roosting and perch habitat are necessary components of holistic nesting habitat, the analysis of just the forest nesting substrate is modeled in this study by 1/10 ac forest inventory plots and ¼ acre plots around nest sites. It is believed that this plot size adequately captures both the characteristics of a potential nest tree and the structure of the forest at that site. Extending plot size is believed to have no significant benefit in the evaluation of the forest nesting substrate.

Table 1: Nest sites at NSFIH, with 2010 measurements of DBH and Height.

Nest Site	**Year Discovered**	**2010 Status**	**Nest Tree Species**	**Nest Tree DBH**	**Nest Tree Ht**
Biazzi	1998	active	BO	29.2	80
Rum Point	2004	active	BO	30.7	100
Bullitt Neck	2006	active	LP	19	90
Riverview	2009	active	LP	22.7	92
Burn Point	2006	active	RO	40.1	118
Area 8	1998	active	SK	33.9	111
Extrusion	2000	historical	SK	39.7	90
Large Motor	2006	active	SK	52	90
Building 1569	2006	inactive	WK	50.4	127
Hyper Velocity #1	2000	historical	WK	61	115
Hyper Velocity #2	2008	active	WK	51	123
Range 6	1996	active	WK	59	91
Range 3	2010	active	WK	55	96

In general forest characteristics on most sites were assumed to have changed minimally since initially selected; however in an attempt to counteract the effects of growth on the plots, a simple method of diameter reduction was conducted to provide an estimate of plot conditions at the time of site selection. Increment core data from a total of 414 increment core samples were used to backdate diameters measured at the nest sites. Growth rates were not available for all species, so increment data was summarized by crown position and plot basal area classes of 40 ft^2 increments: < 80, 80-120, 120-160, and 160-200 and > 200. Growth summaries were based upon the assumption that growth rates relate to crown position and stand density. Average 10 year diameter growth was calculated for each crown/density combination and then divided by 10 to get average annual growth. Nest plot tree diameters were then reduced by annual growth rates year by year according to the basal area of the plot for that year until reaching the year of nest selection,

Development of the Model

Two habitat modeling techniques for use with presence data were used during the development and evaluation of the nest substrate model: 1) MD and 2) a Boolean logic model derived cumulative distribution functions (CDF) of "presence" data and random observations (after Dettmers and Bart 1999). The objective was to develop a model which defined preferred substrate using data from the nest sites and could classify forest inventory plots as "preferred" or "otherwise". This classification allowed the evaluation of the effects of silvicultural treatments on substrate availability over time.

At the outset, MD was believed to provide an objective and sophisticated multivariate method for both defining preferred nesting substrate and rating sample observations based on their dissimilarity to this model. The mathematical complexity involved in calculating MD, however, presents an obstacle for the understanding and use of this statistic by non-statisticians. Such complexity may invoke concern from resource managers wishing to use this method to evaluate nesting substrate. The CDF model, on the other hand, offers a graphical approach to developing a habitat definition and then uses logical (e.g. *and/or*) statements to classify habitat. The CDF model also presents a means to rate the effectiveness of a given habitat definition and investigate the strengths and weaknesses of the MD model. In the final analysis of simulation results MD was used; however the CDF model provided an interesting basis for comparison of the relative fit of the substrate models to the study data. Explanation of these two techniques follows.

Mahalanobis Distance Model

The MD statistic is a measure of dissimilarity between the multivariate mean of the nest observations and the multivariate mean of an individual observation. The mean of nest observations is made up of independent variables to describe the characteristics of used habitat. MD uses the standard deviations of the habitat variables in the covariance matrix and reflects the interactions among the measured variables, allowing a dimensionless, standardized distance measurement which can be produced by multiple combinations of habitat variables (Clark et al. 1993).

The structural variables used in the description of preferred substrate and as input into the substrate model were selected based upon the findings of the literature review, observations during the data collection at the nest sites at NSFIH, compatibility with FVS, and evaluation using the MD technique. Habitat variables were selected that adequately described the unique composition of used habitat independent of other variables.

Perhaps the most important component of forest nesting substrate is a suitable nest tree. The nest tree must have a large crown and sufficient strength to support a nest which is highly correlated to having a large diameter (Dawkins 1963). Additionally, tree diameter is a more important indicator of nest tree selection than tree height (Guinn 2004). Forest sampling at nest sites at NSFIH revealed similar trends in discontinuous forest canopy and large diameter nest trees (Table 1). In addition to a large diameter nest tree, many studies have reported the trend of discontinuous forest canopy at nesting sites and attribute this structure to the need for canopy openings to allow open flight paths for ease of access into and out of the nest (McEwan and Hirth 1979, Andrew and Mosher 1982, Anthony and Isaacs 1989). Out of the different strata of the forest canopy the stratum where the nest is located was assumed to be most important for identifying preferred characteristics of nesting substrate. On average, at the nest observations on NSFIH, the nest was located at a height of 70% of the nest tree total height.

Since a variety of forest structures can produce the type of canopy discontinuity and nest tree dominance preferred by nesting eagles, model variables needed to describe these characteristics while maintaining flexibility in the definition of preferred substrate structure. The simulation of forest conditions using FVS required the use of distance-independent structural metrics as surrogate measures of nest tree dominance and canopy discontinuity. The ideal surrogate metrics were those that specifically described the wildlife-habitat relationship believed to be important (e.g., open flight paths, dominant nest tree) without extraneous structural description which may confound the habitat definition. A range of structural metrics and variable combinations were considered for describing canopy discontinuity and nest tree dominance.

Metrics considered as possible surrogates for describing canopy discontinuity included: basal area, trees per acre, stand density index, percent canopy cover and covariance of tree heights. For nest tree dominance, metrics considered included: maximum height, maximum DBH, percentile of DBH, maximum DBH divided by quadratic stand diameter, and maximum height divided by average height. Many structural metrics are highly correlated with one another or require another metric to qualify the first. For example, basal area may be equal for two stands of different size and trees per acre. Therefore, basal area must be qualified by another metric such as trees per acre or average stand diameter in order to more completely describe the stand structure. Reineke's (1933) stand density index (SDI) is a composite index that addresses this issue by using quadratic stand diameter and trees per acre to describe stand density. Percent canopy cover (PCC) is defined as the percentage of the ground covered by the vertical projection of tree crowns, reflects the dominance of a site by trees, and can be measured by species or for a certain size tree (Jennings et al. 1999). PCC applies most directly to the area of the forest used for nesting and thus is a more logical choice for measuring canopy density compared to SDI or basal area. Covariance of tree heights was highly variable across nest sites and a poor determinant of preferred substrate. As surrogate measures, trees per acre, basal area, covariance of tree height, and SDI all include extraneous structural information which is insignificant to nesting requirements and confounds the substrate model.

Average distance-independent, density metrics become less effective for describing structure in un-even age stands or stands with multimodal diameter distributions as is often the case at nest sites. FVS functionality allows metrics to be calculated for a user-specified subset given a diameter or height range. This enabled isolation of density measurement to the trees which make up the dominant canopy stratum and allowed canopy density to be assessed in the area where nesting is most likely to occur.

For the dominance variables considered, maximum DBH was found to provide the most direct and flexible indicator of the presence of a suitable nest tree. Composite dominance variables such as maximum DBH divided by the average DBH, as well as DBH percentile were found to disallow flexibility in describing the diameter distribution of a preferred nest site. Together, maximum DBH and PCC combine to describe the presence of a suitable nest tree and canopy discontinuity for open flight paths. Increasing the number of structural variables to the model affected the flexibility of the habitat definition by constraining the defining of preferred forest structure with confounding information. Additionally, as the number of variables increases their individual power of classification decreases (Morrison et al. 1998).

Two variables were found to provide the most flexibility and logically describe substrate requirements: PCC of trees at least 70% of maximum height, referred to as PCC of the nesting stratum (PCC_{NS}), and maximum DBH (DBH_{MAX}). PCC_{NS} provides a measurement of the density of the canopy stratum most likely to affect eagle nesting and ignores the forest canopy below this stratum. DBH_{MAX} indicates the presence of a tree most likely to be used for nesting due to its dominant size and the high correlation between diameter and crown size (Dawkins 1963) Simple linear regression showed no significant correlation between DBH_{MAX} and PCC_{NS} ($r^2 = 0.02$). MD was calculated for each possible combination of PCC_{NS} and DBH_{MAX} using Statistical Analysis Software, Interactive Matrix Language (SAS/IML) (Version 9.2, SAS Institute, Inc.). Once calculated, the MD of any possible combination of PCC_{NS} and DBH_{MAX} could easily be identified using Microsoft Excel, enabling rapid evaluation of nesting substrate. Because MD is a continuous measure of dissimilarity, a threshold value was necessary to delineate “preferred” substrate from “otherwise”. The MD threshold was set to a value of 4, a distance which included all nest observation points.

Cumulative Distribution Function Model

Dettmers and Bart (1999) presented an alternative to the MD method for use with presence data. By comparing the CDF of presence observations for a variable against the CDF of all study area observations they were able to identify cutoff values which maximized the difference between presence observations and study area plots. These cutoff values defined the range of values which were considered “good” habitat. They evaluated the relative fit of a given habitat definition by the value $p_o - P_s$, where p_o is the proportion of presence observations classified as good habitat and P_s is the proportion of all observations delineated as good habitat. In all habitat definitions, p_o is required to be greater than *t,* a threshold minimum percentage of presence observations classified as good habitat. The choice of this threshold provides flexibility where a level of habitat protection or conservation exists to meet regulatory requirements for a target species in addition to the consideration of other resource objectives, economics, and/or policy directives (Dettmers and Bart 1999).

Following the methods outlined in Dettmers and Bart (1999), the CDFs of nest observations and random plots were graphed for the variables PCC_{NS} and DBH_{MAX}. Models with $t = 1.0$ and t = 0.9 were evaluated. Threshold values below 0.9 excluded too much of the already limited nest sample. Figure 1 shows how the CDFs were used to determine the range of preferred habitat for PCC_{NS} and DBH_{MAX}. Under t=1.0, the threshold requiring 100% of the nest observations classified as good, the range of PCC_{NS} was defined as ≤ 61% and ≥ 15%. The t = 0.9 model, requiring only 90% of the nest observations to be classified as good, resulted in a reduction of the upper limit of PCC_{NS} to 57% while the minimum cutoff remained at 15%. For DBH_{MAX}, the lower limit for both t=1.0 and t=0.9 which maximized the difference between CDFs was 18.8 in. Combining the two variable ranges using Boolean operators results in the following models for thresholds of 1.0 (Equation 2) and 0.9 (Equation 3).

Equation 2: CDF model of preferred substrate under a classification threshold (t) of 100%

$$Preferred\ substrate|t(1.0) = (18.8 \leq DBH_{max})\ and\ (15\ \leq PCC_{NS} \leq 61)$$

Equation 3: CDF model of preferred substrate under a classification threshold (t) of 90%

$$Preferred\ substrate|t(0.9) = (18.8 \leq DBH_{max})\ and\ (15\ \leq PCC_{NS} \leq 57)$$

All available nest observations were used in the creation of the NSFIH preferred substrate model, which prohibited the use of nest sites for model validation. This particular habitat definition was intended to apply to NSFIH; however this forest only substrate model could be tested using other nesting areas with similar forest types in the Chesapeake Bay region. Additionally, as new nest sites are selected, the model can be tested and improved.

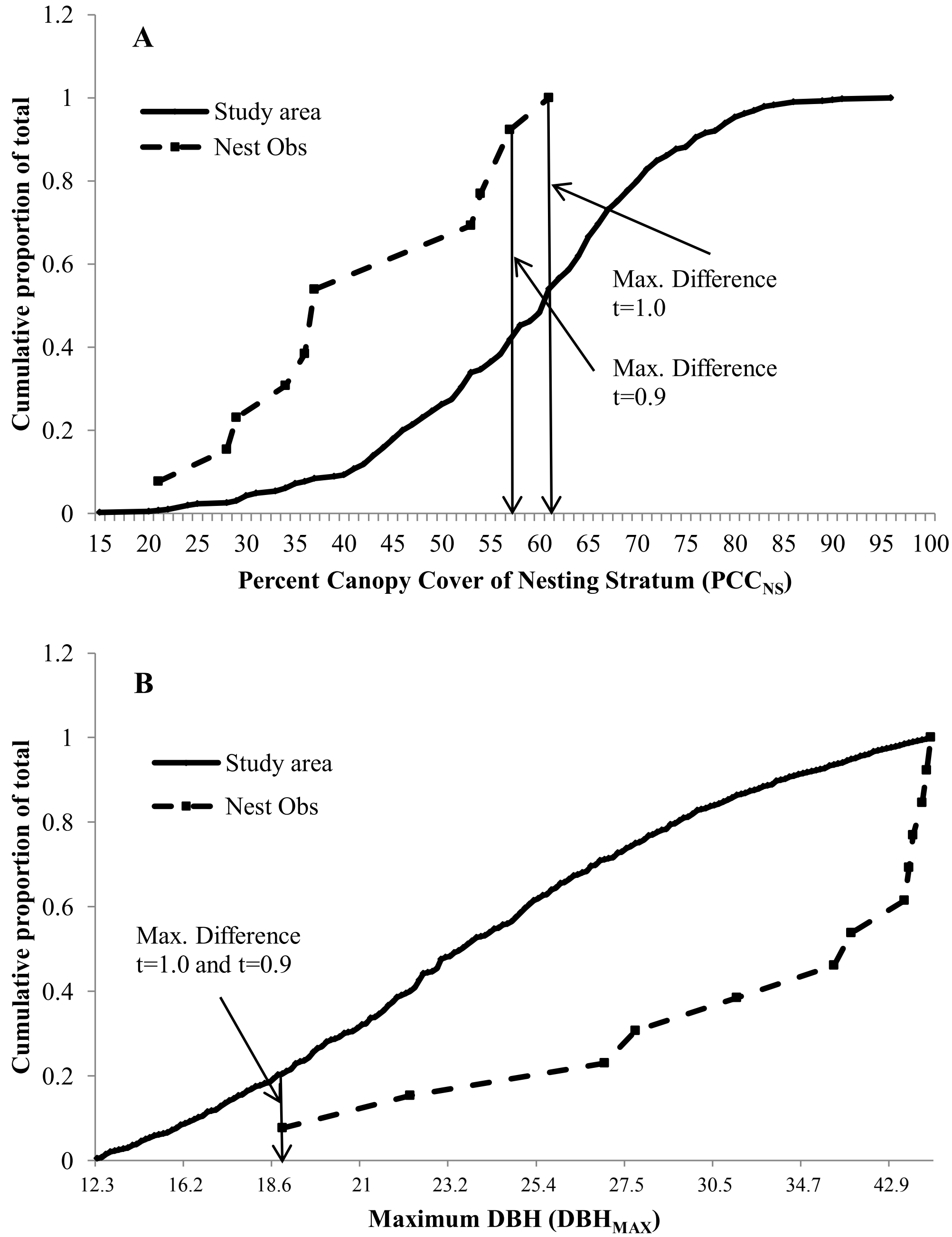

Figure 1: Cumulative distribution functions for PCC_{NS} (A) and DBH_{MAX} (B) used to determine the ranges for the definition of preferred habitat under threshold classification rates of 1.0 and 0.9. Under t=1.0 maximum PCC_{NS} is defined at 61% and 57% for t=0.9. Reducing the threshold had no effect on the minimum DBH_{MAX} which was defined as 18.8 inches.

