Abstract

LEVIN, BENJAMIN ROSS. Pine Plantation Forestry: Prioritizing Ecosystem Services on North Carolina Game Lands. (Under the Direction of Dr. Joseph P. Roise).

Planted pine forests play important roles in providing timber revenue and ecosystem services in the southeastern United States. Trade-offs between management objectives exist, but demonstrating quantitative links between forest stand characteristics and species-specific habitat quality requires models that are scaled appropriately. We identified 24 thinning regimes and 6 planting densities deemed suitable for increasing open-forest condition on loblolly pine plantations. With the identified thinning regimes as our guides, we developed 1,008 prescriptions and associated growth and yield tables for newly regenerated loblolly pine plantations aimed at increasing open-forest condition. We identified the combination of thinning regime and initial planting density that generated the highest mean open-forest habitat suitability index scores. Then, we updated the North Carolina Wildlife Resources Commission's Woodstock model by replacing the original regenerated growth and yield tables with the growth and yield tables that generated the highest habitat suitability index scores. We ran both the original and updated Woodstock models for 100 years and determined that the updated growth and yield tables generated a higher total habitat suitability index score during the modeled horizon than the original growth and yield tables. Using the updated outputs, we developed a production possibilities frontier to demonstrate the tradeoffs between managing for species-specific habitat objectives and providing sustainable revenue generation. Ultimately, we provided additional evidence that thinning pine plantations often and to below 11.5 m^2/ha (50 ft^2/ac) is more advantageous for open forest associated wildlife species.

Pine Plantation Forestry: Prioritizing Ecosystem Services on North Carolina Game Lands

by

Benjamin Ross Levin

A thesis submitted to the Graduate Faculty of
North Carolina State University in
partial fulfillment of the
requirements for the degree of
Master of Science

Forestry and Environmental Resources

Raleigh, North Carolina
2025

APPROVED BY:

Joseph P. Roise Committee Chair	Rachel L. Cook
Christopher E. Moorman	Casey E. Phillips

DEDICATION

To my wife Leanna, for your constant love, support, and belief. Your example and relentless dedication to growth and light lifts all those around you. To my Los Angeles parents, Marjorie and Steve, and my North Carolina parents, Betsy and Laura, for their unwavering support and love. To my sister Rachel, for your sense of humor, go-getter attitude, and drive. Although I'm the first born, you're a tough act to follow. To my brother Nathan, for your determination and proclivity to create success. To Grammy, Poppy, Nana, and Gumpa, for your never-ending love and support. To Poppy Harry, for passing on your knack for language and tinkering, and for building bridges to support Allied troop movements during the World's most consequential war. Finally, to my Aunt Nancy, for bringing the music.

BIOGRAPHY

Ben was born and raised in Los Angeles, California. He quickly developed a love of the outdoors and exploration, relishing his time trapsing about in the Angeles National Forest and Sierra Nevada Mountains. He earned a B.A. in Biology from Guilford College, with a minor in German Language Studies. He and his now wife Leanna moved to Rogers Park in Chicago, Illinois, while she earned her M.S. in Chemistry from Northwestern University. There, he spent three years working with neurodivergent elementary schoolers in preparation for becoming a science teacher. After struggling to answer each and every natural science question posed by his highly inquisitive students, and while witnessing America's alarmingly slow response to mitigate the impacts of climate change, he decided to rekindle his own curiosities and pursue graduate studies in forestry at NC State. His research interests include climate-smart forestry, ecological economics, and socio-ecological systems, to name a few. When he isn't reading books, walking the dog with his wife, or tinkering in the workshop, he can often be found playing tennis or helping his in-laws with farm projects.

ACKNOWLEDGMENTS

It goes without saying that the list of people that have played an integral part in my life far exceeds the space allotted here. We are but a sum of our experiences, and I owe so much to so many. D. Limburg, M. Dery, and the many world-class faculty members at Guilford College encouraged my love of learning. E. Washington, T. Immanuel, and my family at Mosaic Elementary, who taught me how to be resilient during tough times, all while putting the needs of others before your own. K. Vetter and H. Shoier kindled my love of calculus and statistics. N. Giertych helped me debug code. My fellow CNR graduate students always offered sound advice and support. L. David and M. Castle for their patience and troubleshooting assistance with FVS. I. Lodge for his Woodstock advice. G. DaSilva for giving me the opportunity to garner more experience with Woodstock. D. Goodwin helped set up the remote connection for running Woodstock.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Chapter 1: Systems Ecology and the Growth of Loblolly Pine: A Literature Review

Introduction

Forests play critical roles in mitigating climate change and providing ecosystem services. Forests can be managed to store carbon, provide wood products, decrease soil erosion, regulate temperature, protect keystone species, and clean water, for example. Optimizing the effects and magnitude of both priced and unpriced forest benefits is of the utmost importance.

The aim of this chapter is to focus on loblolly pine (*Pinus taeda*) plantations in the North Carolina Wildlife Resource Commission's Forest Planning Model and the foundational social and ecological factors that underpin current forest management decision-making. As such, a comprehensive literature review was conducted to highlight the often-overlooked connection between human conceptions and ecological realities, but with a high degree of specificity.

Forest managers are responsible for critically evaluating how present actions can alter financial and ecological outcomes, but more attention should be paid to assessing how current systems are undoubtedly shaped by past beliefs and customs. By focusing our review on systems ecology, modeling fundamentals, silvics, and southern pine plantation management we illustrate the importance of more critically justifying management decisions, and, perhaps more importantly, questioning what we *know*. This is especially salient as predicting and reacting to the effects of anthropogenic climate change necessitates speedy and extensive examination of a constantly changing social and ecological landscape.

Specific to modeling loblolly pine plantations, we home in on the views laid out by systems ecologists to punctuate the epistemological challenges with which foresters must grapple. Building and refining a model is an ongoing exercise in obtaining useful results in the face of vast uncertainty and consistent change. Put simply, in this review, we have striven to answer the forthcoming question: what complexities inform the decisions of those who manage loblolly pine plantations for habitat in the American south?

We used this review to hone our methodology in making modifications to an existing linear programming model. Our goal was to optimize the production of conditions for open-forest associate species on North Carolina game lands by replacing the model's original regenerated growth and yield tables. This required careful development and testing of over 1,000 unique timber prescriptions.

Systems Ecology

Ecological networks are complex, as each species affects all others, either directly or indirectly (Williams et al., 2002). Organisms are bound to encounter a wide variety of disturbances that differ in their spatial extents, durations, and frequencies (MacDougall et al., 2013; Pincebourde et al., 2012). Such notions of ecological complexity are not new (Ives & Carpenter, 2007; Orians, 1975; Pimm, 1984), and attempts to develop frameworks in response to knowledge gaps have been numerous. Although Charles Darwin referred to the natural world as a "tangled bank" (Darwin & Beer, 1996), Western scientists, for much of the 20th century viewed ecology through a species-specific lens. The works of brothers Eugene and Howard Odum (Montague, 2022), heavily influenced by the aftermath of World War 2 and commencement of the atomic age, catalyzed a shift in the way biologists approached ecology (Hall, 2021). Their work prompted serious consideration of ecological systems as interconnected and interdependent. Eugene Odum famously echoed urgency for disciplinary change and offered perhaps the first mention of systems ecology:

> Granting that the subject matter and general aims of ecology as a branch of biology have remained unchanged for a century or more, the field has nevertheless recently achieved a maturity (p.14)…*The new ecology is thus a systems ecology*- or, to put it in other words, the ecology deals with the structure and function of levels of organization beyond that of the individual or species (p.15)… If biologists do not rise to the challenge, who will advise on the management of man's environment… (p.16) (Odum, 1964).

But ecologists have struggled to adopt uniform terminology (Margalef, 1963) (Grimm & Wissel, 1997), exhibited difficulty bridging the gap between theoretical and empirical work, and display a restricted understanding of the multidimensional nature of disturbances and stability (Donohue et al., 2016). Ecologists are not alone in struggling to understand and predict environmental change and response. While advances in science have spurred significant disciplinary change, heightened public attention has continued to influence managers, thereby indirectly affecting ecosystems themselves (Puettmann et al., 2012). Unlike precise fields like physics or engineering, social and environmental sciences have high degrees of uncertainty as they are complex, adaptive, and rife with indeterminacies (Dietz, 2003). Forestry professionals, as well as those in other disciplines, must also work to understand a planet comprised of non-linear dynamic systems that are, as of now, inherently unpredictable (Dawson et al., 2010). Forest managers and other natural resource professionals frequently design and implement practices over expansive temporal and spatial scales. Depending on the objectives or constraints associated with certain projects, especially those featuring diverse and sizable scales, complexity can increase rapidly (Weintraub et al., 2000). At certain scales, management decisions produce bidirectional effects for both the natural and human environment (Gibson et al., 2000). Shrinking empirical and theoretical gaps can be accomplished by developing models consistent in scale with reputable parameters. Such models offer additional utility as they can, if developed properly, simultaneously weigh economic and ecological projections.

Appropriately Scaled and Fungible Models

While the results of predictive mechanisms and measured outcomes will never coincide, establishing a better balance between anticipation, monitoring, and adaptation can reduce surprising findings (Holling, 1985). Models developed for explicit scales of interest cannot be naively applied from one scale to the next. Scaling from leaf to ecosystem to landscape and beyond (Jarvis & McNaughton, 1986) requires a robust understanding of how information is shifted from narrow to wide scopes, and conversely (Levin, 1992). Those who wish to manage and model ecosystems must not fall prey to these pitfalls: incorrectly assuming a simple solution and stagnation in the face of staggering complexity (DeFries & Nagendra, 2017). Developing adequate frameworks that entirely clarify ecological systems is impossible as our knowledge of any system is imperfect (Lindblom, 1977). Though, some modeling frameworks can be useful if constructed appropriately. When modeling spatially explicit forest growth and yield to prioritize species-specific habitat, great care must be taken to accurately link stands with observed characteristics.

In the second chapter of this work, we modified an existing linear programming model that was meticulously built to avoid the above pitfalls. Alterations to the model were made to improve conditions for open-forest associate species on North Carolina game lands. Making changes to an existing model can be risky. Replacing the model's original regenerated loblolly pine growth and yield tables with many new, seemingly frivolous yield tables may inadvertently decrease the model's efficiency or render a solution infeasible. Guided by the works referenced here, we developed 1,008 alternative timber management prescriptions, identified a thinning regime and planting density combination that scored highest in generating open-forest condition, implemented the associated growth and yield tables to preserve the model's structure.

Initially, the discipline of forestry arose from central Europe out of concerns about timber supply, industrialization, and the disintegration of communal land rights during the 1700's (Bennett, 2015). Foresters have dealt with complex challenges by adapting mathematical programming models to define and solve management problems (Bettinger & Chung, 2004; Davis et al., 2017). Most often, such models prioritize financial return and forest productivity by including a maximized net-present value in the objective function (Buongiorno & Gilless, 2003; Clutter et al., 1983). Systematic emphasis on satisfying human preferences (Huntsinger & McCaffrey, 1995) hinders the discipline's effectiveness in combatting environmental justice, biodiversity loss, and climate change (Himes & Dues, 2024). Though, shifts in socioeconomic, demographic, technological, lifestyle, policy, and institutional factors continue to catalyze and shape forest management decisions (Daigneault & Favero, 2021). As a result, natural resource professionals now more often create tools, multiple-value frameworks, and indicators that are not expressed solely in economic terms (Bengston, 1994).