Simulating Forest Harvesting Effects

Forest Vegetation Simulator

FVS was used to simulate forest management treatments, calculate the nesting substrate variables, and estimate the value of harvested volume. FVS was developed by the US Forest Service (USFS) and is used for forest growth and yield modeling, forest planning, and research. *Suppose* (version 2.20), the graphical user interface of FVS, was used because of its simpler approach. FVS provides flexibility in the design of treatments and is applicable to a wide variety of cover types, stand structures, and geographic regions. The southern variant of FVS was used because NSFIH is situated at the southern edge of the recommended region for the northern variant and the forest types present on the installation more closely resemble southern pine and hardwood forests than forests of the regional extent of the northern variant.

Extensions to FVS are available for expanding the analytical capabilities of the base model. Economic analysis was facilitated using ECON, the economic analysis extension of FVS. ECON allows the user to set the per unit value by species and merchantability limits. The methodological approach of this study relating to the use of FVS follows. For a more detailed explanation of FVS functions refer to Essential FVS (Dixon 2002), Southern Variant Overview (Keyser 2008), Keyword Reference Guide for the Forest Vegetation Simulator (Van Dyck 2000), and User Guide to the Economic Extension (ECON) of the Forest Vegetation Simulator (Martin 2009).

Simulation Approach

NSFIH forest inventory data was formatted for input into FVS using the database extension capabilities of *Suppose* and Microsoft Access. Management treatments were simulated on a plot level since each plot represents a unique observation of potential nesting substrate. Management was simulated on 385 out of the 388 forest inventory plots classified into forest cover types of loblolly pine (*Pinus taeda*) (n=30), sweetgum/yellow poplar (*Liquidambar styraciflua/Liriodendron tulipifera*) (n=65), upland oak (*Quercus spp.*)(n=167), and mixed hardwood (n=124). The remaining 3 plots were not used because they belonged to cover types which were not significant on the forest: tree of heaven (*Ailanthus altissima)*, Virginia pine (*Pinus Virginiana*), and black locust (*Robinia pseudoacacia*)). Stratifying plots by cover type allowed increased sample sizes and greater variation in conditions by cover type. Due to the silvical differences between cover types and resulting behavior under management simulation, there was little utility in combining simulation results of plot from different cover type.

Diameter growth, live crown ratio, and site index data from the inventory aided growth model calibration. The southern variant of FVS estimates volume using stem profile equations from Clark (1991) and Lasher (as cited in Keyser 2008). FVS sawtimber estimates were adjusted to match conservative volume estimates from the forest inventory using a ratio of inventory volume to FVS gross volume. This ratio was averaged by species and diameter class and input into FVS using the BFDefect keyword to adjust FVS sawtimber volume estimates throughout the simulation period.

Harvest values were calculated for sawtimber and pulpwood product classes. The ECON extension provided valuation of harvested sawtimber volumes. ECON does not provide direct functionality to value for pulpwood, so pulpwood was valued by computing the harvested pulpwood volume, multiplying volume by the value by species group, and using the special revenue (SpecRevn) keyword to input the pulpwood values. Stumpage prices used in harvest valuation were guided by 2nd Quarter of 2009 estimates for the eastern region of Virginia published in Timber Mart South (Norris Foundation 2009). Table 2 provides the stumpage value and minimum DBH for merchantable species and species groups valued during the simulations.

Table 2: Stumpage prices for merchantable species and species groups guided by Timber Mart South 2nd Quarter prices for 2009.

Species	$/unit	Min. DBH (in.)
Loblolly pine sawtimber	$169/MBF	10
Sweetgum sawtimber	$85/MBF	12
Yellow poplar sawtimber	$150/MBF	12
White oak sawtimber	$150/MBF	12
Red oak sawtimber	$150/MBF	12
Other oak sawtimber	$130/MBF	12
Virginia pine sawtimber	$80/MBF	12
Black cherry sawtimber	$125/MBF	12
Black walnut sawtimber	$200/MBF	12
Mixed hardwood sawtimber	$80/MBF	12
Mixed hardwood pulpwood	$10/CCF	4.5
Virginia pine pulpwood	$12.8/CCF	4.5
Loblolly pine pulpwood	$12.8/CCF	4.5

The red oak sawtimber group included the more valuable oaks in the red oak group: northern red oak (*Quercus rubra*), black oak (*Q. velutina*), southern red oak (*Q. falcata*), and willow oak (*Q. phellos*). The "other oak" species group included less valuable oak species: chestnut oak (*Q. prinus*), post oak (*Q. stellata*) and scarlet oak (*Q. coccinea*). The mixed hardwood sawtimber species group included: American beech (*Fagus grandifolia*), ash species (*Fraxinus spp.*), bigtooth aspen (*Populus grandidentata*), black gum (*Nyssa sylvatica*), elm species (*Ulmus spp.*), hackberry (*Celtis occidentalis*), hickory (*Carya spp.*), red maple (*Acer rubra*), and sycamore (*Platanus occidentalis*). Mixed hardwood pulpwood included all hardwood species of pulpwood specifications. The ECON summary output provides the undiscounted and discounted costs and revenues, present net value (PNV), and merchantable board foot volume harvested by projection cycle.

No data on forest management costs at NSFIH were available for use in the economic analysis; however, costs were necessary to realistically compare the economic outcomes of treatments with varying requirements for administrative support. Management costs for timber sales were based on estimates of the relative difficulty and man hours required for marking and administration of a given harvest treatment. Thinning and partial harvests requiring significant timber marking (i.e., UEA management, hardwood thinning, and shelterwood cuts), were assigned a cost of $30/ac at each harvest event. Seed tree and clearcut with legacy trees were assigned a cost of $20/ac because of less time required for marking leave trees. Clearcuts with no legacy trees and un-marked thinning of pine stands were assigned a cost of $15/ac to account for administration hours but no marking. Planting costs, as reported in Dubois et al. (1999), were set at $0.05 per seedling plus $0.07 for planting labor, or $120 per thousand trees planted.

Regeneration Method

The southern variant of FVS uses a partial establishment regeneration model, meaning that regeneration from stump sprouting can be input automatically by the model after cutting, but natural regeneration from seed must be input by the user. Regeneration is input using the PLANT or NATURAL keywords which include parameters for the species, quantity, size, and survival rate of the regeneration. PLANT and NATURAL differ only in that PLANT can trigger economic costs. To automatically input natural seeding under the partial establishment model a method was devised which calculated and input natural regeneration according to the stocking and composition of the canopy. The silvical characteristics of important species were used to develop linear relationships between seedling quantity and canopy TPA which were then used for interpolating seedling quantity and survival rate by species. Interpolated seedling quantity and survival were then used in the NATURAL keywords for each ecologically and economically important species.

Seed production, dispersal, and shade tolerance information from Silvics of North America (Burns and Honkala 1990) guided the establishment of linear relationships for natural seeding. Linear relationships between seedling quantity and reproductive TPA were developed for each major species or species group with similar seed production and dispersal rates and shade tolerance. Integrated into this relationship was the shading effect of increased canopy cover on seedling establishment. Figure 2 provides an example of the linear relationship developed for loblolly pine. Quantity of seedlings by species was estimated based on the number of reproductively mature species and the effect of shading from canopy cover on seedling survival. For all species except red maple, black cherry, bigtooth aspen, ash, and beech, 8 in. DBH was set as the minimum reproductive size. For red maple, black cherry, and bigtooth aspen, which can produce seed earlier, 6 in. DBH was used. Beech is reproductively mature around 40 years, so reproductive maturity was set at a minimum of 10 in. DBH.

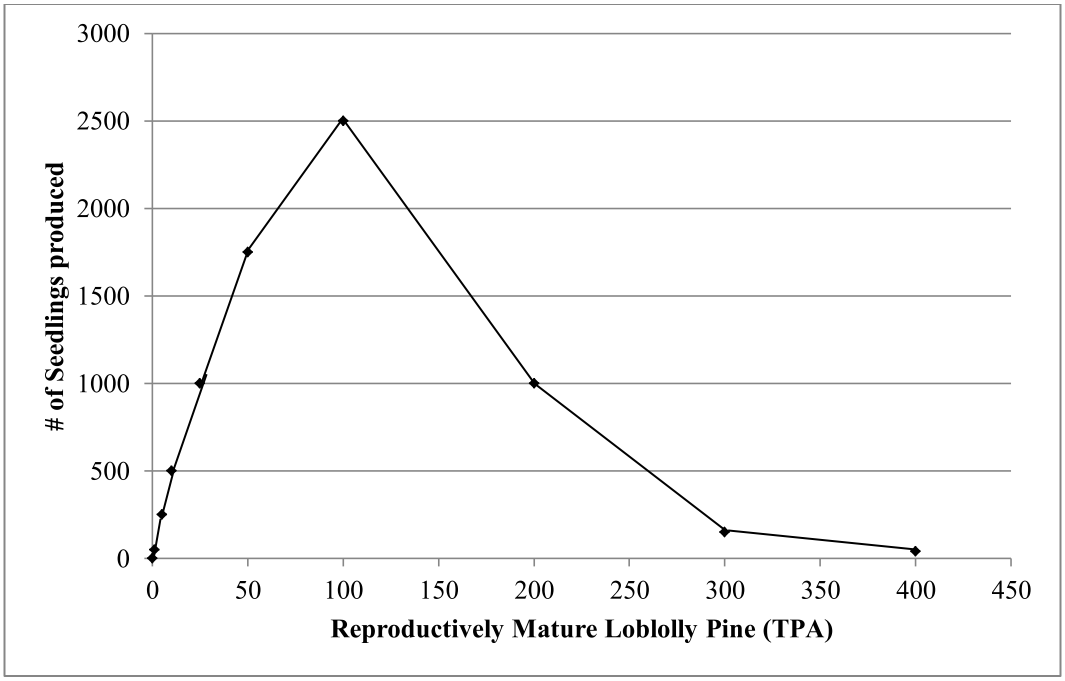

Figure 2: Example for loblolly pine of the modeled linear relationship between seedlings produced per reproductively mature TPA. Linear relationships were developed for each major species or species group with similar seed production and dispersal rates and shade tolerance.

At each 10 year projection cycle or following a harvest event, FVS was programmed to input natural regeneration by first, generating computed variables representing the reproductively mature TPA for each important species. Computed variables can be used as parameters in other FVS functions. FVS provides a linear interpolation function (LinInt) which returns an interpolated value of a variable based on a linear relationship between user-defined parameters. The seedling quantity relationships as depicted in the example in Figure 2 provided the parameters for the linear interpolation of seedling quantity given reproductive TPA of a species. The example code provided in Example 1 shows the LinInt function code used for this interpolation for loblolly pine.

Example 1: FVS Linear Interpolation function code for calculating loblolly pine seedling quantity per residual TPA of loblolly pine.

$$LinInt\ (ResLP, 0, 1, 5, 10, 25, 50, 100, 200, 300, 400, \&$$
$$0.50.250.500.1000.1750.2500.1000, 150, 40)$$

In Example 1, ResLP is the computed variable of reproductive TPA of loblolly pine present in the canopy and the X input for which the Y value, seedling quantity, is interpolated based on the succeeding series of parameters. The ordered series on the first line are the X values of the linear relationship, in this case TPA of reproductively mature loblolly pine. The "&" symbol is used to indicate the continuation of the function across lines. The second line is the ordered series of Y values representing seedling quantity per corresponding TPA value (X) as depicted in Figure 2.

In order to prevent the input of seedlings beyond maximum site occupancy given pre-existing advance regeneration, a multiplier (R_{MULT}) was generated using another linear interpolation (Example 2) to reduce the quantity calculated in the first interpolation based on the quantity of existing advance regeneration.

Example 2: FVS Linear Interpolation function code for calculating the regeneration multiplier (R_{MULT}) for natural regeneration of loblolly pine seedlings.

$$R_{MULT} = LinInt\ (SpMcDBH(\ 1, All, 0, 0, 5, 0, 500, 0, 0), 0, 100, 200, 300, 400, 500, 600\ \&$$
$$1.0, 1.0, 0.8, 0.7, 0.6, 0.5, 0.0)$$

In Example 2, the computed variable R_{MULT} is the regeneration multiplier interpolated by the LinInt function; the first parameter *SpMcDBH(1,All,0,0,5,0.,500.,0,0.)* provides the X input, in this case the TPA for all species between 0 and 5 inches DBH; the series 0 to 600 provides the X values; and the series 1.0-0.0 provides the Y-values. Figure 3 shows the linear relationship between R_{MULT} and existing advance regeneration used to reduce natural regeneration input.

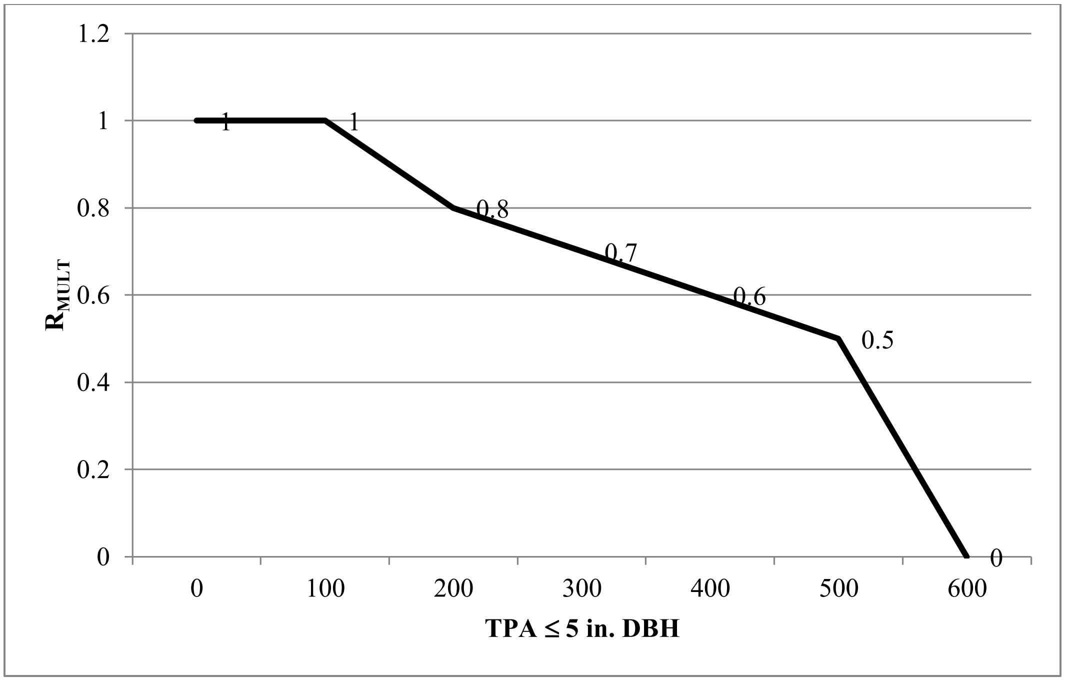

Figure 3: Linear relationship between R_{MULT} and TPA ≤ 5 in. DBH, which formed the parameters for interpolation of R_{MULT}. R_{MULT} reduced the quantity of natural regeneration to avoid input of regeneration beyond maximum site occupancy.