North Carolina's Pine Forests in the Anthropocene: Economy and Ecology

The southern United States is often called the "wood basket", as the region is responsible for 71% of the nation's planted timberland (Oswalt et al., 2019). The region is comprised of Alabama, Arkansas, Florida, Georgia, Kentucky, Louisiana, Mississippi, North Carolina, Oklahoma, South Carolina, Tennessee, Texas, and Virginia, and the acreage of planted pine forests in the region soared from 1.8 million acres in 1952 to 32 million acres by the year 2000 (The South's Fourth Forest: Opportunities for the Future, 1988; Wear & Greis, 2002). As of 2017, the total acreage of planted pine was more than 34 million acres (Oswalt et al., 2019). The southeastern United States supplies more timber than any other country and produces more than 26% of wood products nationally (Guo et al., 2023). Additionally, softwood lumber production is projected to increase in the Southeast region over the next 50 years (Guo et al., 2023). More specifically, North Carolina's $35.3 billion dollar forest products sector plays a large role in the States's economy by: supporting about 139,700 part-time and full-time jobs, representing approximately $1.74 billion dollars in trade value, and contributing close to $184 million dollars in state taxes (federal taxes amount to about $434.4 million dollars) (North Carolina Forest Service, 2024).

In North Carolina loblolly pine and shortleaf pine (*Pinus echinata*) are frequently coupled to form a singular forest type, though loblolly pine is far more abundant. North Carolina boasts close to 18.8 million acres of forest land, of which softwoods account for about 6.4 million acres. Loblolly-shortleaf forest types make up <5.8 million acres, about 90% of all softwood growth (Brown & Lambert, 2024). Over 525,000 non-industrial private landowners (NIPF) manage 12,258,717 million acres of forestland statewide (North Carolina Forest Service, 2024). As urbanization is the greatest threat to forest cover in the United States (U.S. Department of Agriculture, Forest Service, 2023), it is vital to offer NIPFs incentives to keep their land forested (Abt et al., 2012; Loehle et al., 2024). If able to tap in to financial returns associated with responsible timber harvesting, NIPFs are less likely to sell to convert or develop their land (Betts et al., 2017; Loehle et al., 2024).

North Carolina is the 6th fastest growing state by population and saw the third largest percentage growth in urban lands, about 87.8 %, in the nation (U.S. Department of Agriculture, Forest Service, 2023). Acres of the wildland urban interface (WUI), where human development merges with undeveloped wildland, forest, or vegetative fuels, is more abundant (~13.5 million acres) in North Carolina than any other state (N.C. Forest Service, 2025; North Carolina Forest Service, 2024). The average southern state, in comparison, has only an average of 6.8 million acres of WUI (Andreu & Hermansen-Baez, 2008). Measured in 2020, 21% of houses in North Carolina are in the vicinity of the WUI, while 24% of homes are intermingled with the WUI (USDA Forest Service Northern Research Station, 2023).

Much of the vegetation in the South is adapted to, and in some cases dependent on, fire (Andreu & Hermansen-Baez, 2008). Both longleaf and shortleaf pine are more capable of using fire to their advantage than loblolly pine. Longleaf pine's proclivity to remain in a grass stage after establishment encourages hardy root development. In the grass stage, longleaf pine terminal buds hover at ground level, well protected by a dense mass of long needles (Wahlenberg, 1946).

Frequent low intensity fires may destroy much of the tuft, but adequate root establishment and terminal bud security promotes quick needle regrowth. Shortleaf pine seedlings and saplings can survive top-kill by resprouting from a basal crook containing dormant buds (Stewart et al., 2015; W.R. Mattoon, 1915). Loblolly pine, on the other hand, is one of the most susceptible of the southern pines to mortality caused by fire. Unlike other southern pines, though, loblolly pine manufactures innumerably more seed, establishes with greater ease, and grows expeditiously from the outset (Guldin, 2008). Once loblolly pines mature, they are less susceptible to fire related mortality than seedlings and saplings. In even aged loblolly pine plantations, fire has been used to decrease competition among crop trees and unwanted vegetation, especially volunteer hardwoods. Great care must be taken when introducing fire on a stand. Mature (~ 30 years old) pine stands in the Triassic basin that feature montmorillonite clay, have been "hot" burned with great success (Doug Duncan, personal correspondence), though this strategy may not apply to younger stands planted on less productive Cecil soils. Where once low intensity fires would favor that of longleaf and shortleaf pines, recent trends of fire suppression have allowed loblolly to outcompete its relatives (Guldin, 2008).

Where revenue generation and carbon storage are concerned, tree growth deficiency and mortality can have grievous ecological and economic effects. Detecting the exact cause of unwanted or unexpected results is challenging, though, there are instances where the underlying cause can be identified with relative ease (non-native insects and/or fungi notorious for being vigorous invaders, or destructive weather events such as ice storms or hurricanes) (Coyle et al., 2020). Trees die due to competition, advanced age, natural disturbance, or biotic agents such as bark beetles and fungi (Sinclair, 1966). When rotation length hovers between 100-150 years, competition-based mortality may cause 30-40% of tree death (Pretzsch et al., 2023), whereas advanced age accounts for the mortality of residual trees (Joe Roise, personal correspondence).

The effects of climate change are varied and expected to considerably transform the productive capability of loblolly pine forests in the southern region (Wertin et al., 2010). The chemical composition of the atmosphere is changing, and there are associated climatic implications (Körner, 2006). Carbon dioxide has long been a fundamental resource for any organism capable of eukaryotic photosynthesis (Knoll, 2003), and coniferous trees have been present for more than 100 million years (Farjon, 2008; Neale et al., 2014). During that time climatic changes indeed occurred, but the periodicity at which they transpired is in stark contrast to current trends. The most notable temperature shifts during the long history of the pines took place recently during the Pleistocene Ice Ages (1.6 million years ago), when glaciers advanced and retreated over the course of tens of thousands of years. These periods of adjustment were adequate to allow for conifer migration to more habitable areas (Schmidtling, 2003)..

While it is not possible to perfectly extrapolate future conditions, forest managers can use the best information available to make more informed decisions. Flexibility to modify silvicultural practices is exercised frequently by natural resource professionals when natural disturbances disrupt long-term plans. Forest ownership patterns, decision making responsibilities, required capital, and the source of that capital present major obstacles to employing climate smart management practices (Guldin, 2014). Managing pine forests for revenue generation, wildlife habitat, or additional environmental services does not entirely neglect non-prioritized objectives. At any given point during the life of a pine stand it offers benefits for each, though to varying degrees.

Managing Loblolly Pine for Sawtimber Revenue

Loblolly pine is the most abundant tree species to be managed for timber crops in the South as it: (1) exhibits effective natural and artificial regeneration over expansive areas, (2) grows rapidly on a host of diverse sites, (3) handles easily in the forest and mill, and (4) produces wood products that exhibit steady demand and prices (W.G. Wahlenberg, 1960). Dimensional lumber is the most common product made from loblolly pine, but other popular products include pulp, plywood, engineered and composite products, poles and pilings, and biofuel (Oswalt et al., 2019; Shephard et al., 2022). Loblolly pine grows in a straight grained fashion, grades highly in nail-holding capacity, and can easily be impregnated with preservatives that increase durability and usefulness tenfold (Gaby, 1985).

Pine plantation management plays a large part in determining the performance and product mix of every stand. Before planting crews plant a single seedling, landowners and foresters can choose the provenance of their trees. State-run nurseries in North Carolina, along with other Southern states, sell high quality, often regionally tailored seedlings. Paying to source crops from seed orchards that develop and incubate genetically improved seedlings has proved to be economically justified (Perry & Wang, 1958). Although improved genetics has become a staple of southern forestry (Fox et al., 2007) and can have an outsized positive impact on productive sites (Jett et al., 1991), it alone cannot account for complete success or failure. If soil, climates, and silvicultural inputs are not carefully matched to complement (McKeand et al., 2006) rather than hinder tree productivity, predicted return on investment may not be actualized.

Competition for sunlight and resources occurs both among loblolly pines and between loblolly pines and other competitors. Methods of chemical site preparation, namely herbicide application, can interrupt the growth of non-crop plants (i.e., species that compete with loblolly pine). Loblolly pine seedlings that are established under conditions that favor intraspecific competition can more easily use available nutrients. Suppressing undesirable vegetation with herbicides has been shown to increase merchantable pine volume by between 17-149% as compared to non-herbicide control treatment, with increases varying in response to application frequency, range of weeds controlled, and pre-existing non-crop vegetation (Miller et al., 2003). Herbicide application targeting all non-crop vegetation during the first 5 years after seedling establishment can result in taller trees, larger boles, and greater weight gains in both measurement and span (28 years post-treatment) in comparison to one-time treatments after planting (Blazier et al., 2017). An inclination to maximize productivity without consideration paid to the long-term financial ramifications of early rotation spending may result in a weaker financial performance. One should weigh the costs associated with variations of site preparation against the expected revenue generation from product yield. Stand density management (by way of planting and/or thinning) is the most consequential tool for managing stem size (Jokela et al., 2004). Initial spacing between seedlings, and in turn stand density, is determined by weighing factors such site quality, desired end-product, and probability and magnitude of mid-rotation stand treatments (Harms & Lloyd, 1981). Initial planting density and post-planting treatments have implications for biological outcomes (e.g., tree height, diameter, crown, stem quality, basal area, and volume development) and operational considerations (e.g., harvesting, thinning, site prep, and other cultural treatments) (Smith & Strub, 1991). Loblolly pine plantations managed for higher revenue generation (i.e. sawtimber and chip'n'saw) are typically planted with genetically improved seedlings at a density of 600-700 trees per acre (a traditional spacing for this range would be 7x10 ft, ~622 trees per acre) (Hoover et al., 2014).

Loblolly pine's native range spans 14 states from southern New Jersey to central Florida, and west to eastern Texas (Baker & Langdon, 1990). For pines in their native range, predicted increases in carbon dioxide could increase net photosynthesis, but decreased precipitation caused by 2-3 °C rises in temperature will likely cause net photosynthesis to decline significantly (Wertin et al., 2010). Rising temperatures and more frequent droughts alter hydrologic connectivity in temperate forests, which may have negative impacts on downslope vegetation (McQuillan et al., 2023). Additional water stress applied to loblolly pines may decrease productivity, though, pines bred to better withstand climatic uncertainty may be better suited in the future (Matallana-Ramirez et al., 2021). Hydroclimate volatility, rapid shifts from drought-like conditions to exceptionally wet ones, and vice-versa, can also have adverse effects on pine forests (Swain et al., 2025). Widespread climate related stress induction in southern forests will increase tree susceptibility to pests (Peterson et al., 2014). Higher levels of atmospheric carbon dioxide do increase photosynthetic efficiency, but confounding factors listed above may limit or possibly negate crop-tree productivity.

Soil microbes such as ectomycorrhizal fungi cultivate symbiotic relationships with about 95% of fine roots in evergreen trees in temperate forests, including the southern pines (J. J. Hackman et al., 2022; Rose, 2023). These interactions help trees access soil water and nutrients (Becquer et al., 2019; Lee et al., 2010) while enhancing the host's ability to fend off abiotic and biotic stressors (Franco & Castro, 2015; Onwuchekwa et al., 2014). Pine plantations are often located on phosphorus deficient, acidic soils (Comerford et al., 2002), and silvicultural actions taken to increase phosphorus availability using ectomycorrhizal fungi may increase crop tree productivity and stress mitigation (J. Hackman et al., 2024).