The seedling survival parameter of the PLANT/NATURAL keywords represents an additional control on the quantity of seedling establishment. Linear relationships between percent canopy cover and survival rate were developed for shade tolerance classes of very intolerant (VINT), intolerant (INT), intermediate (INTM), tolerant (TOL), and very tolerant (VTOL) corresponding to each species or species group (Figure 4). Again, LinInt functions were used to interpolate the survival rate (%) for each shade tolerance class as shown in Equation 4 through Equation 8:

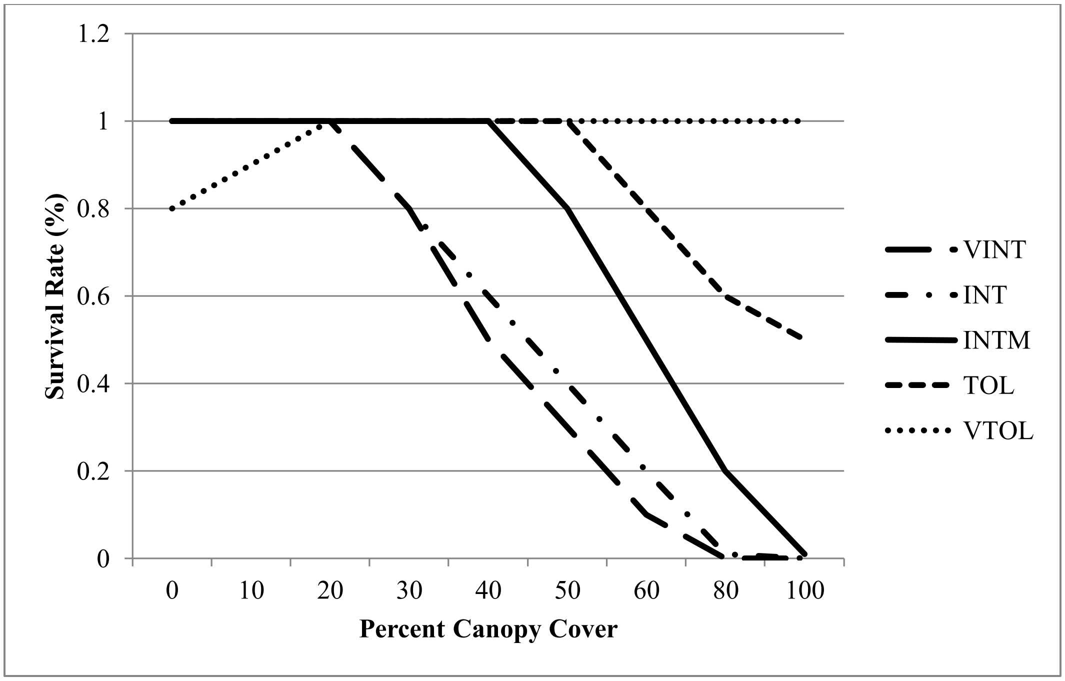

Figure 4: Linear relationships between percent canopy cover and seedling survival rate for shade tolerance classes of very intolerant (VINT), intolerant (INT), intermediate (INTM), tolerant (TOL), and very tolerant (VTOL).

Equation 4: FVS linear interpolation function for survival rate (%) of very shade intolerant species.

$$VINT = LinInt\ (ACanCov, 0, 10, 20, 30, 40, 50, 60, 80, 100, \&$$
$$100, 100, 80, 50, 30, 10, 0, 0)$$

Equation 5: FVS linear interpolation function for survival rate (%) of shade intolerant species.

$$INT = LinInt\ (ACanCov, 0, 10, 20, 30, 40, 50, 60, 80, 100, \&$$
$$100, 100, 100, 80, 60, 40, 20, 1, 0)$$

Equation 6: FVS linear interpolation function for survival rate (%) of species with intermediate shade tolerance.

$$INTM = LinInt\ (ACanCov, 0, 10, 20, 30, 40, 50, 60, 80, 100, \&$$
$$100, 100, 100, 100, 100, 80, 50, 20, 1)$$

Equation 7: FVS linear interpolation function for survival rate (%) of shade tolerant species

$$TOL = LinInt\ (ACanCov, 0, 10, 20, 30, 40, 50, 60, 80, 100, \&$$
$$100, 100, 100, 100, 100, 100, 80, 60, 50)$$

Equation 8: FVS linear interpolation function for survival rate (%) of very shade tolerant species

$$VTOL = LinInt\ (ACanCov, 0, 10, 20, 30, 40, 50, 60, 80, 100, \&$$
$$80, 90, 100, 100, 100, 100, 100, 100, 100)$$

where VINT = survival % of very intolerant species; INT= survival % of intolerant species; INTM = survival % of intermediate species; TOL = survival % of tolerant species; VTOL = survival % of very tolerant species; and ACanCov is the computed variable of residual percent canopy cover and the X input in the interpolation function. The first series, 0-100, defines the X values for percent canopy cover. The Y value series on the second line represents the survival percentages. Figure 4 shows these relationships graphically.

The final NATURAL keyword code was combined using the PARMS keyword format which allows the incorporation of computed variables as parameters within the fields of the NATURAL keyword. Example 3 provides an example of the NATURAL keyword format used for input of loblolly pine regeneration.

Example 3: NATURAL keyword code for natural regeneration of loblolly pine using the PARMS keyword formatting which allows the incorporation of computed variables in parameter fields. The final code incorporated a computed regeneration multiplier to limit input below an assumed maximum level of site occupancy, a computed variable for the TPA of the given species included in an interpolation function for seedling quantity, and a computed survival rate.

$$NATURAL \quad 0 \quad PARMS(\ LP, (R_{MULT} * LinInt(\ ResLP, 0, 1, 5, 10, 25, 50, 100, 200, 300, 400\ \&$$
$$0, 50, 250, 500, 1000, 1750, 2500, 1000, 150, 40)), \text{INTLSRV}, 1, 0.5, 0),$$

Natural regeneration was triggered every 10 years, corresponding with projection cycle boundaries, and the year following a harvest. FVS always inputs regeneration occurring during a cycle at the end of that cycle. Therefore, in all simulations, a cycle boundary was added one year following each harvest so that natural regeneration stimulated by harvesting was input and allowed to grow immediately. This regeneration was assumed to be 0.5 ft. tall and one year old at the time of establishment.

Herbivory is a significant concern at NSFIH and constraint on forest management (Navy 2011). Herbivory was accounted for by the FIXMORT keyword, which applied an additional 40% mortality rate to all hardwood species less than 2 inches DBH.

Simulation Periods

The condition of the sample plot as measured in 2010, or the “initial condition”, occurs at different points along the rotation length for different plots of the same cover type and management regime. Because of different initial conditions, each management simulation included both a transition period (R1) and a complete future rotation (R2), which together are referred to as the entire simulation period. R1 brought all plots to rotation age at which point the plot was subject to a regeneration cut. Plots with estimated ages beyond the rotation length were regenerated at the end of 2010 and R1 consisted of 1 year. For plots younger than rotation length, R1 included any intermediate management activities as scheduled per the management regime and the length of R1 is equal to the number of years, counting 2010 as one year, until regeneration. For example, for a treatment with one thinning at age 20 and a rotation length of 30 years, a plot with an age of 10 years would be allowed to grow for 10 years, thinned at 2020 and regenerated in 2030 under the R1 period. Then the plot was grown from regeneration with thinning at age 20 and a final harvest at age 30 during the R2 period. In UEA treatments, the first cutting cycle was considered R1 and the following cutting cycles of the simulation period were averaged to derive an average volume yield and economic value per cycle, providing the values for R2.

The period of R2 allowed all plots to be evaluated for a complete rotation and isolated the impact of initial conditions on the economic and habitat evaluation of the management regime. Additionally, R2 can be assumed to be perpetually repeating and was useful for evaluating the long term effects of a given management regime, whereas the entire simulation period provides a non-repeating, short term look at the effects of a particular management regime.

There is a high level of uncertainty involved in projecting a no-action treatment over a long time period, making comparison of no-action to a perpetually repeating R2 of an action treatment unreliable. Instead, no-action treatments are compared to action treatments over the entire simulation period. Simulations were projected in cycles of 10 years, beginning with the initial condition, as measured during the forest inventory of 2010, and ending at the decade of the regeneration harvest or last cutting cycle. Ten years is the default cycle length for the Southern Variant of FVS, and is based on the measurement interval of plots used to develop the growth relationships used in the model variant (Dixon 2002, Keyser 2008). Simulation results may be affected by the length of the projection cycle and bias may result from deviating from the default cycle length. Evaluating the simulation period at a regular interval enabled an unbiased sampling of nesting substrate over the simulation period, similar to a “real-life” sampling of fixed plots in the field every 10 years during the course of a management rotation.

Management simulations

Management simulations were centered on four common silvicultural treatments: clearcut, seed tree, shelterwood, and UEA management. The seed tree simulation was actually a seed tree with reserves (STR) because seed trees were not removed during the regeneration harvest. Additionally, all plots were simulated under no-action to represent a “hands off” management approach. From the four regeneration systems, variations were created with legacy trees, different thinning regimes, and varied rotation lengths. The base simulations and variations resulted in a total of 142 unique treatments.

Regeneration System Specifications

In all clearcuts the minimum diameter to cut was 0 in. DBH. This was done to reflect a silvicultural clearcut where all stems are severed and no unmerchantable material is left standing. Clearcut was performed using the stock clearcut function in *Suppose.* Seed Tree was performed using *Suppose* thinning keywords. At rotation age, the thin by diameter (ThinDBH) keyword was used to remove all species less than 14 in. DBH. Concurrently, thin by trees per acre (ThinBTA) was used to harvest all but 5 TPA in trees greater than or equal to 14 in. DBH. Shelterwood treatments consisted of a shelterwood cut and a removal cut 5 years later. For the initial shelterwood cut, the *Suppose* thin by canopy cover (ThinCC) keyword reduced the plot to a residual percent canopy cover of 50%, or as close as possible for a given plot, by cutting all species greater than or equal to 10 in. DBH. Thinning was performed from below, removing the smallest diameter trees first. Concurrently, ThinDBH was used to remove all trees less than 10 in. DBH. Five years after the shelterwood cut, a removal cut was implemented using the *Suppose* clearcut function, cutting all trees greater than or equal to 10 in. DBH. A complete rotation for shelterwood treatments began and ended after completion of the removal harvest.

Legacy tree simulations retained three trees per acre greater than or equal to 16 in. DBH, where present. Legacy trees were only simulated for clearcut and shelterwood treatments. Since STR and UEA management leave residual trees no additional legacy trees were reserved.

Separate UEA treatments were simulated for pine stands versus hardwood stands. UEA management in pine was conducted under cutting cycles of 5 and 8 years while cutting cycles of 20 years were used for hardwood plots. Instead of using the stock single tree or group selection functions in *Suppose,* a simpler and more direct method of modeling UEA management was accomplished by thinning to a target diameter distribution and residual basal area at each cutting cycle using the BDQ approach. The BDQ method uses 3 parameters: residual basal area (B), maximum DBH (D), and a Q-factor (Q) which determines the slope of the diameter distribution, to develop a target uneven-age diameter distribution. The maximum diameter value was used to set the target distributions, however, no upper diameter limit was set when thinning the maximum diameter class to allow both the harvest and the retention of trees larger than specified by D. In all UEA distributions a class width of 2 inches was used. To gradually regulate plots towards the target distribution, cutting efficiency was set at 50% to remove only half of the trees targeted for thinning during the first two cutting cycles. This was to simulate a regulation phase allowing gradual reduction in stand basal area and reducing the potential for damage from wind and epicormic sprouting caused by rapid density reduction. After the first two cycles, the cutting efficiency was set to 100%. Table 3 shows the target diameter distributions for the six UEA treatments.

Table 3: Target diameter distributions used in UEA management simulations. Options A and B were used for hardwood plots. C through F were used for pine plots. Values are shown in trees per acre per 2 inch diameter class.

UEA Management Distributions						
	Hardwood		**Pine**			
DBH class	**A**	**B**	**C**	**D**	**E**	**F**
6*	28.7	18.6	19.4	19.4	17	17
8	19.1	14.3	13.9	13.9	13.1	13.1
10	12.7	11.0	9.9	9.9	10.1	10.1
12	8.5	8.5	7.1	7.1	7.8	7.8
14	5.7	6.5	5	5	6.0	6.0
16	3.8	5.0	3.6	3.6	4.6	4.6
18	2.5	3.9	2.6	2.6	3.5	3.5
20	1.7	3.0	1.8	1.8	2.7	2.7
22	1.1	2.3	1.3	1.3	2.1	2.1
24	0.8	1.8	0.9	0.9	1.6	1.6
26	0.5	1.3				
28	0.3					
30**	0.2					
B	55	65.0	45	45	55	55
Q	1.5	1.3	1.4	1.4	1.3	1.3
D	30	26.0	24	24	24	24
Cycle	20	20.0	5	8	5	8
* Lowest class goes to 4.5 in.						
** Highest class has no upper limit						

In UEA treatments with multiple cutting cycles, hardwood plots were simulated for a minimum of 5 cutting cycles and long enough for plot age to reach 150 years. Pine plots were simulated for at least 10 cutting cycles and long enough for the plot to reach 90 years of age. Plots less than 30 years old were grown until age 30 and then the first cutting cycle was initiated. For all plots 30 years and older, the first cutting cycle was initiated in 2010.

In the no-action treatment, plots were allowed to grow and develop for 25 cycles (240 years). The no-action simulation period was then segmented into time periods equal to the different rotation ages used in even-age simulations to allow comparisons of the entire simulation period. This procedure was used to generate entire simulation periods for each plot under no-action equal to the entire simulation periods under active management with rotation lengths of 50, 70, 80, 100, and 120 years.

Intermediate Management Specifications

Simulations were developed under different thinning regimes to simulate two intensities of management and investigate the effect of timing. A total of 4 thinning regimes were developed. Thinning regimes consisted of *one thin* or *two thins*. Timing of thinning was simulated under two schedules. The first schedule thinned the plot at age 20 and the second schedule delayed thinning until 30 years of age. For two thins under both schedules, the second thinning occurred 20 years after the first thinning, except in rotation ages where a regeneration cut would occur at this time. A window of 10 years was required between the last thinning and regeneration harvest. Where a second thinning would have occurred during this window, the second thinning was implemented 10 years after the first thinning. In the case of the 30 year rotation length, two thins were not possible. All thinning treatments were conducted from below and left 70 ft^2 of basal area/ac in trees greater than 4.5 inches.

Hypotheses

From the review of the literature and in development of the substrate model and simulation method several hypotheses were developed regarding the potential effects of silviculture on substrate and economic yields.

1. Rotation lengths which allow establishment of large diameter trees are necessary for provision of preferred nesting substrate. Short rotations will result in the lowest amount of available nest substrate and increasing rotation length will improve overall nest substrate availability.
2. Treatments which leave residual forest canopy will have greater nesting substrate than treatments which leave no residual canopy.
3. The earlier thinning schedule will provide greater substrate yields because of the encouragement of faster diameter growth and the prevention of overstocking.
4. In some cases silvicultural treatment will result in greater provision of preferred nesting substrate than management by no-action.

Method of Analysis

For each simulation, individual plot results were grouped and averaged by treatment and cover type. Management regimes were evaluated over both the entire simulation (R1 plus R2) and the perpetually repeating R2 using the habitat and economic metrics described below.

Due to different initial conditions, a plot, or group of plots, must be compared against itself for a meaningful evaluation of different management regimes. Similarly, forest cover types have different silvical characteristics, such as reproductive and growth characteristics, which limit the utility of comparing different treatments across different types. At best, the same treatment can be compared across different cover types to provide insight into the suitability of treatments for use on a given cover type.

Habitat Evaluation Criteria

The proportion of the measurement decades of a given evaluation period classified by the MD model as having "preferred" nesting substrate is referred to as the *Percent Substrate Availability* (PSA) (as shown in Equation 9).

Equation 9: Percent Substrate Availability (PSA)

$$PSA = \frac{\#\ measurement\ decades\ classified\ as\ preferred}{total\ \#\ of\ measurement\ decades}$$

PSA must be interpreted differently depending on the evaluation period in question. For R2, PSA is assumed to repeat perpetually, thus over an infinite period of time different rotation lengths having equal PSA can be said to provide equal amounts of preferred substrate. For the entire simulation period, PSA represents the proportion of available habitat over the window of a short-term and non-repeating evaluation period. For the entire simulation period, equal PSA values from different rotation lengths do not represent equal amounts of time. For this reason, PSA over the entire simulation period is limited to comparisons with no-action over equal time periods. When comparing the substrate availability of different active management treatments, PSA calculated over R2 is preferred because of its long term implications.