Pine trees on drier sites are more susceptible to beetle attacks than those on moist sites. It has been observed that water stressed trees exhibit lower levels of oleoresin exudation pressures, which appears to be favorable for pine beetle establishment (Lorio & Hodges, 1968). Additionally, higher levels of atmospheric water content are projected to increase frequencies of extreme and intense precipitation (Kunkel et al., 2020). Higher precipitation at certain times will not render severe water stress caused by rising temperatures/drought less problematic. For, root systems subjected to severe water stress show diminished permeability for several days after rewatering (Kramer, 1950). Water uptake and availability play a major role in secondary wood production during the growing season (Panshin & de Zeeuw, 1980). Severe water stress may curtail diameter growth, a critical component of managing for sawtimber.

Thinning loblolly pine stands and reducing planting densities can ameliorate the effects of severe water stress. Heavily stocked stands intended for sawlog production are less likely to be maintained without adequate water supply, while water availability poses less concern in sparser stands (Zahner & Whitmore, 1960). Bassett (1964) recorded that plots in a 30-year-old even aged loblolly stand (with a site index of 90) grew differently depending on evapotranspiration rates and water availability. Trees on plots thinned to 125 ft^2/ac ceased measurable diameter growth when under-crown water dropped below 40% in the surface foot and daily potential evapotranspiration eclipsed 0.24 inches of water. Distinctly, trees on plots thinned to 55 ft^2/ac grew continuously (Bassett, 1964). In other cases, thinning without fertilization has been deemed efficient in both control and drought scenarios, regardless of stand age (Bose et al., 2018; Shephard et al., 2021). Thinned stands should maintain between 61 ft^2/ac and 91 ft^2/ac (Stokes & Watson, 1996). However, studies indicate that thinning does not inherently increase total stand basal area, as basal area development in thinned stands often converges with that of unthinned counterparts over time (Andrulot, 1970; Pienaar, 1979). Thinning decreases intraspecific competition while increasing interspecific competition. As trees are removed from the stand to prioritize crop trees, understory plants use once intercepted sunlight and resources. Although crop trees have fewer pines as competition, the proliferation of other woody species, forbs, and shrubs presents unique challenges and opportunities.

Managing Loblolly Pine for Ecosystem Services

The IPCC estimated in 2022 that the probability of limiting global warming to below 2 °C dropped to 67% (IPCC, 2023). It has been estimated that forests sequester 7.6 $GtCO_2e$ $year^{-1}$, while program impetus could augment between 1.2–5.8 $GtCO_2e/yr^{-1}$ (Daigneault et al., 2022; Harris et al., 2021). Regardless of transitory losses after timber harvest, many analyses surmise that carbon storage capacities of southern pine plantations and subsequent harvested wood products can grow (Fuller & Dwivedi, 2021; Gonzalez-Benecke et al., 2011; Jonker et al., 2018; Sohngen & Brown, 2008). Puls et al. (2024) reported that future carbon storage and loss in pine plantations is dependent on the productivity of a particular site and ensuing rotation length.

Lower crown foliage in thinned pine plantations has water potentials, photosynthetic rates, and conductance levels akin to sun-grown needles in the upper crowns of thinned and unthinned stands (Ginn et al., 1991). Sites in the Piedmont region of the southeast United States often have low soil carbon levels, and afforestation combined with silvicultural inputs prioritizing hasty growth may increase soil carbon stocks (Vogel et al., 2022). Managing pine plantations for carbon storage implies managing crop trees for harvested wood products that provide stable, long term carbon storage. Composite logs offer the most robust carbon storage potential, but pole logs, large saw logs, veneer logs, saw logs, and chip'n'saw logs offer exceptional alternatives, while pulp logs offer less long term carbon storage (Puls et al., 2024). Highly productive planted forests provide valuable wood products, conserve habitat for numerous wildlife, and help offset the need to extract resources from pristine forests (Paquette & Messier, 2010). Recent evidence that biodiversity loss can hamper terrestrial carbon storage (Weiskopf et al., 2024) proves the need to explore plantation management regimes that prioritize both objectives.

Nature-based markets have made inroads in response to the failure of traditional markets. Such market failures have been caused by negative externalities associated with global energy production/consumption, manufacturing techniques, and land use change. In 2022, $1.7 trillion USD and $5 trillion USD from the public and private sector, respectively, financed nature-negative activities. On the other hand, public finance for nature-based solutions totaled $165 billion USD, whereas private sector finance amounted to $35 billion USD (UNEP, 2023). In cases of market failure, efficient government intervention requires accurate identification of when market failures exist, studying the intricacies of different intervention options, and assessment of specific levers that are needed for policy implementation (Phaneuf & Requate, 2016). Concerns about the fickle nature of government intervention and the prospect of shrinking private sector nature-negative finance by reallocating billions of dollars to funding nature-based solutions (UNEP, 2023), in part explains the global push toward a robust voluntary carbon market (TSVCM, 2021). Planted forests are expected to continue playing major roles in the carbon economy, but some have laid out general, but valid, concerns: biodiverse forests could be cleared to establish monoculture tree plantations, planted trees may become invasive, and tree plantations may negatively affect key ecosystem processes such as fire and hydrological regimes (Lindenmayer et al., 2012).

Although interest in biodiversity markets has spiked, critics (Josefsson et al., 2021; Theis et al., 2020; zu Ermgassen et al., 2023) have argued that offsetting is more effective in less ecologically complex or faster-maturing cover types such as certain kinds of wetlands, while inferior outcomes occur in slow-maturing types like forest and woodlands. However, the evidence for such claims is not convincing, and is underpinned by weak study designs (zu Ermgassen et al., 2023). Additionally, there are countless biodiversity metrics (Chao et al., 2014; Lammerant et al., 2021), disagreement around biodiversity baselines (Mehrabi et al., 2022), and difficulties in accurately surveying and quantifying biodiversity (Bull et al., 2022; Coles, 2023). Rather than separating the two markets, some have advocated for a co-crediting system (Deutz et al., 2020; Tedersoo et al., 2024).