The delay, in number of measurement decades, following a regeneration cut before preferred substrate is available, is termed the *Substrate Recovery Delay* (SRD). SRD is calculated using the longest simulated rotation length for a given treatment type in order to capture the maximum delay time. Where plots never attained preferred substrate, SRD was set to the maximum number of decades in the simulation. Therefore a treatment showing an SRD equal to the maximum decade length for R2 means the sample for that treatment never attained preferred substrate.

Economic Evaluation Criteria

Soil Expectation Value

As with PSA, the ability to compare management regimes of different rotation lengths is possible when they are perpetually repeating. The economic counterpart to PSA used in this study is soil expectation value (SEV), also known as bare land value or land expectation value. SEV is the present value of all cash flows in a perpetually repeating management regime at a given discount rate. SEV is calculated by the following equation:

Equation 10: Soil Expectation Value

$$SEV = PNV * (1.04^{RL})/(1.04^{RL} - 1)$$

where *PNV* is the present net value, or the sum of the revenues discounted to the present (present value revenues) minus the sum of the costs discounted to the present (present value costs) over the course of an investment period. The equation for PNV is as follows:

Equation 11: Present Net Value

$$PNV = \sum_{y=0}^{n} \left[\frac{R_y}{(1+r)^y}\right] - \sum_{y=0}^{n} \left[\frac{C_y}{(1+r)^y}\right]$$

where *R* is revenue, *C* is cost, *r* is the interest rate (or discount rate), and *y* is the number of years in the investment period. Harvests that occur in 2010 are assumed to occur at the end of the year and thus assigned an investment period of one year. A discount rate of 4% was used in the calculation of PNV, because federal agencies such as the DOD are comparatively less motivated by maximizing profit and do not require as great a return on investment. PNVs were calculated for R1 and R2. For UEA management, PNV was calculated for R2 using the average net value of all cutting cycles after the first and discounting the average by the length of the cutting cycle. Average BDFT yield was calculated for R2 in this manner.

Value of Forest

For evaluating the economic value of a management regime over the entire simulation period, value of forest (VOF) was used. VOF represents the value of existing timber and land at the midpoint of a rotation given a perpetual management regime. VOF is the PNV of managing initial conditions to harvest plus the SEV discounted for the delay in initiating the perpetual rotation, shown by the following equation:

Equation 12: Value of Forest

$$VOF = PNVR1 + SEV/(1+r)^{DELAY\ PERIOD})$$

where *PNVR1* is the present net value of R1, *SEV* is the soil expectation value, *r* is the interest rate, and *delay period* is the time in years before the perpetual management regime is initiated. The delay period for each plot simulation was determined by the number of years until the end of the transition period, counting 2010 as one year.

Chapter 4: Results and Discussion

Model Comparisons

The MD ≤ 4 model was compared alongside CDF models with classification thresholds of 1.0 and 0.9 to assess the MD model performance in terms of the relative fit of the models to the observation data and to explore the strengths and weaknesses of the MD model. Relative model fit was evaluated using the criterion $p_o - P_s$ where p_o is the proportion of nest points classified as preferred and P_s is the proportion of study area points classified as preferred (after Dettmers and Bart 1999).

Figure 5 plots the area of preferred habitat as defined by the MD model and the CDF models. The blue ellipse created by all values with an MD less than or equal to 4 portrays how this model follows the variation and trend of the nest observations (yellow) which displays a trend of decreasing PCC_{NS} as DBH_{MAX} increases. Because of the nature of MD, this ellipse provides less flexibility in variable combinations outside of what was produced by the variation in the presence observations and the threshold value. In contrast, the CDF models shown in the black and orange rectangles do not fit the trend of the nest observations as neatly and have "corners" of habitat far from the nest mean deviating in an opposite direction from the trend in the presence data. The linearity of these CDF models may create more seemingly arbitrary boundaries between good habitat and otherwise. Because of this linearity however, the CDF models allow greater flexibility in the combination of variables outside of the ellipse of the variation of the nest observation data. In this case where sample size is limited, the CDF model may offer advantages by allowing a more flexible definition based on the ranges of the presence data rather than the variation. This allows inclusion of areas that might conceptually be considered preferred habitat but are not represented by the presence data such as the lower corner in Figure 5.

The CDF method also had greater relative discriminating power of presence observations and study area observations, measured by $p_o - P_s$. The t= 1.0 definition resulted in $1.0 - 0.39 = 0.61$ and the t=0.9 definition resulted in $0.92 - 0.28 = 0.65$, while the MD model resulted in $1.0 - 0.69 = 0.31$. Because presence data does not necessarily indicate the unsuitability of non-presence observations, this criterion does not necessarily indicate accuracy; however, it does show the ability of the CDF method to provide a more exclusive model by placing less importance on the trend of the variability of the data. The $MD \leq 4$ model is more inclusive of study area substrate observations because of the spread in the observation data and thus performs more poorly using this criterion. Reducing the MD threshold to 3 might have resulted in greater discriminating power, but would have excluded one nest observation.

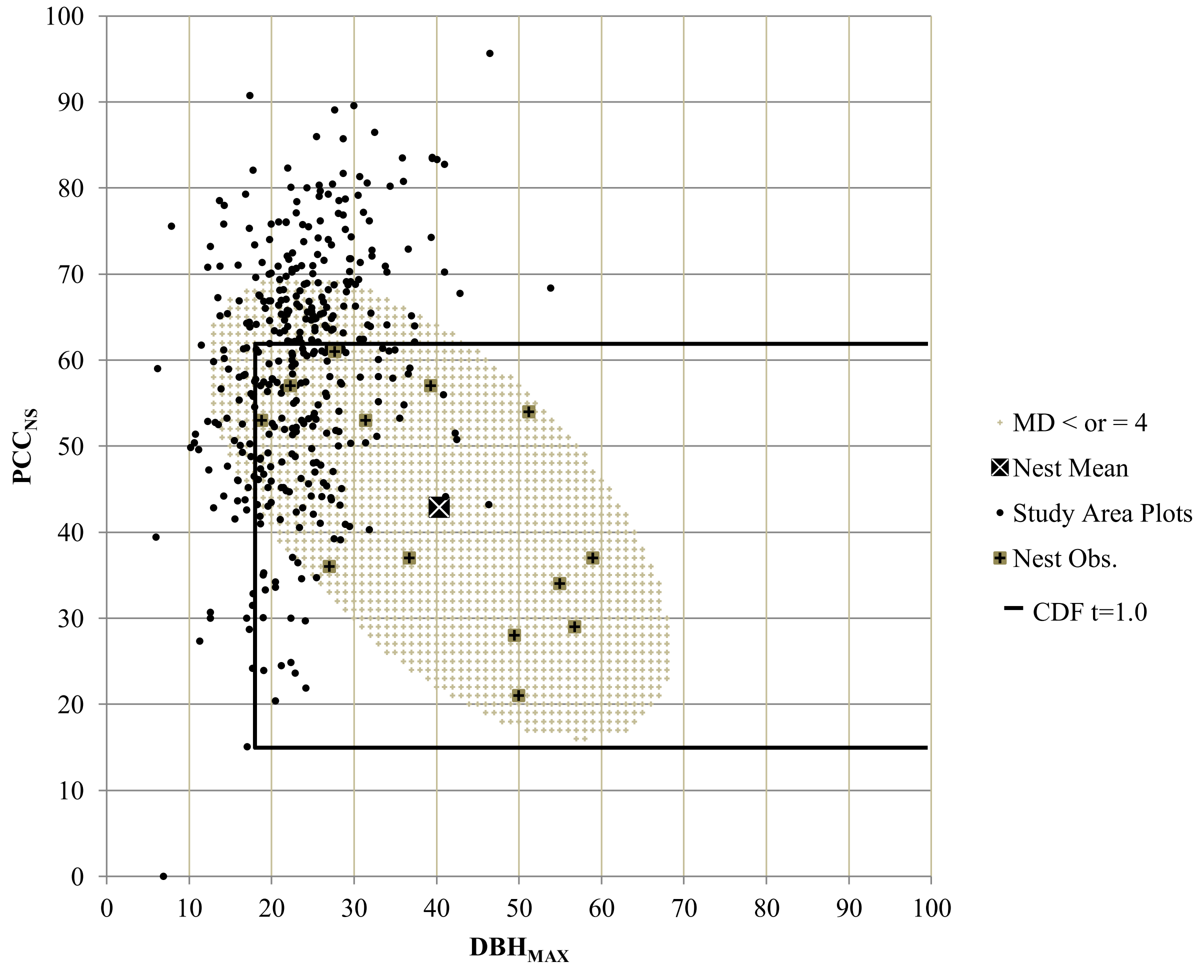

Figure 5: Scatterplot of the relative fit of the MD and CDF models. The MD model neatly fits the trend of the nest observations whereas the CDF model's linear representation includes areas further from the nest mean. The CDF models represent greater flexibility in combinations of variables by using the ranges rather than the variation of the observation data. The CDF models are more exclusive of the study area sample, whereas the MD model is more inclusive of the study area sample.

Cover Type Results

The following sections present the substrate and economic yields for each cover type. PSA tables are provided for R2 and the entire simulation period. SEV results are also provided for R2. Tradeoffs between the management objectives are also examined in tables showing the yields of top performing treatments.

Loblolly Pine Cover Type:

Substrate Yields

Average PSA values for treatments on the loblolly pine cover type over the R2 period are provided in Table 4. Top performing rotation lengths for each treatment and are shaded gray.

A general increase in PSA was found as thinning frequency increased, especially in longer rotation lengths. The lowest overall PSA values were produced by clearcut with no thinning. Even-age management with thinning consistently outperformed UEA management in loblolly pine which had significantly lower PSA compared to UEA management on hardwood plots.

The greatest gains in substrate due to thinning are evident in the clearcut and shelterwood treatments which leave the least residual canopy. In these treatments, dramatic gains were observed in shifting from the 20 year to the 30 year thinning. When timing of thinning was the same, improved PSA was observed by increasing the frequency of thinning from one thin to two thins, however, it appears that the greatest impact to PSA was attributed to timing. This trend was not significant in STR treatments and actually showed an opposite effect in legacy treatments with one thin. In this case greater improvement in PSA was observed in the earlier thinning schedule, demonstrating a synergistic effect between legacy trees and the earlier thinning schedule in the one-thin regime.

Table 4 also shows a trend of increasing PSA as rotation length increases and for most non-legacy treatments, the longest rotation length of 70 produced the highest proportion of nesting substrate. Leaving legacy trees resulted in the peak PSA values shifting to shorter rotation lengths in thinning regimes. Increases in rotation length generally increased PSA up to a peak rotation length, except in the case of clearcut and shelterwood with one thin at 20 years where results showed PSA declining as rotation length increased to the maximum of 70 years. The type of regeneration system had a greater impact on PSA in shorter rotation lengths (e.g. 30 years), because of the greater proportion of the rotation consisting of recovery delay.

Table 4: Average plot PSA for the loblolly pine cover type over R2. Highest PSA values by rotation lengths for each treatment and are shaded gray to highlight trends.

Loblolly pine		**Rotation Length**					
		Non-legacy			**Legacy**		
Treatment	**Regime**	**30**	**50**	**70**	**30**	**50**	**70**
CC	no thin	0%	0%	0%	4%	5%	7%
CC	1 thin age 20	23%	15%	13%	21%	45%	56%
CC	1 thin age 30		39%	49%		35%	21%
CC	2 thins age 20		35%	36%		51%	42%
CC	2 thins age 30		40%	57%		46%	57%
STR	no thin	9%	11%	15%			
STR	1 thin age 20	29%	47%	42%			
STR	1 thin age 30		50%	60%			
STR	2 thins age 20		61%	63%			
STR	2 thins age 30		49%	63%			
SW	no thin	15%	16%	16%	19%	22%	21%
SW	1 thin age 20	28%	24%	23%	38%	57%	61%
SW	1 thin age 30		47%	53%		37%	25%
SW	2 thins age 20		42%	46%		53%	46%
SW	2 thins age 30		50%	58%		56%	65%
Treatment	**Regime**	**5**	**8**				
UEA	B45 D24 Q1.4	11%	19%				
UEA	B55 D24 Q1.3	17%	31%				

CC - clearcut, STR - Seed tree with reserves, SW - shelterwood, UEA - uneven-age management

STR showed the shortest SRD (Table 5) of all even-age regeneration systems across all thinning regimes, the shortest being STR with two thins at 20 years which also had the highest PSA for STR. Except for the no thin treatment, STR treatments also had lower SRD compared to UEA management for the loblolly pine cover type. SRD was also much longer for UEA management relative to even-age treatments in the loblolly pine cover type than in hardwood cover types.

Table 5: Average plot SRD for the loblolly pine cover type. SRD was measured as the average number of decades after regeneration harvest until preferred substrate is available. Lowest SRD (bold) was attributed to STR with two thins at 20 years.

Loblolly Pine		**Average Substrate Recovery Delay (Decades)**	
Treatment	**Regime**	**Non-Legacy**	**Legacy**
CC	no thin	6.8	5.5
CC	1 thin age 20	4.1	2.7
CC	1 thin age 30	2.9	3.5
CC	2 thins age 20	3.3	2.5
CC	2 thins age 30	2.9	2.8
STR	no thin	4.1	
STR	1 thin age 20	2.2	
STR	1 thin age 30	2.2	
STR	2 thins age 20	**1.8**	
STR	2 thins age 30	2.3	
SW	no thin	6.5	4.4
SW	1 thin age 20	4.7	2.5
SW	1 thin age 30	3.0	5.0
SW	2 thins age 20	3.2	3.3
SW	2 thins age 30	3.0	2.6
UEA	B45 D24 Q1.4	3.6	
UEA	B55 D24 Q1.3	2.9	

CC - clearcut, STR - Seed tree with reserves, SW - shelterwood, UEA - uneven-age management

Table 6: Average plot PSA for the entire simulation for the loblolly pine cover type. Values shaded gray indicate the value is less than or equal to no-action under the same evaluation period.

Loblolly pine		Rotation Length					
		Non-legacy			Legacy		
Treatment	Regime	30	50	70	30	50	70
CC	no thin	13%	16%	13%	16%	19%	17%
CC	1 thin age 20	30%	27%	22%	35%	51%	53%
CC	1 thin age 30		46%	49%		43%	28%
CC	2 thins age 20		45%	52%		57%	58%
CC	2 thins age 30		50%	64%		55%	65%
STR	no thin	20%	23%	22%			
STR	1 thin age 20	35%	49%	41%			
STR	1 thin age 30		54%	56%			
STR	2 thins age 20		63%	67%			
STR	2 thins age 30		56%	68%			
SW	no thin	33%	34%	29%	35%	38%	32%
SW	1 thin age 20	40%	40%	34%	47%	63%	61%
SW	1 thin age 30		56%	56%		48%	35%
SW	2 thins age 20		54%	59%		62%	60%
SW	2 thins age 30		61%	67%		65%	72%
Treatment	Regime	5	8				
UEA	B45 D24 Q1.4	17%	23%				
UEA	B55 D24 Q1.3	22%	33%				
NA	no-action	21%	16%	13%			

CC - clearcut, STR - Seed tree with reserves, SW - shelterwood, UEA - uneven-age management, NA - no-action

Table 6 provides the PSA values calculated for the entire simulation period. Due to the influence of initial conditions during R1, the entire simulation period is limited to making comparisons of active management with no-action over the same time period. Values shaded gray indicate PSA values less than that provided by no-action over the same evaluation period. In loblolly pine, active management showed significant improvement in PSA over the no-action alternative. As no-action evaluation periods increased in length there was a steady decline in PSA, however it is assumed that given a longer time period, PSA might increase because of natural density reduction from mortality, development of a more uneven-age structure with canopy gaps, and a greater number of "superdominant" pines.