Both traditional and nature-based markets are commonly stifled, as decision makers, buyers, and sellers have imperfect knowledge. The benefits of obtaining good, even adequate information must be weighed against the opportunity costs, and excessive deliberation or too much information penalizes buyers, sellers, and other parties (Cubbage et al., 1993). Such traditional neoclassical economic notions are tested by free market failures and time limitations. Now, excess deliberation may not only delay or deny participants from capitalizing on market benefits, but inaction will inevitably create and exacerbate the effects of negative externalities. In forestry, secondary outputs are widespread, both amongst current forest landowners and amongst present and future generations (Cubbage et al., 1993). Although elimination of negative consequences may not be possible, it is critical to employ modeling techniques that offer land managers a more holistic scope from which they make informed decisions. Savannas and woodlands are defined by open canopies, frequent disturbances, a scarce to modest midstory layer, and a dense herbaceous understory (Greene et al., 2019) . The extent of open forests and woodlands has declined substantially post Euro-American settlement (Hanberry & Thompson, 2019). In general, regenerated and thinned pine stands can approximate open-forest condition as long as they meet minimum patch size and connectivity requirements (Greene et al., 2019). Moreover, young loblolly pine provide habitat for shrubland birds, cottontail rabbits, and numerous other wildlife species year round (Novak et al., 2016). By employing a modified Delphi approach, NCWRC foresters and biologists narrowed open- forest focal species to include the red-headed woodpecker (*Melanerpes erythrocephalus*), eastern wild turkey (*Meleagris gallopavo silvestris*), timber rattlesnake (*Crotalus horridus*), white-tailed deer (*Odocoileus virginianus*), and black bear (*Ursus americanus*). To evaluate habitat requirements for these focal species, they conducted a literature review (this process was repeated for each of the four guilds, not solely open forests), ultimately selecting 11 forest condition metrics that offered adequate structural and compositional conditions. For an in-depth examination of the methods developed by NCWRC staff, see Phillips (2023). Based on the condition metrics, stands were designated into three conditions: "Best", "Good", and "Poor". This condition class approach translates quantitative values into qualitative categories, which allows stakeholders to more clearly answer the following questions…1) Does this forest structure exclude any of the focal species from the matrix, and by association the forest itself? 2) To what degree does the structure of this forest allow for the focal species to thrive? Species in the open-forest guild are more likely to be present if forest conditions feature less dense canopy cover (i.e., less shade, greater areas in which light reaches the ground), shorter fire return intervals (i.e., the frequency at which low intensity fires occur, where in this case the ideal interval is between 2-4 years) and low basal area (i.e., the cross-sectional area of trees). Prescribed fire can be used to maintain open woodlands with sparse midstory and a lush herbaceous layer with patches of low-growing woody plants in the past (Nowacki & Abrams, 2008). However, smoke management and weather constraints limit the use of prescribed burning in North Carolina and other areas of the eastern US. Because of the logistical challenges associated with prescribed fire, NCWRC staffers have chosen to eliminate prescribed burning on many of their loblolly pine stands (Casey Phillips, personal correspondence). Thinning, then, becomes the primary method of increasing "Good" quality open-forest condition.

Thinning from below to improve open forest guild species habitat will allow for greater light penetration to the forest floor. To encourage appropriate conditions for open-forest associate species, basal area thinning targets should be less than 65 ft^2/ac (Peitz et al., 1999) to 70 ft^2/ac (Blair & Enghardt, 1976), though recent studies have reported such targets as conservative Although open-forest associate species benefit from thinned and burned loblolly pine forests additional species in the shrubland guild, including the northern bobwhite (*Colinus virginianus*), eastern cottontail rabbit (*Sylvilagus floridanus*), indigo bunting (*Passerina cyanea*), prairie warbler (*Dendroica discolor*), and American woodcock *(Scolopax minor*), are highly likely to use recently regenerated pine stands that were harvested less than five years previously (Phillips, 2023).

Works Cited

Abt, K. L., Abt, R. C., & Galik, C. (2012). Effect of Bioenergy Demands and Supply Response on Markets, Carbon, and Land Use. *Forest Science*, *58*(5), 523–539. https://doi.org/10.5849/forsci.11-055

Andreu, A., & Hermansen-Baez, L. A. (2008). Fire in the South 2: The southern wildfire risk assessment. *A Report by the Southern Group of State Foresters, 32 p.* https://research.fs.usda.gov/treesearch/34087

Andrulot, E. (1970). *Effects of Thinning on Yield of Loblolly Pine (Pinus Taeda L.) in Central Louisiana.* [Doctor of Philosophy, Louisiana State University and Agricultural & Mechanical College]. https://doi.org/10.31390/gradschool_disstheses.1769

Baker, J. B., & Langdon, G. (1990, December 1). *Loblolly Pine | Silvics of North America*. https://research.fs.usda.gov/silvics/loblolly-pine

Bassett, J. R. (1964). *Diameter Growth of Loblolly Pine Trees as Affected by Soil-Moisture Avalability* (United States Forest Service Research Paper Nos. S0-9). U.S. Department of Agriculture, Forest Service.

Becquer, A., Guerrero-Galán, C., Eibensteiner, J. L., Houdinet, G., Bücking, H., Zimmermann, S. D., & Garcia, K. (2019). The ectomycorrhizal contribution to tree nutrition. In *Advances in Botanical Research* (Vol. 89, pp. 77–126). Elsevier. https://doi.org/10.1016/bs.abr.2018.11.003

Bengston, D. N. (1994). Changing forest values and ecosystem management. *Society & Natural Resources*, *7*(6), 515–533. https://doi.org/10.1080/08941929409380885

Bennett, B. M. (2015). *Plantations and Protected Areas: A Global History of Forest Management*. https://direct.mit.edu/books/monograph/2293/Plantations-and-Protected-AreasA-Global-History-of

Bettinger, P., & Chung, W. (2004). The Key Literature of, and Trends in, Forest-Level Management Planning in North America, 1950–2001. *International Forestry Review*, *6*(1), 40–50. https://doi.org/10.1505/ifor.6.1.40.32061

Betts, M. G., Wolf, C., Ripple, W. J., Phalan, B., Millers, K. A., Duarte, A., Butchart, S. H. M., & Levi, T. (2017). Global forest loss disproportionately erodes biodiversity in intact landscapes. *Nature*, *547*(7664), 441–444. https://doi.org/10.1038/nature23285

Blair, R., & Enghardt, H. (1976). Deer forage and Overstory in a Loblolly Pine Plantation. *Journal of Range Management*, *29*, 104.