Economic Yields

Table 7 provides the SEV results for R2 for the loblolly pine cover type. Loblolly pine produced the highest economic yields of all cover types. This is in part due to the lower defect percentage of loblolly pine and the higher stocking and volume yields under shorter rotation lengths. The highest SEV ($999) was produced under UEA option D and the second highest SEV ($948) was the shelterwood treatment with one thin at 20 years and a 30 year rotation length.

Table 7: Average plot SEV for silvicultural simulations on the loblolly pine cover type calculated over the R2 evaluation period. Top performing rotation lengths for each treatment and are shaded gray.

Loblolly pine		**Rotation Length**					
		Non-legacy			**Legacy**		
Treatment	**Regime**	**30**	**50**	**70**	**30**	**50**	**70**
CC	no thin	$750	$756	$378	$695	$709	$353
CC	1 thin age 20	$743	$776	$453	$655	$711	$537
CC	1 thin age 30		$760	$572		$754	$437
CC	2 thins age 20		$858	$737		$801	$663
CC	2 thins age 30		$756	$713		$699	$659
STR	no thin	$653	$604	$315			
STR	1 thin age 20	$484	$549	$356			
STR	1 thin age 30		$597	$480			
STR	2 thins age 20		$581	$552			
STR	2 thins age 30		$452	$582			
SW	no thin	$846	$788	$434	$764	$723	$410
SW	1 thin age 20	$948	$879	$529	$836	$699	$527
SW	1 thin age 30		$789	$587		$794	$482
SW	2 thins age 20		$890	$801		$806	$745
SW	2 thins age 30		$730	$734		$650	$653
Treatment	**Regime**	**5**	**8**				
UEA	B45 D24 Q1.4	$829	$999				
UEA	B55 D24 Q1.3	$760	$927				

CC - clearcut, STR - Seed tree with reserves, SW - shelterwood, UEA - uneven-age management

Table 8 provides a comparison of the highest yielding treatments for the economic and substrate metrics. The comparisons in Table 8 show what is given up in the maximum potential yield of one objective by maximizing the other objective. Under the alternatives simulated, managing loblolly pine for maximum habitat under a shelterwood with legacy trees versus maximum economic yield results in a loss of $294 in potential SEV resulting from UEA management and a loss of $1,038 in potential VOF resulting from clearcutting. Conversely, management which seeks to maximize VOF would result in a reduction of PSA from the maximum of 65% to 23%. Management to maximize SEV would reduce PSA from 65% to 19%. It appears that some balance in objectives might be achieved by managing under the shelterwood with legacy tree system with a rotation length between 30 and 70 years and early and frequent thinning.

Table 8: Comparisons of top performing treatments for economic and substrate criteria on the loblolly pine cover type. Values in bold indicate the maximum value for that criterion for the respective regeneration system.

Loblolly pine					
Treatment	**Regime**	**RL**	**PSA (R2)**	**SEV**	**VOF**
CC	1 thin age 20	30	23%	$743	**$3,050**
CC	2 thins age 20	50	35%	**$858**	$2,838
CC	Legacy, 2 thins age 30	70	**57%**	$659	$2,142
CC	no thin	50	0%	$756	$2,475
STR	2 thins age 20	70	**63%**	$552	$2,253
STR	2 thins age 30	70	**63%**	$582	$2,021
STR	no thin	50	11%	$604	$2,209
STR	no thin	30	9%	**$653**	**$2,781**
SW	1 thin age 20	30	28%	**$948**	**$2,872**
SW	Legacy, 2 thins age 30	70	**65%**	$653	$2,013
SW	no thin	50	16%	$788	$2,344
UEA	B45 D24 Q1.4	8	19%	**$999**	$1,808
UEA	B55 D24 Q1.3	8	**31%**	$927	**$1,978**

CC - clearcut, STR - Seed tree with reserves, SW - shelterwood, UEA - uneven-age management, RL - Rotation length

Mixed Hardwoods Cover Type:

Substrate Yields

In this cover type, and in the other hardwood cover types, the UEA prescription had the highest PSA of all regeneration systems (Table 9). The UEA distribution with slightly higher residual basal area, UEA option B, outperformed UEA option A. This distribution also had greater weight in TPA of large diameter classes. UEA resulted in an average SRD of 0.3 measurement decades, indicating very little interruption in substrate availability across cutting cycles (Table 10).

The even-age treatment with the highest PSA occurred under SWL with two thins beginning at 30 years of age under a 70 year rotation length. SRD values for even-age treatments were highest for clearcut and shelterwood. Thinning and leaving legacy trees helped to reduce SRD in these systems (Table 10). STR had only slightly lower delays but generally provided the lowest SRD for even-age treatments.

Increases in rotation length had a less pronounced effect on gains in PSA in this cover type. After peak rotation lengths, typically 70-80 years, changes in PSA with increasing rotation length were minimal. Additionally, rotations shorter than the peak length were often only marginally lower in PSA than peak rotation lengths. In even-age treatments, STR treatments resulted in higher PSA under shorter rotation lengths, peaking or beginning to level off in 50-70 year rotation lengths. In clearcut treatments, there were also marginal gains in PSA from 70 years to the peak rotation length of 80 years. This cover type followed the trend shown in loblolly pine of increased PSA with increased frequency of thinning. In peak rotations with two thins, there was a narrow range in difference across PSA values for STR, shelterwood and shelterwood with legacy (SWL) treatments.

Table 9: Average plot PSA for the mixed hardwoods cover type over R2. Top performing rotation lengths for each treatment and are shaded gray to highlight trends.

Mixed Hardwoods								
Non-legacy		Rotation Length						
Treatment	**Regime**	**20**	**30**	**50**	**70**	**80**	**100**	**120**
CC	no thin		3%	14%	23%	23%	21%	22%
CC	1 thin age 20		11%	13%	15%	19%	18%	19%
CC	1 thin age 30			19%	27%	28%	25%	25%
CC	2 thins age 20			20%	34%	36%	33%	35%
CC	2 thins age 30			22%	37%	40%	38%	40%
STR	no thin		24%	34%	35%	33%	31%	28%
STR	1 thin age 20		27%	34%	33%	32%	30%	28%
STR	1 thin age 30			45%	44%	42%	37%	35%
STR	2 thins age 20			41%	49%	49%	46%	43%
STR	2 thins age 30			45%	53%	54%	52%	49%
SW	no thin		5%	25%	29%	28%	28%	28%
SW	1 thin age 20		4%	24%	28%	27%	28%	27%
SW	1 thin age 30			36%	39%	38%	36%	34%
SW	2 thins age 20			33%	45%	45%	43%	41%
SW	2 thins age 30			39%	50%	51%	51%	47%
UEA	B55 D30 Q1.5	89%						
UEA	B65 D26 Q1.3	92%						
Legacy		**Rotation Length**						
Treatment	**Regime**	**20**	**30**	**50**	**70**	**80**	**100**	**120**
CC	no thin		12%	27%	33%	33%	30%	30%
CC	1 thin age 20		11%	31%	38%	38%	34%	35%
CC	1 thin age 30			28%	32%	32%	29%	30%
CC	2 thins age 20			33%	44%	45%	41%	44%
CC	2 thins age 30			35%	45%	47%	43%	40%
SW	no thin		14%	36%	36%	34%	32%	29%
SW	1 thin age 20		14%	41%	46%	44%	40%	37%
SW	1 thin age 30			38%	39%	37%	34%	31%
SW	2 thins age 20			43%	51%	49%	46%	43%
SW	2 thins age 30			46%	55%	55%	52%	49%

CC - clearcut, STR - Seed tree with reserves, SW - shelterwood, UEA - uneven-age management

Table 10: Average plot SRD for the mixed hardwoods cover type. SRD was measured as the average number of decades after regeneration harvest until preferred substrate is available. Lowest SRD (bold) was attributed to the UEA management treatments.

Mixed Hardwoods		**Average Substrate Recovery Delay (Decades)**	
Treatment	**Regime**	**Non-Legacy**	**Legacy**
CC	no thin	6.4	4.7
CC	1 thin age 20	6.6	3.7
CC	1 thin age 30	5.8	4.2
CC	2 thins age 20	4.6	3.6
CC	2 thins age 30	4.4	3.6
STR	no thin	4.1	
STR	1 thin age 20	3.9	
STR	1 thin age 30	3.4	
STR	2 thins age 20	3.1	
STR	2 thins age 30	3.0	
SW	no thin	6.7	5.7
SW	1 thin age 20	6.7	3.9
SW	1 thin age 30	5.0	4.4
SW	2 thins age 20	4.2	3.6
SW	2 thins age 30	3.9	3.6
UEA	B55 D30 Q1.5	**0.3**	
UEA	B65 D26 Q1.3	**0.3**	

CC - clearcut, STR - Seed tree with reserves, SW - shelterwood, UEA - uneven-age management

Comparisons of active management to no-action over the entire simulation period showed slightly greater provision of substrate in select even-age management treatments in the short term (Table 11, unshaded values). These were typically systems which maximized residual canopy and utilized frequent thinning. Only two non-legacy clearcut treatments outperformed a similar evaluation period of no-action, while clearcut with legacy (CCL) treatments with two thins provided slightly better results. Even-age treatments with two thins outperformed no-action in all but the longest rotation length. UEA management, however, provided over twice the highest value of PSA under no-action. On average, mixed hardwoods plots simulated under the no-action treatment showed a steady increase in PSA as rotation length increased. Relative to the loblolly pine cover type, a greater majority of mixed hardwoods plots had preferred nesting substrate and more uneven-age structure relative at initial conditions.

Table 11: Average plot PSA for the entire simulation for the mixed hardwoods cover type. Values shaded gray indicate the value is less than or equal to no-action under the same evaluation period.

Mixed Hardwoods								
Non-legacy		**Rotation Length**						
Treatment	**Regime**	**20**	**30**	**50**	**70**	**80**	**100**	**120**
CC	no thin		19%	23%	28%	28%	26%	26%
CC	1 thin @ 20		25%	22%	25%	25%	23%	23%
CC	1 thin @ 30			27%	32%	32%	29%	29%
CC	2 thins @ 20			28%	38%	39%	36%	38%
CC	2 thins @ 30			30%	41%	43%	40%	42%
STR	no thin		35%	39%	39%	37%	35%	32%
STR	1 thin @ 20		37%	39%	38%	36%	33%	32%
STR	1 thin @ 30			46%	47%	45%	41%	38%
STR	2 thins @ 20			46%	52%	51%	48%	45%
STR	2 thins @ 30			49%	55%	55%	53%	50%
SW	no thin		30%	38%	39%	38%	36%	35%
SW	1 thin @ 20		30%	38%	38%	37%	36%	34%
SW	1 thin @ 30			47%	47%	46%	43%	40%
SW	2 thins @ 20			45%	52%	51%	49%	46%
SW	2 thins @ 30			49%	56%	56%	55%	51%
UEA	B55 D30 Q1.5	87%						
UEA	B65 D26 Q1.3	90%						
Legacy		**Rotation Length**						
Treatment	**Regime**	**20**	**30**	**50**	**70**	**80**	**100**	**120**
CC	no thin		26%	34%	38%	37%	34%	34%
CC	1 thin @ 20		25%	37%	42%	41%	37%	38%
CC	1 thin @ 30			35%	37%	36%	32%	33%
CC	2 thins @ 20			39%	47%	48%	43%	46%
CC	2 thins @ 30			40%	48%	50%	45%	48%
SW	no thin		36%	47%	45%	42%	39%	36%
SW	1 thin @ 20		36%	51%	53%	50%	46%	43%
SW	1 thin @ 30			48%	47%	45%	41%	38%
SW	2 thins @ 20			52%	57%	55%	51%	48%
SW	2 thins @ 30			54%	60%	59%	57%	53%
NA	no-action		36%	39%	41%	42%	44%	49%

CC - clearcut, STR - Seed tree with reserves, SW - shelterwood, UEA - uneven-age management, NA - no-action

Economic Yields

Table 12 provides the average SEV values for the treatments on the mixed hardwoods cover type. Rotation lengths with peak SEV are centered primarily around 50 years. As with loblolly pine, shelterwood consistently resulted in the highest SEV among even-age treatments for each rotation length. The highest SEV ($197) resulted from shelterwood with one thin at 20 years under a 50 year rotation length. Shelterwood with two thins at 20 years under the 50 yr. rotation length resulted in only $1 less in SEV. Table 13 provides the comparison of the treatments resulting in maximum economic and substrate yields. Under the alternatives simulated, substrate availability and SEV can both be maximized by utilizing UEA management in the mixed hardwoods cover type. This suggests an opportunity for silviculture to provide for both long-term nesting capacity and economic benefit. No even-age treatments appear competitive with UEA management in terms of offering a balance between long term economic and substrate yields. Maximizing short term gains over the entire simulation period, as measured by VOF, would be achieved under clearcut with one thin at 20 and a 50 year rotation length at a tradeoff of maximum potential PSA from 92% to 13%. Conversely, managing mixed hardwoods for maximum habitat under UEA management versus maximum VOF results in a loss of $762 in VOF.

Table 12: Average plot SEV for treatments on the mixed hardwoods cover type calculated over the R2 evaluation period. Top performing rotation lengths for each treatment and are shaded gray.

Mixed Hardwoods								
Non-legacy		**Rotation Length**						
Treatment	**Regime**	**20**	**30**	**50**	**70**	**80**	**100**	**120**
CC	no thin		$72	$109	$87	$69	$49	$17
CC	1 thin @ 20		$102	$129	$85	$62	$41	$18
CC	1 thin @ 30			$103	$88	$70	$37	$25
CC	2 thins @ 20			$100	$96	$77	$56	$38
CC	2 thins @ 30			$96	$95	$83	$65	$45
STR	no thin		$94	$101	$70	$53	$26	$12
STR	1 thin @ 20		$68	$89	$61	$42	$16	$1
STR	1 thin @ 30			$85	$72	$57	$31	$16
STR	2 thins @ 20			$84	$83	$69	$43	$26
STR	2 thins @ 30			$76	$85	$77	$55	$39
SW	no thin		$160	$172	$130	$95	$47	$21
SW	1 thin @ 20		$154	$197	$125	$88	$38	$12
SW	1 thin @ 30			$186	$139	$107	$59	$32
SW	2 thins @ 20			$196	$161	$130	$82	$53
SW	2 thins @ 30			$176	$161	$140	$99	$70
UEA	B55 D30 Q1.5	$358						
UEA	B65 D26 Q1.3	$305						
Legacy		**Rotation Length**						
Treatment	**Regime**	**20**	**30**	**50**	**70**	**80**	**100**	**120**
CC	no thin		$111	$118	$86	$65	$46	$16
CC	1 thin @ 20		$85	$108	$85	$65	$44	$19
CC	1 thin @ 30			$111	$82	$59	$38	$6
CC	2 thins @ 20			$102	$96	$78	$58	$35
CC	2 thins @ 30			$100	$100	$88	$72	$49
SW	no thin		$130	$156	$117	$84	$41	$17
SW	1 thin @ 20		$100	$163	$120	$91	$49	$26
SW	1 thin @ 30			$169	$110	$77	$33	$9
SW	2 thins @ 20			$169	$141	$115	$73	$48
SW	2 thins @ 30			$151	$145	$127	$89	$64

CC - clearcut, STR - Seed tree with reserves, SW - shelterwood, UEA - uneven-age management

Table 13: Comparisons of top performing treatments for economic and substrate criteria on the mixed hardwoods cover type. Values in bold indicate the maximum value for that criterion for the respective regeneration system.