Blazier, M. A., Clason, T., Dipesh, K. C., Taylor, E., Tanger, S., & Holley, G. (2017). Rotation-Length Effects of Diverse Levels of Early Competition Suppression and Precommercial Thinning on Loblolly Pine Stand Development. *Forest Science*, *63*(5), 537–548. https://doi.org/10.5849/FS-20l6-1l6R2

Bose, A. K., Nelson, A. S., Kane, M., & Rigling, A. (2018). Density reduction in loblolly pine (Pinus taeda L.) stands to increase tree C assimilation: An approach with the dual δ13C and δ18O isotope signatures in needles. *Annals of Forest Science*, *75*(1), 1–12. https://doi.org/10.1007/s13595-017-0687-1

Brown, M. J., & Lambert, S. G. (2024). *North Carolina's Forests, 2018*. https://doi.org/10.2737/SRS-RB-239

Bull, J. W., Taylor, I., Biggs, E., Grub, H. M. J., Yearley, T., Waters, H., & Milner-Gulland, E. J. (2022). Analysis: The biodiversity footprint of the University of Oxford. *Nature*, *604*(7906), 420–424. https://doi.org/10.1038/d41586-022-01034-1

Buongiorno, J., & Gilless, K. (2003). *Decision Methods for Forest Resource Management*. Academic Press.

Chao, A., Chiu, C.-H., & Jost, L. (2014). Unifying Species Diversity, Phylogenetic Diversity, Functional Diversity, and Related Similarity and Differentiation Measures Through Hill Numbers. *Annual Review of Ecology, Evolution, and Systematics*, *45*, 297–324.

Clutter, J. L., Fortson, J. C., Pienaar, L. V., Brister, G. H., & Bailey, R. L. (1983). *Timber Management: A Quantitative Approach*. Krieger Publishing Company.

Coles, T. (2023, January 21). *Identifying an agreed unit of biodiversity change for inclusion in a biodiversity definition*. OBE-CEO rePlanet.

Comerford, N. B., McLeod, M., & Skinner, M. (2002). Phosphorus form and bioavailability in the pine rotation following fertilization: P fertilization influences P form and potential bioavailability to pine in the subsequent rotation. *Forest Ecology and Management*, *169*(3), 203–211. https://doi.org/10.1016/S0378-1127(01)00680-6

Coyle, D. R., Barnes, B. F., Klepzig, K. D., Koch, F. H., Morris, L. A., Nowak, J. T., Otrosina, W. J., Smith, W. D., & Gandhi, K. J. K. (2020). Abiotic and Biotic Factors Affecting Loblolly Pine Health in the Southeastern United States. *Forest Science*, *66*(2), 145–156. https://doi.org/10.1093/forsci/fXz054

Cubbage, F. W., O’Laughlin, J., & Bullock lll, C. S. (1993). *Forest Resource Policy*. John Wiley & Sons.

Daigneault, A., Baker, J. S., Guo, J., Lauri, P., Favero, A., Forsell, N., Johnston, C., Ohrel, S. B., & Sohngen, B. (2022). How the future of the global forest sink depends on timber demand, forest management, and carbon policies. *Global Environmental Change : Human and Policy Dimensions*, *76*, 1–13. https://doi.org/10.1016/j.gloenvcha.2022.102582

Daigneault, A., & Favero, A. (2021). Global forest management, carbon sequestration and bioenergy supply under alternative shared socioeconomic pathways. *Land Use Policy*, *103*, 105302. https://doi.org/10.1016/j.landusepol.2021.105302

Darwin, C., & Beer, G. (1996). *The Origin of Species*. Oxford University Press. https://research.ebsco.com/linkprocessor/plink?id=a417d398-68fa-3d09-ab0b-0bfff0af6b77

Davis, P. B., Munn, I. A., Henderson, J. E., & Strickland, B. K. (2017). Economic tradeoffs of managing for timber production or wildlife habitat. *The Journal of Wildlife Management*, *81*(8), 1363–1371. https://doi.org/10.1002/jwmg.21330

Dawson, T. P., Rounsevell, M. D. A., Kluvánková-Oravská, T., Chobotová, V., & Stirling, A. (2010). Dynamic properties of complex adaptive ecosystems: Implications for the sustainability of service provision. *Biodiversity and Conservation*, *19*(10), 2843–2853. https://doi.org/10.1007/s10531-010-9892-z

DeFries, R., & Nagendra, H. (2017). Ecosystem management as a wicked problem. *Science*, *356*(6335), 265–270.

Deutz, A., Heal, G. M., Niu, R., Swanson, E., Townshend, T., Zhu, L., Delmar, A., Meghji, A., Sethi, S. A., & Tobin-de la Puente, J. (2020). *Financing Nature: Closing the Global Biodiversity Financing Gap*. The Paulson Institute, The Nature Conservancy, and the Cornell Atkinson Center for Sustainability.

Dietz, T. (2003). What is a Good Decision? Criteria for Environmental Decision Making. *Human Ecology Review*, *10*(1), 33–39.

Donohue, I., HIllebrand, H., Montoya, J., Petchey, O., Pimm, S., Fowler, M., Healy, K., Jackson, A., Lurgi, M., Deirdre, M., Nessa, O., O'Gorman, E., & Qiang, Y. (2016). Navigating the complexity of ecological stability. *Ecology Letters*. https://doi.org/10.1111/ele.12648

Farjon, A. (2008). *The Natural History of Conifers*. Timber Press.