Mixed hardwoods					
Treatment	**Regime**	**RL**	**PSA (R2)**	**SEV**	**VOF**
CC	1 thin age 20	50	13%	**$129**	**$1,394**
CC	2 thins age 20	80	36%	$77	$1,336
CC	Legacy, 2 thins age 30	80	**47%**	$88	$1,256
STR	2 thins age 30	80	**54%**	$77	$1,117
STR	2 thins age 30	100	52%	$55	$1,092
STR	no thin	50	34%	**$101**	**$1,148**
SW	1 thin age 20	50	24%	**$197**	**$1,203**
SW	2 thins age 20	80	45%	$130	$1,146
SW	Legacy, 2 thins age 30	70	**55%**	$145	$1,075
UEA	B55 D30 Q1.5	20	89%	**$358**	**$632**
UEA	B65 D26 Q1.3	20	**92%**	$305	$581

CC - clearcut, STR - Seed tree with reserves, SW - shelterwood, UEA - uneven-age management, RL - Rotation length

Sweetgum/Yellow Poplar Cover Type:

Substrate Yields

Average PSA values for treatments on plots of the sweetgum/yellow poplar cover type over the R2 period are provided in Table 14. Again UEA management had the highest PSA of all regeneration systems and UEA option B outperformed UEA option A. UEA also provided an average SRD of 0.4 measurement decades, indicating very little interruption in substrate availability across cutting cycles (Table 15).

In non-legacy even-age treatments, STR produced the highest PSA over all thinning regimes and rotation lengths. As shown in other cover types, leaving legacy trees resulted in improved PSA in clearcut and shelterwood treatments. The treatment which resulted in the highest PSA for the cover type was SWL with two thins at 30 years under an 80 year rotation length.

Frequent thinning improved PSA and had the biggest impact in the longest rotation lengths and frequency may be more important that thinning timing. In the clearcut regeneration system, one thin at 20 years resulted in lower PSA values compared to no thinning in all rotation lengths except 30 years, showing that early thinning generally had a negative effect on PSA while thinning at 30 years had a positive effect. However, two thins with the 20 year timing provided an even greater positive effect on PSA.

Simulation of no-action shown in Table 16 showed a consistent provision of nesting substrate across all rotation lengths, with PSA values staying around 50-55%. Average PSA values in most even-age treatments were less than no-action except for select STR, shelterwood, CCL, and SWL treatments with frequent or timely thinning. Where active management showed a clear improvement over no-action was in UEA management, which provided a considerably higher proportion of substrate availability than the highest PSA value for no-action.

Table 14: Average plot PSA for the sweetgum/yellow poplar cover type over R2. Top performing rotation lengths for each treatment are shaded gray.

Sweetgum/Yellow Poplar								
Non-legacy		**Rotation Length**						
Treatment	**Regime**	**20**	**30**	**50**	**70**	**80**	**100**	**120**
CC	no thin		8%	20%	27%	29%	26%	24%
CC	1 thin age 20		17%	16%	20%	21%	22%	21%
CC	1 thin age 30			25%	33%	33%	32%	28%
CC	2 thins age 20			27%	39%	39%	34%	32%
CC	2 thins age 30			30%	44%	46%	42%	42%
STR	no thin		22%	32%	36%	35%	36%	32%
STR	1 thin age 20		27%	36%	36%	36%	33%	31%
STR	1 thin age 30			46%	50%	49%	41%	41%
STR	2 thins age 20			44%	53%	53%	49%	44%
STR	2 thins age 30			46%	58%	60%	58%	55%
SW	no thin		13%	26%	25%	26%	26%	24%
SW	1 thin age 20		14%	27%	27%	29%	27%	26%
SW	1 thin age 30			42%	45%	43%	39%	37%
SW	2 thins age 20			39%	49%	48%	42%	39%
SW	2 thins age 30			45%	56%	59%	56%	52%
UEA	B55 D30 Q1.5	85%						
UEA	B65 D26 Q1.3	**93%**						
Legacy		**Rotation Length**						
Treatment	**Regime**	**20**	**30**	**50**	**70**	**80**	**100**	**120**
CC	no thin		16%	26%	34%	35%	33%	34%
CC	1 thin age 20		19%	36%	44%	44%	41%	41%
CC	1 thin age 30			30%	32%	34%	31%	34%
CC	2 thins age 20			35%	46%	47%	42%	47%
CC	2 thins age 30			37%	51%	55%	50%	45%
SW	no thin		18%	33%	33%	33%	33%	32%
SW	1 thin age 20		22%	47%	54%	51%	47%	44%
SW	1 thin age 30			36%	35%	36%	35%	33%
SW	2 thins age 20			44%	54%	53%	48%	45%
SW	2 thins age 30			48%	59%	62%	59%	55%

CC - clearcut, STR - Seed tree with reserves, SW - shelterwood, UEA - uneven-age management

Table 15: Average plot SRD for the sweetgum yellow poplar cover type. SRD was measured as the average number of decades after regeneration harvest until preferred substrate is available. Lowest SRD (bold) was attributed to UEA management.

Sweetgum/Yellow poplar		**Average Substrate Recovery Delay (Decades)**	
Treatment	**Regime**	**Non-Legacy**	**Legacy**
CC	no thin	6.8	5.1
CC	1 thin age 20	6.9	3.3
CC	1 thin age 30	5.6	4.5
CC	2 thins age 20	4.1	3.3
CC	2 thins age 30	4.2	3.6
STR	no thin	4.5	
STR	1 thin age 20	4.4	
STR	1 thin age 30	3.1	
STR	2 thins age 20	3.1	
STR	2 thins age 30	3.0	
SW	no thin	8.0	5.9
SW	1 thin age 20	7.4	3.3
SW	1 thin age 30	4.4	5.0
SW	2 thins age 20	3.5	3.4
SW	2 thins age 30	3.2	3.4
UEA	B55 D30 Q1.5	0.5	
UEA	B65 D26 Q1.3	**0.4**	

CC - clearcut, STR - Seed tree with reserves, SW - shelterwood, UEA - uneven-age management

Table 16: Average plot PSA for the entire simulation period for the sweetgum/yellow poplar cover type. Values shaded gray indicate the value is less than or equal to no-action under the same evaluation period.

Sweetgum/Yellow Poplar								
Non-legacy		**Rotation Length**						
Treatment	**Regime**	**20**	**30**	**50**	**70**	**80**	**100**	**120**
CC	no thin		24%	29%	32%	34%	31%	29%
CC	1 thin @ 20		32%	26%	28%	29%	26%	25%
CC	1 thin @ 30			35%	39%	40%	36%	33%
CC	2 thins @ 20			36%	45%	44%	39%	37%
CC	2 thins @ 30			38%	48%	51%	46%	46%
STR	no thin		34%	39%	40%	39%	39%	36%
STR	1 thin @ 20		39%	43%	40%	40%	37%	34%
STR	1 thin @ 30			50%	53%	52%	48%	44%
STR	2 thins @ 20			50%	57%	56%	52%	48%
STR	2 thins @ 30			51%	61%	63%	60%	57%
SW	no thin		35%	40%	37%	37%	35%	33%
SW	1 thin @ 20		36%	41%	38%	38%	35%	33%
SW	1 thin @ 30			52%	53%	51%	46%	43%
SW	2 thins @ 20			50%	56%	55%	49%	45%
SW	2 thins @ 30			55%	62%	64%	60%	57%
UEA	B55 D30 Q1.5	85%						
UEA	B65 D26 Q1.3	93%						
Legacy		**Rotation Length**						
Treatment	**Regime**	**20**	**30**	**50**	**70**	**80**	**100**	**120**
CC	no thin		31%	34%	39%	39%	37%	37%
CC	1 thin @ 20		33%	44%	48%	48%	44%	44%
CC	1 thin @ 30			37%	37%	38%	34%	37%
CC	2 thins @ 20			42%	51%	51%	45%	49%
CC	2 thins @ 30			44%	55%	58%	53%	54%
SW	no thin		38%	45%	43%	42%	40%	39%
SW	1 thin @ 20		41%	56%	59%	57%	53%	50%
SW	1 thin @ 30			48%	44%	44%	42%	40%
SW	2 thins @ 20			54%	60%	59%	54%	51%
SW	2 thins @ 30			57%	64%	66%	63%	60%
NA	no-action		53%	55%	55%	54%	53%	54%

CC - clearcut, STR - Seed tree with reserves, SW - shelterwood, UEA - uneven-age management, NA - no-action

Economic Yields

Behind loblolly pine, the sweetgum/yellow poplar cover type resulted in the second highest economic values (Table 17). Similar to the loblolly pine cover type, this cover type displays rapid growth rates and can maintain volume growth under high densities, allowing earlier production of sawtimber and higher stocking.

UEA option A again provided the highest SEV and the shelterwood treatment resulted in the highest SEV out of the even-age regeneration types. Maximum SEV ($381) was produced by shelterwood with 2 thins at age 20 and a 50 year rotation length, which is somewhat competitive with UEA management. In short rotation legacy treatments the effect of harvesting the held-over legacy trees resulted in higher SEVs compared to non-legacy counterparts.

Similar to the competing benefits of the UEA management options, the earlier thinning shown to be worse for habitat provided greater SEV than the delayed thinning in shorter rotations where SEV was highest. Where peak rotations lengths for PSA were generally in the 70-80 year range, peak rotations for SEV and VOF were in the 30-50 year range. Table 18 provides the comparison of treatments maximizing economic or substrate yields. Under the alternatives simulated, maximizing SEV resulted in only a minor reduction of potential maximum PSA from 93%, provided under UEA option B, to 85% under UEA option A. Maximizing VOF, resulted in a more significant substrate reduction to a PSA of 27% under clearcut with two thins at 20 under a 50 year rotation length. Management for maximum habitat resulted in a $670 reduction of potential VOF, but only a $60 reduction in SEV.

Table 17: Average plot SEV for treatments on the sweetgum/yellow poplar cover type calculated over the R2 evaluation period. Top performing rotation lengths for each treatment and are shaded gray.

Sweetgum/Yellow Poplar								
Non-legacy		**Rotation Length**						
Treatment	**Regime**	**20**	**30**	**50**	**70**	**80**	**100**	**120**
CC	no thin		$198	$185	$121	$91	$63	$22
CC	1 thin @ 20		$220	$194	$128	$88	$59	$27
CC	1 thin @ 30			$197	$149	$112	$64	$44
CC	2 thins @ 20			$203	$176	$137	$104	$72
CC	2 thins @ 30			$179	$138	$150	$117	$84
STR	no thin		$217	$175	$99	$75	$36	$16
STR	1 thin @ 20		$158	$185	$113	$76	$33	$11
STR	1 thin @ 30			$180	$143	$123	$69	$48
STR	2 thins @ 20			$195	$162	$158	$105	$77
STR	2 thins @ 30			$160	$172	$177	$130	$100
SW	no thin		$318	$294	$185	$138	$66	$29
SW	1 thin @ 20		$324	$358	$209	$145	$69	$30
SW	1 thin @ 30			$330	$236	$191	$109	$70
SW	2 thins @ 20			$381	$299	$253	$186	$141
SW	2 thins @ 30			$310	$281	$254	$206	$166
UEA	B55 D30 Q1.5	$457						
UEA	B65 D26 Q1.3	$397						
Legacy		**Rotation Length**						
Treatment	**Regime**	**20**	**30**	**50**	**70**	**80**	**100**	**120**
CC	no thin		$238	$196	$116	$89	$59	$20
CC	1 thin @ 20		$191	$210	$157	$130	$85	$50
CC	1 thin @ 30			$208	$128	$89	$56	$14
CC	2 thins @ 20			$198	$173	$148	$120	$73
CC	2 thins @ 30			$190	$184	$163	$140	$105
SW	no thin		$274	$267	$166	$122	$57	$25
SW	1 thin @ 20		$237	$282	$205	$168	$97	$63
SW	1 thin @ 30			$321	$185	$128	$61	$27
SW	2 thins @ 20			$323	$262	$222	$163	$124
SW	2 thins @ 30			$263	$254	$225	$178	$142

CC - clearcut, STR - Seed tree with reserves, SW - shelterwood, UEA - uneven-age management

Table 18: Comparisons of top performing treatments for economic and substrate criteria on the sweetgum/yellow poplar cover type. Values in bold indicate the maximum value for that criterion for the respective regeneration system.

Sweetgum/yellow poplar					
Treatment	**Regime**	**RL**	**PSA (R2)**	**SEV**	**VOF**
CC	2 thins age 20	80	39%	$137	$1,284
CC	2 thins age 20	50	27%	$203	**$1,361**
CC	Legacy	30	16%	**$238**	$1,310
CC	Legacy, 2 thins age 30	80	**55%**	$163	$1,218
STR	2 thins age 20	80	53%	$158	$1,070
STR	2 thins age 30	80	**60%**	$177	$1,079
STR	no thin	30	22%	**$217**	**$1,156**
SW	2 thins age 20	70	49%	$299	$1,134
SW	2 thins age 20	50	39%	**$381**	**$1,200**
SW	Legacy, 2 thins age 30	80	**62%**	$225	$1,004
UEA	B55 D30 Q1.5	20	85%	**$457**	**$691**
UEA	B65 D26 Q1.3	20	**93%**	$397	$634

CC - clearcut, STR - Seed tree with reserves, SW - shelterwood, UEA - uneven-age management, RL - Rotation length

Upland Oak Cover Type:

Substrate Yields

Average PSA values for treatments on the loblolly pine cover type over the R2 period are provided in Table 19. Consistent with all other hardwood cover types, the UEA option B resulted in the highest PSA values and lowest SRD (Table 20) for the cover type. Also consistent was the high PSA value provided by the STR treatment amongst non-legacy treatments and the highest overall PSA for even-age management going to the SWL treatment with frequent thinning. Rotation lengths of 70 and 80 provided the highest PSA for the top performing SWL treatment. STR treatments were very competitive with SWL over many rotation lengths and thinning regimes.

Table 19: Average plot PSA for the upland oak cover type over R2. Top performing rotation lengths for each treatment and are shaded gray.

Upland Oak								
Non-legacy		Rotation Length						
Treatment	Regime	20	30	50	70	80	100	120
CC	no thin		4%	11%	18%	19%	16%	15%
CC	1 thin age 20		9%	11%	11%	18%	15%	15%
CC	1 thin age 30			12%	19%	19%	17%	17%
CC	2 thins age 20			13%	25%	28%	26%	29%
CC	2 thins age 30			13%	27%	30%	28%	32%
STR	no thin		15%	36%	38%	36%	31%	27%
STR	1 thin age 20		16%	36%	38%	35%	31%	27%
STR	1 thin age 30			45%	41%	39%	34%	29%
STR	2 thins age 20			38%	48%	47%	44%	41%
STR	2 thins age 30			40%	50%	51%	49%	46%
SW	no thin		4%	20%	26%	26%	24%	21%
SW	1 thin age 20		3%	21%	26%	25%	22%	20%
SW	1 thin age 30			24%	29%	29%	27%	24%
SW	2 thins age 20			24%	38%	39%	39%	36%
SW	2 thins age 30			25%	39%	41%	42%	40%
UEA	B55 D30 Q1.5	92%						
UEA	B65 D26 Q1.3	95%						
Legacy		Rotation Length						
Treatment	Regime	20	30	50	70	80	100	120
CC	no thin		9%	29%	35%	34%	29%	26%
CC	1 thin age 20		9%	30%	37%	35%	30%	26%
CC	1 thin age 30			29%	34%	32%	27%	25%
CC	2 thins age 20			31%	42%	42%	37%	37%
CC	2 thins age 30			31%	43%	45%	41%	34%
SW	no thin		10%	30%	38%	36%	31%	27%
SW	1 thin age 20		9%	37%	43%	41%	35%	31%
SW	1 thin age 30			32%	37%	35%	31%	27%
SW	2 thins age 20			36%	47%	47%	45%	42%
SW	2 thins age 30			38%	50%	51%	49%	47%

CC - clearcut, STR - Seed tree with reserves, SW - shelterwood, UEA - uneven-age management

Table 20: Average plot SRD for the upland oak cover type. SRD was measured as the average number of decades after regeneration harvest until preferred substrate is available. Lowest SRD (bold) was attributed to UEA management.

Upland Oak		**Average Substrate Recovery Delay (Decades)**	
Treatment	**Regime**	**Non-Legacy**	**Legacy**
CC	no thin	7.8	4.0
CC	1 thin age 20	7.7	3.7
CC	1 thin age 30	7.5	4.1
CC	2 thins age 20	5.9	3.7
CC	2 thins age 30	5.7	4.0
STR	no thin	3.6	
STR	1 thin age 20	3.7	
STR	1 thin age 30	3.3	
STR	2 thins age 20	3.3	
STR	2 thins age 30	3.2	
SW	no thin	7.4	4.7
SW	1 thin age 20	7.2	4.0
SW	1 thin age 30	6.7	4.6
SW	2 thins age 20	5.0	3.8
SW	2 thins age 30	5.1	3.8
UEA	B55 D30 Q1.5	**0.3**	
UEA	B65 D26 Q1.3	**0.3**	

CC - clearcut, STR - Seed tree with reserves, SW - shelterwood, UEA - uneven-age management

Table 21 provides PSA values for the entire simulation period for upland oak. Simulation of no-action shows a slight decline in PSA as rotation length increases to 70 years and leveling off at roughly 30% for longer rotations. The findings in Table 21 indicate that most management treatments which have intermediate management, and a few that do not, outperform no-action over equal evaluation periods.

Table 21: Average plot PSA for the entire simulation for the upland oak cover type. Values shaded gray indicate the value is less than or equal to no-action under the same evaluation period.

Upland Oak								
Non-legacy		**Rotation Length**						
Treatment	**Regime**	**20**	**30**	**50**	**70**	**80**	**100**	**120**
CC	no thin		18%	19%	23%	23%	20%	19%
CC	1 thin @ 20		22%	19%	22%	22%	19%	19%
CC	1 thin @ 30			20%	24%	24%	21%	20%
CC	2 thins @ 20			21%	30%	31%	29%	32%
CC	2 thins @ 30			21%	31%	33%	31%	34%
STR	no thin		26%	40%	41%	39%	34%	30%
STR	1 thin @ 20		27%	40%	40%	38%	33%	29%
STR	1 thin @ 30			42%	43%	41%	36%	32%
STR	2 thins @ 20			42%	49%	49%	45%	42%
STR	2 thins @ 30			43%	51%	52%	50%	47%
SW	no thin		28%	34%	36%	35%	32%	29%
SW	1 thin @ 20		27%	34%	35%	34%	31%	28%
SW	1 thin @ 30			37%	38%	37%	34%	31%
SW	2 thins @ 20			37%	45%	45%	44%	42%
SW	2 thins @ 30			38%	47%	47%	47%	45%
UEA	B55 D30 Q1.5	92%						
UEA	B65 D26 Q1.3	95%						
Legacy		**Rotation Length**						
Treatment	**Regime**	**20**	**30**	**50**	**70**	**80**	**100**	**120**
CC	no thin		22%	34%	38%	36%	31%	29%
CC	1 thin @ 20		22%	35%	39%	38%	33%	29%
CC	1 thin @ 30			34%	37%	35%	30%	28%
CC	2 thins @ 20			36%	44%	44%	39%	38%
CC	2 thins @ 30			35%	45%	46%	42%	44%
SW	no thin		32%	41%	45%	43%	38%	33%
SW	1 thin @ 20		31%	46%	49%	47%	41%	37%
SW	1 thin @ 30			43%	44%	42%	38%	34%
SW	2 thins @ 20			46%	53%	52%	49%	46%
SW	2 thins @ 30			47%	55%	55%	53%	51%
NA	no-action		35%	34%	30%	29%	27%	30%

CC - clearcut, STR - Seed tree with reserves, SW - shelterwood, UEA - uneven-age management, NA - no-action

Economic Yields

Table 22 provides the average SEV values for the treatments on the upland oak cover type. On average, treatments on upland oak plots had the lowest SEV of all cover types. The plots which make up this cover type were often located on low quality, poorly stocked upland sites, and composed of lower value oak species such as chestnut oak, found during the inventory to have a high defect percentage. These reasons, in addition to the increased difficulty of regeneration in upland oak forests, are likely the reason for such low volume and value yield. Consistent with other hardwood cover types, UEA option A had the highest SEV overall and shelterwood treatments resulted in the highest SEV for even-age management regimes.

Shelterwood with 1 thin at 30 years under a 50 year rotation was the even-age management regime that resulted in the highest SEV ($123). Unlike other cover types, upland oak SEV showed benefits from the delayed thinning in peak SEV rotation lengths for non-legacy STR and shelterwood treatments. Likewise, thinning treatments actually caused a reduction in SEV during peak rotation lengths for clearcut, STR, CCL, and SWL. Thinning in rotation lengths longer than the peak the rotation length for SEV showed a small but positive increase on SEV.

Table 22: Average plot SEV for silvicultural simulations on the upland oak cover type calculated over the R2 evaluation period. Top performing rotation lengths for each treatment and are shaded gray.

Upland Oak									
Non-legacy		**Rotation Length**							
Treatment	**Regime**	**20**	**30**	**50**	**70**	**80**	**100**	**120**
CC	no thin		$50	$85	$66	$53	$39	$14
CC	1 thin @ 20		$67	$76	$59	$43	$28	$15
CC	1 thin @ 30			$75	$66	$51	$26	$20
CC	2 thins @ 20			$70	$69	$56	$42	$34
CC	2 thins @ 30			$69	$70	$61	$49	$38
STR	no thin		$48	$55	$44	$35	$18	$9
STR	1 thin @ 20		$26	$42	$32	$23	$6	-$3
STR	1 thin @ 30			$43	$39	$31	$15	$6
STR	2 thins @ 20			$37	$40	$34	$18	$9
STR	2 thins @ 30			$34	$44	$40	$27	$18
SW	no thin		$92	$109	$91	$69	$35	$17
SW	1 thin @ 20		$71	$117	$80	$56	$22	$3
SW	1 thin @ 30			$123	$94	$72	$37	$18
SW	2 thins @ 20			$111	$95	$76	$43	$25
SW	2 thins @ 30			$114	$107	$93	$64	$47
UEA	B55 D30 Q1.5	$246						
UEA	B65 D26 Q1.3	$212						
Legacy		**Rotation Length**						
Treatment	**Regime**	**20**	**30**	**50**	**70**	**80**	**100**	**120**
CC	no thin		$73	$82	$63	$49	$36	$13
CC	1 thin @ 20		$48	$71	$60	$47	$33	$12
CC	1 thin @ 30			$66	$53	$38	$25	$1
CC	2 thins @ 20			$58	$60	$49	$37	$20
CC	2 thins @ 30			$63	$66	$59	$47	$33
SW	no thin		$69	$101	$82	$61	$30	$14
SW	1 thin @ 20		$40	$101	$79	$60	$30	$14
SW	1 thin @ 30			$99	$68	$47	$17	$1
SW	2 thins @ 20			$92	$80	$64	$35	$20
SW	2 thins @ 30			$92	$91	$79	$54	$38

CC - clearcut, STR - Seed tree with reserves, SW - shelterwood, UEA - uneven-age management

Table 23 provides the comparison of treatments maximizing economic or substrate yields for upland oak. Under the alternatives simulated, maximizing SEV under UEA option A resulted in a minor reduction of potential maximum PSA from 95% under to UEA option B to 92%. Maximizing VOF resulted in a more significant reduction from 95% to 11% under clearcut with no thinning under a 50 year rotation length. Managing upland oak for maximum substrate yield resulted in a reduction in potential VOF by $811, but only a $35 reduction in SEV.

Table 23: Comparisons of top performing treatments for economic and substrate criteria on the upland oak cover type. Values in bold indicate the maximum value for that criterion for the respective regeneration system.

Upland oak					
Treatment	**Regime**	**RL**	**PSA (R2)**	**SEV**	**VOF**
CC	2 thins age 20	80	28%	$56	$1,255
CC	Legacy, 2 thins age 30	80	**45%**	$59	$1,167
CC	no thin	50	11%	**$85**	**$1,286**
STR	2 thins age 30	80	**51%**	$40	$1,021
STR	2 thins age 30	100	49%	$27	$1,008
STR	no thin	50	36%	**$55**	**$1,036**
SW	1 thin age 30	50	24%	**$123**	**$1,075**
SW	2 thins age 20	80	**39%**	$76	$1,037
SW	Legacy, 2 thins age 30	80	51%	$79	$953
UEA	B55 D30 Q1.5	20	92%	**$246**	**$508**
UEA	B65 D26 Q1.3	20	**95%**	$212	$475

CC - clearcut, STR - Seed tree with reserves, SW - shelterwood, UEA - uneven-age management, RL - Rotation length

Discussion

Nesting Substrate Yields

Substrate and economic yields were affected by multiple factors including cover type, regeneration system, rotation length, intermediate management regime, and the interactions between these factors. General trends observed are summarized in the following sections. Additionally, support or alternate reasoning is provided in regards to the following hypotheses:

1. Short rotations will result in the lowest amount of available nest substrate and increasing rotation length will improve overall nest substrate availability.
2. Treatments which leave residual forest canopy will have greater nesting substrate than treatments which leave no residual canopy.
3. The earlier thinning schedule will provide greater substrate yields because of the encouragement of faster diameter growth and the prevention of overstocking.
4. In some cases silvicultural treatment will result in greater provision of preferred nesting substrate than management by no-action.

Regeneration System

Among the silvicultural systems evaluated, regeneration systems which maintain residual structure (e.g., reserved seed or legacy trees and UEA management) were found to be better for providing eagle nesting substrate, accepting hypothesis 2. Consequently, clearcut generally provided the lowest PSA and shelterwood was often not very different. In treatments with only a regeneration harvest and no intermediate management, shelterwood closely resembled clearcut in terms of PSA and in some cases clearcut outperformed shelterwood in peak PSA rotations. This is not surprising because the shelterwood treatment differed from clearcut only across a 5 year period before complete removal of mature canopy. This 5 year period is believed to account for the slight improvement in shelterwood PSA over clearcut in most comparisons.

Out of non-legacy even-age treatments, STR left the greatest residual structure and consistently provided the highest PSA. In some cases STR outperformed legacy treatments as well. The even-age regeneration system which consistently out-performed STR and provided the overall highest PSA was SWL. Out of all systems, UEA management was the top performer in terms of PSA except in the 5 and 8 year cutting cycles for loblolly pine (Table 4).

Treatments which left reserve trees almost always resulted in an increased PSA and reduced SRD over non-legacy counterparts because reserve trees increase the proportion of the evaluation period with available substrate. The legacy tree prescription was found to have a positive effect in clearcut and shelterwood treatments, but in the absence of intermediate stand management the legacy trees were not adequate by themselves for maximizing preferred substrate over the rotation. Several factors suggest that the legacy prescription is not adequate for "bridging" substrate availability across rotations. For one, legacy treatments without thinning resulted in lower PSA than non-legacy treatments with ideal thinning regimes. Secondly, the average plot SRD of legacy treatments still represented a significant period before preferred substrate was made available. The STR prescription, which may provide greater PCC_{NS} depending on the legacy trees available, generally outperformed the clearcut with legacy CCL prescription. This suggests that the legacy prescription used in the simulations results in less than ideal residual forest substrate and that increasing both minimum diameter limit and TPA for the legacy prescription would likely improve the efficacy of the legacy treatment.

In all cover types except for loblolly pine, UEA management consistently resulted in the highest PSA value. The success of UEA management was expected because of greater control of stand structure through frequent thinning to a target UEA diameter distribution. By default, the inverse-J diameter distribution of uneven-age stands provides a minority of larger diameter classes and a majority of smaller diameter classes in subdominant canopy positions. This creates an overstory made up of large diameter trees with discontinuous canopy shown to be favored by nesting bald eagles. Comparing the two distributions for both pine and hardwood cover types, greater PSA was provided by the UEA distribution with a higher residual basal area (Table 3). The poor performance of UEA management prescriptions in loblolly pine suggests that the residual structure provided by this UEA prescription is inadequate as substrate.

As rotation length increases, regeneration system has less impact on overall PSA due to the reduced proportion of the rotation consisting of SRD. In short rotations however, regeneration system can have a more significant effect on PSA. Where rotations are short, leaving residual trees becomes increasingly important for maintaining high PSA. STR and legacy treatments showed greater PSA yields in these cases.

Rotation Length and Intermediate Density Management

Even-age treatments that utilized intermediate density management proved to be effective in increasing PSA in most cases. Thinning treatments showed a significant improvement in substrate availability over no-thin treatments especially in regeneration systems which lack residual forest structure such as clearcut and shelterwood. As to hypothesis 1, increases in rotation length also resulted in increases in PSA but only up to a point. PSA generally reached its peak before the maximum rotation length for active management treatments. The success of a management regime for maximizing PSA depended on the interactions between residual seed sources, thinning timing, frequency of thinning, and rotation length. Much of the effect of thinning timing and frequency on PSA was found to be primarily a function of rotation length and conversely, the effect of rotation length on PSA appears to be dependent on the presence and timing of thinning.

The decline in PSA after peak rotation lengths was attributed to the lack of intermediate density management. An example of this is in shelterwood and clearcut treatments in loblolly pine with one thin at 20 years showing a decline in PSA as rotation length increased from 30 years to the maximum of 70 years (Table 4). It is assumed that the lack of thinning late in the rotation results in a denser and more continuous canopy. This decline or leveling of PSA may be remedied during long rotations by increasing thinning frequency. Delaying thinning may also have a greater impact on a larger proportion of the rotation when thinning is infrequent. A delayed thinning schedule prevents the latter portion of the rotation going without density management. Higher PSA values often resulted from the two thin at 20 year treatment compared to the one thin at 30 year treatment. In this case, the earlier thinning in conjunction with a second thinning resulted in higher PSA than a single delayed thinning, indicating a greater importance of increased thinning frequency throughout the rotation and reduced importance of timing for the first thinning. This provides alternative reasoning to the logic of hypothesis 3.

Where rotation lengths were long, increasing thinning frequency and delaying thinning had a positive effect on PSA because of the more frequent and lasting effect of density management. However, in shorter rotations two thins had a reduced positive effect on PSA compared to one thin and in some cases one thin conducted early was found to provide greater PSA than two thins. This is believed to be because shorter rotations provide less time for stand density to increase beyond ideal levels for substrate, making two thins less imperative. Two thins may in fact result in overharvest of existing and potential nesting substrate. In this case, the earlier single thinning regime allows a greater amount of time for response to the thinning in shorter rotation lengths, supporting hypothesis 3.

In non-legacy treatments with no seed sources for regeneration, it was found that delayed thinning provided the greatest positive effect on PSA. It is believed that delaying thinning allowed more favorable nesting substrate to develop, whereas earlier thinning created less favorable conditions. However, where residual seed sources were present earlier thinning had greater benefit. This trend reversal was noted in the legacy treatments. In these treatments earlier thinning at 20 years showed a significant improvement over delayed thinning. The positive synergy of legacy trees and early thinning is believed to be a function of increased regeneration and stand densities resulting from seed provided by legacy trees. In this case, the earlier thinning schedule counteracts greater stand density and encourages productive growth of future nesting substrate. This follows recommendations for thinning young stands to encourage future nesting substrate (Arnett et al. 2001, Anthony and Isaacs 1989). This is especially important in stands that regenerate readily from seed such as loblolly pine and sweetgum/yellow poplar.

The absence of this synergy in STR treatments, which provide slightly more residual forest canopy on average, was puzzling. One possible explanation is that the legacy tree prescription as simulated in the model, is as successful for producing natural regeneration as the STR prescription and the reduced residual canopy cover allows faster increases in growth and stand density, necessitating timely thinning. In the case of STR, the increased canopy cover results in slightly reduced growth rates for regeneration and slower increases in stand density due to shading effects, thus reducing the significance of thinning at 20 years versus delaying thinning to 30 years. The synergistic reversal effect found in legacy treatments was not common in the two-thin regime for legacy trees, again supporting the greater benefit of frequent thinning throughout the rotation over the timing of the first thinning.

Comparisons to no-action

With regard to hypothesis 4, acceptance was dependent on treatment type, initial conditions, and cover type; however, select active management treatments were available on all cover types which produced greater substrate than no-action.

In hardwood cover types, select even-age treatments outperformed no-action, however the majority of even-age treatments provided PSA values slightly lower than no-action. These results are not surprising, considering that even-age rotations involved a complete regeneration of the stand. Also, many hardwood cover types had preferred substrate at the initial condition and maintained PSA under no-action as the simulation period increased in length. The closeness in PSA values to no-action for many active management treatments does show that even-age management can provide significant economic benefit while not significantly reducing the overall provision of nesting substrate over the entire simulation period. In the case of UEA management on hardwood plots, active management did consistently outperform no-action because of the frequent density management which maintained almost continuous preferred substrate availability.

In the loblolly pine cover type (Table 6), the majority of even-age and some uneven-age treatments outperformed no-action. This was expected for planted (non-natural) loblolly pine stands with moderate to high stocking rates of artificial regeneration, illustrating the benefit of management of loblolly pine stands over the "hands off" approach over the same evaluation period.

Economic Yields

The effect of rotation length on SEV and VOF is significant because present values decline as investment period increases. Less emphasis is placed on VOF in this analysis because of the high influence of initial conditions on VOF values. Because of the influence of past management which differed from the prescribed management regimes, the effect of prescribed management is better assessed by SEV. However, VOF does provide an economic companion to the calculation of PSA over the entire simulation period, both of which can be weighed against the results of no-action over equivalent evaluation periods. Realistically, in management focused on maximizing economic benefit, VOF is a more valuable metric because it includes the harvest value of the current stand. Because of the mature state of most of the forest plots on NSFIH, the highest VOF value is generally produced by clearcut treatments with short rotations which harvest the most existing timber. In general, treatments which harvested the most volume and left the least residual forest, provided the greatest SEV, VOF, and BDFT/year yields.

For SEV in even-age treatments, shelterwood treatments consistently yielded the highest values for all cover types. Clearcut was second highest and STR generally resulted in lower SEV than clearcut as a result of the reserve trees reducing harvest volume. The high economic performance of shelterwood is attributed to earlier revenue generation and release of crop trees. The first shelterwood cut allows about 50% of the canopy cover to be harvested 5 years prior to the end of the rotation providing reduced discounting effect on a significant amount of volume. Secondly, the shelterwood cutting acts as a crop tree release allowing high value sawtimber trees to grow under reduced competition for 5 years before harvesting. Lower value in clearcut treatments is due to the single stage harvest of clearcut and lack of the releasing effect of crop trees five years prior to harvesting. Perhaps a clearcut with a later thinning would be more competitive with shelterwood in terms of SEV.

Legacy treatments with reduced harvest volume resulted in a slight reduction in SEV. In some cases, especially where initial conditions are young to intermediate in age and rotation lengths are short, legacy treatments actually had higher SEV. In this situation legacy trees left after R1 may continue to grow and add value and then be harvested at the end of R2. Greater regeneration resulting from increased seed trees combined with thinning could also have contributed to the higher value of these residual treatments by promoting better stocking.

Over a perpetual management regime UEA treatments most often resulted in the highest SEV compared to even-age treatments because of consistent cash flow realized earlier. The present net value per cutting cycle had a considerably shorter investment period than the rotation lengths of even-age treatments. Even-age treatments which produced similarly high SEVs typically resulted from rotation lengths just short enough to produce sawtimber and/or which had sufficient intermediate revenue generation from thinning. Opposite from the trend in PSA yields, the UEA distributions with lower residual basal area produced higher SEV because of increased harvest volume.

Similar to UEA management, in long rotation lengths for even-age management, thinning had a more important role in providing relatively high SEV by maintaining cash flow. In the longer rotation lengths there was a noticeable increase in SEV with thinning frequency. Shorter rotations showed less impact from thinning in terms of maximizing SEV. In some cases thinning regimes reduced economic yield in shorter rotations by harvesting volume prematurely and not giving the residual trees enough time to benefit from the treatment. Where thinning was employed it was most often the case that the earlier thinning schedule provided the greatest value because of less discounting effect and improvements in the growth of the residual stand.

As shown with substrate yields, active management can provide net economic benefits, compared to no-action, which can be used to support ecosystem management. The results showed areas where tradeoffs in the two objectives can be minimized. In programs which seek to balance economic goals with eagle management, comparisons of PSA and SEV of different rotation lengths can identify areas where minor losses in PSA result in considerable gains in SEV and vice versa.

Management Implications

It has been shown that active silvicultural management can provide both enhanced economic and nesting benefits compared to no-action over equal time periods. Silvicultural treatments which maintained residual canopy across regeneration cuts and incorporated frequent density management such as even-age legacy treatments with thinning and UEA management, provide opportunities to balance the objectives of economic benefit and substrate availability. The tradeoffs of the two objectives are clear, however the results also show that given a threshold of PSA, a silvicultural regime can be identified which can provide a balance between economic benefit and provision of nesting substrate over time. In some cases, as with loblolly pine, the results suggest that lack of silviculture could result in a loss of land capability to support eagle nesting. Depending on the willingness of the installation and conservation partners (e.g., USFWS and state agencies) to design active management to meet ecosystem objectives and mitigate unwanted impacts, these balanced management regimes present a means to address multiple ecological goals and maintain nesting capacity as it relates to forest substrate, meanwhile providing some degree of financial self-sufficiency. Implementing bald eagle best management practices such as the use of protective zones, legacy trees, visual buffer strips, and appropriately timing operations will be necessary in order to ensure eagle nesting success and no net loss of military mission. Due to the management of forests for revenue being a low priority, installations should not be averse to taking these extra precautions. Similarly, a silvicultural approach based on long term substrate and economic yields, measured by PSA and SEV, is favorable over treatments which maximize short term gains as measured by VOF.

Management guidelines which recommend shelterwood harvesting for managing for nesting habitat, as the NSFIH BEMP (2010) does, should take care to specify that an adequate minimum number of reserve trees be retained and that timely thinning of regeneration should be implemented to provide future nesting substrate. The minimum number of reserve trees should be greater than the prescription for legacy trees in this study. Looking at long term production of substrate over the entire management regime, shelterwood treatments were found to provide minimal benefit over clearcutting in PSA. This is because shelterwood differs from clearcut only in the short period of time when the shelterwood canopy exists. However, the most effective treatment in terms of PSA was shelterwood with legacy. This treatment type is similar to the silvilcultural treatment more commonly referred to as *shelterwood with reserves*, which does not harvest a significant portion of the shelterwood canopy.

Thinning is especially important in stands that regenerate well by natural seeding such as loblolly pine and sweetgum/yellow poplar. The effect of residual canopy cover on regeneration should also be monitored in order to maintain the survival and growth of adequate future nesting substrate. Advance regeneration in difficult to regenerate species such as oak should receive extra care in tending and release.

As rotation lengths increase, the importance of thinning is found to be more significant than the type of regeneration system. Type of regeneration system was found to have less of an impact on PSA than the presence of intermediate density management in moderate to long rotations because of the reduced proportion of a rotation made up in the substrate recovery phase, as measured by SRD. UEA management was found to be the most beneficial silvilcultural system in hardwood stands for maximizing long term nesting substrate availability because preferred conditions were regularly maintained by thinning to a favorable target stand structure. Similarly, in even-age treatments, managing structure through density management was found to increase the suitability of a given management regime.

Up to a point, longer rotation lengths generally provided the highest PSA values as long as adequate intermediate density management was implemented. Where thinning is lacking, for the range of rotation lengths evaluated, PSA was found to decline as rotation lengths were extended. Therefore, PSA may be maximized over the long run by providing adequate density management throughout the rotation. Alternatively, regeneration of a stand at the rotation length of peak PSA would theoretically result in the most substrate availability over the long run. This is similar to the concept of harvesting a stand at the point of peak growth rate of the culmination of mean annual increment to maximize economic yields. Under this strategy, legacy and residual treatments present the interesting side effect of allowing greater economic yields by enabling earlier harvests due to shortened peak rotation lengths for PSA.

UEA management is subject to ecological constraints not depicted in this study which should be taken into account when considering this system. UEA management can be difficult to administer and achieve silvicultural goals, especially in the case of oak stands. The UEA management method simulated in this study regulated the stand to a target diameter distribution but made no attempt to simulate the effects of spatial distribution as related to single tree selection, group selection, or a hybrid selection method. Nor did this analysis characterize species composition over the simulation period. From an ecosystem management perspective, species composition and biodiversity are both important management objectives which were not evaluated in this study. Single tree selection may change the composition of forest stands over time to more shade tolerant species. In slower growing shade intermediate and intolerant species such as oaks, group selection is generally advised in combination with some form of competition control in order to regenerate preferred species.

Management of legacy trees is also an important consideration. Simulations showed that in some shorter rotation lengths there was higher economic yield in legacy and STR treatments compared to non-legacy counterparts. It is believed that harvest of the last rotation’s residuals was partly responsible for this increase in value. Harvesting the last rotation’s residual trees should be evaluated on a tree by tree basis based on the form, health, and age of a given tree. In some cases, overmature nest trees may present a hazard for nesting success because of greater probability of mortality, crown breakage, and windthrow. In this case, the more vigorous residuals established from the last regeneration cut may be preferred for continued nesting use. However, overmature trees will provide good perch habitat if located close to water, even as snags.

Chapter 5: Conclusion

Department of Defense installations are obliged to manage forests for multiple ecological objectives. As part of forest management planning requirements, NSFIH must evaluate the potential effects of proposed forest management treatments on bald eagle nesting and incorporate this information in their forest management plan. This study used computer simulation to evaluate common silvicultural management regimes based on yields of bald eagle nesting substrate and economic benefit. Economic benefit provides a method of rating the opportunity costs of a management alternative as well as a means for funding additional ecosystem management projects on installations.

A model of preferred bald eagle nesting substrate was developed using observations of forest structure at nesting sites at NSFIH. Structural variables of percent canopy cover of the nesting stratum (PCC_{NS}) and maximum DBH (DBH_{MAX}) were used to make comparisons of forest sample observations conditions to the preferred nesting condition. Mahalanobis distance was used to measure the dissimilarity of the variables of sample plots compared to the multivariate mean of the variables for preferred substrate observations. The fit of Mahalanobis distance model was compared to a Boolean logic model which enabled an evaluation of the comparative strengths and weaknesses of the model. The Forest Vegetation Simulator was then used to simulate the common silvicultural treatments of clearcut, seed tree, shelterwood, and uneven-age management, as well as no-action, under varied rotation lengths, thinning regimes, and with legacy trees. Sample plots were simulated over a transition period from initial conditions to regeneration and a complete future rotation. FVS allowed calculation of the nesting substrate variables as well as the economic costs and revenues resulting from the management regimes at 10 year intervals. Management regimes were then evaluated using the habitat and economic criteria to determine how each regime met the two management objectives.

Simulation results were presented along with analysis of the trends in nesting substrate and economic yields and the management implications were discussed. The results show that appropriate management regimes can provide greater availability of nesting substrate and net economic benefit when compared to allowing the stand to develop under the no-action alternative. In other cases active management provides comparable substrate yields to no-action. Treatments which maintained eagle habitat over the greatest proportion of the evaluation period were seed tree and legacy treatments and UEA management. In the case of UEA management, this study showed that continual regulation of nesting substrate in hardwood cover types by cutting cycles occurring every 20 years resulted in almost continuous availability of preferred nesting substrate. The UEA management options for hardwood cover types outperformed all even-age management regimes in terms of nesting substrate availability and SEV.

The results also show the importance of intermediate stand management. Management guidelines should place more emphasis on the value of residual forest canopy, UEA management and intermediate density management, and less emphasis on the regeneration system which affects substrate for only a portion of the rotation and thus depends greatly on rotation length.

Implementing silvicultural treatments which resulted in the highest economic benefit often involved a reduction in potential nesting substrate and vice versa. However, this study highlights areas where tradeoffs can be minimized by increasing or decreasing rotation length, or by increasing intermediate density management.

Recommendations for Future Research

This study evaluated a limited range of silvicultural possibilities. More sophisticated iterative simulation is recommended for identifying greater nuances in the trends and developing prescriptions which can optimize the given objectives. The high performance of UEA management especially demands greater evaluation of a wide variety of UEA distributions and cutting cycle lengths. Simulation combined with more sophisticated optimization methods could identify which treatment would provide an optimum balance of the two objectives given desired thresholds of substrate and economic yields. Additionally, more detailed analysis of the patterns and timing of substrate availability across the time series would allow researchers to identify when, during a particular management regime, is substrate available and when is intervention needed to encourage substrate.

A complete evaluation of the simulated treatments using the CDF model was not performed during this study; however, it would be interesting to see how the results from the CDF model would compare with MD over various thresholds. From the limited analysis with the CDF model that was done, it was found that the CDF model generally results in slightly lower PSA values for the treatments and slightly greater values of SRD, except in UEA treatments where SRD was considerably lower in the CDF model versus the MD model. Lower SRD in UEA treatments is because the CDF model covered greater area of substrate structure with lower PCC_{NS} and lower

DBH_{MAX}, which were produced during UEA management. Additionally, a greater sample of nest sites would improve the confidence in the substrate model and enable stratification of nest sites by cover type. At a minimum, it would be useful to have a larger sample of pine nest sites to create separate models for pine and hardwood.

Due to the small sample of available plots per stand, this analysis was performed on a non-spatially referenced, cover type level to determine the average effect for that cover type. Given an adequate sample of plots for a specific stand, analysis could be performed on the suitability of a given forest area and the spatial implications of certain treatments. For a partial harvest of a given area spatial variation in the provision of substrate will occur. In this way an adequate systematic random sample of a harvested area could provide an area based assessment of nesting substrate availability using the substrate models discussed in this study.

This study focused on the defining the type of forest structure preferred as bald eagle nesting habitat. Prior to this study, modeling of habitat components at this level of detail had not been done because of the focus instead on the holistic habitat requirements. Improved modeling of the forest component could be accomplished using more precise measures of stand structure. Descriptions and characterization of the presence of such canopy gaps would ideally be accomplished by spatially-explicit distance dependent structural metrics such as those presented by Pommerening (2002). Providing advanced measurement of the spatial arrangement of nest habitat might uncover improved variables for identifying preferred habitat. This approach was not undertaken due to the distance independent nature of the data collected and the use of FVS, a distance independent model.

Disturbance is probably the most important habitat factor relative to this study which was not assessed. Logging related disturbances have been shown to have negative impacts on eagles. However, in most cases the direct disturbances related to logging such as noise and human activity are temporary. More data and rigorous study is required to refine understanding of the effects of logging disturbances on nest site selection and nesting success.

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