Fox, T. R., Jokela, E. J., & Allen, H. L. (2007). The Development of Pine Plantation Silviculture in the Southern United States. *Journal of Forestry*, *105*(7), 337–347. https://doi.org/10.1093/jof/105.7.337

Franco, A. R., & Castro, P. M. L. (2015). Inoculation of Pinus pinea seedlings with Pisolithus tinctorius and Suillus bellinii promotes plant growth in benfluralin contaminated soil. *Plant and Soil*, *386*(1), 113–123. https://doi.org/10.1007/s11104-014-2247-x

Fuller, M., & Dwivedi, P. (2021). The Cost of Carbon Stored on Afforested Lands in the Southern United States. *Trees, Forests and People*, *6*, 100129. https://doi.org/10.1016/j.tfp.2021.100129

Gaby, L. I. (1985). *The Southern Pines: An American Wood* (No. FS-256). U.S. Department of Agriculture, Forest Service, Southeastern Forest Expirement Station, Forestry Sciences Laboratory.

Gibson, C. C., Ostrom, E., & Ahn, T. K. (2000). The concept of scale and the human dimensions of global change: A survey. *Ecological Economics*, *32*(2), 217–239. https://doi.org/10.1016/S0921-8009(99)00092-0

Ginn, S. E., Seiler, J. R., Cazell, B. H., & Kreh, R. E. (1991). Physiological and Growth Responses of Eight-Year-Old Loblolly Pine Stands to Thinning. *Forest Science*, *37*(4), 1030–1040. https://doi.org/10.1093/forestscience/37.4.1030

Gonzalez-Benecke, C. A., Martin, T. A., Jokela, E. J., & Torre, R. D. L. (2011). A Flexible Hybrid Model of Life Cycle Carbon Balance for Loblolly Pine (Pinus taeda L.) Management Systems. *Forests*, *2*(3), 749–776. https://doi.org/10.3390/f2030749

Greene, R. E., Iglay, R. B., & Evans, K. O. (2019). Providing open forest structural characteristics for high conservation priority wildlife species in southeastern U.S. pine plantations. *Forest Ecology and Management*, *453*, 117594. https://doi.org/10.1016/j.foreco.2019.117594

Grimm, V., & Wissel, C. (1997). Babel, or the Ecological Stability Discussions: An Inventory and Analysis of Terminology and a Guide for Avoiding Confusion. *Oecologia*, *109*(3), 323–334.

Guldin, J. M. (2008). The silviculture of restoration: A historical perspective with contemporary application. *In: Deal, Robert L., Tech. Ed. Integrated Restoration of Forested Ecosystems to Achieve Multiresource Benefits: Proceedings of the 2007 National Silviculture Workshop; 2007 May 7-10; Ketchikan, AK. Gen. Tech. Rep. PNW-GTR-733. Portland, OR: USDA-Forest Service, Pacific Northwest Research Station: 23-35*. https://research.fs.usda.gov/treesearch/33730

Guldin, J. M. (2014). Adapting Silviculture to a Changing Climate in the Southern United States. In *Climate Change Adaptation and Mitigation Management Options: A Guide for Natural Resource Managers in Southern Forest Ecosystems* (pp. 173–192). CRC Press-Taylor and Francis.

Guo, J., Prestemon, J., & Johnston, C. (2023). Forest market outlook in the Southern United States. *Forest Policy and Economics*, *157*. https://doi.org/10.1016/j.forpol.2023.103091

Hackman, J. J., Rose, B. D., Frank, H. E. R., Vilgalys, R., Cook, R. L., & Garcia, K. (2022). ACORN Review: NPK fertilizer use in loblolly pine plantations: Who are we really feeding? *Forest Ecology and Management*, *520*, 120393. https://doi.org/10.1016/j.foreco.2022.120393

Hackman, J., Woodley, A., Carter, D., Strahm, B., Averill, C., Vilgalys, R., Garcia, K., & Cook, R. (2024). Fungal biomass and ectomycorrhizal community assessment of phosphorus responsive Pinus taeda plantations. *Frontiers in Fungal Biology*, *5*, 1401427. https://doi.org/10.3389/ffunb.2024.1401427

Hall, C. A. S. (2021). Systems Ecology and Limits to Growth: History, Models, and Present Status. In G. S. Metcalf, K. Kijima, & H. Deguchi (Eds.), *Handbook of Systems Sciences* (pp. 943–980). Springer. https://doi.org/10.1007/978-981-15-0720-5_77

Hanberry, B. B., & Thompson, F. R. (2019). Open forest management for early successional birds. *Wildlife Society Bulletin. Doi: 10.1002/Wsb.957.* https://doi.org/10.1002/wsb.957

Harms, W. R., & Lloyd, F. T. (1981). Stand structure and yield relationships in a 20-Year-Old loblolly pine spacing study. *Southern Journal of Applied Forestry*, *5*, 162–166. https://doi.org/10.1093/sjaf/5.3.162

Harris, N. L., Gibbs, D. A., Alessandro, B., A, B. R., Sytze, de B., Farina, M., Lola, F., Hansen, M. C., Herold, M., Houghton, R. A., Potapov, P. V., Suarez, D. R., Roman-Cuesta, R. M., Saatchi, S. S., Slay, C. M., Turubanova, S. A., & Alexandra, T. (2021). Global maps of twenty-first century forest carbon fluxes. *Nature Climate Change*, *11*(3), 234–240. https://doi.org/10.1038/s41558-020-00976-6

Himes, A., & Dues, K. (2024). Relational forestry: A call to expand the discipline's institutional foundations. *Ecosystems and People*. https://www.tandfonline.com/doi/abs/10.1080/26395916.2024.2365236

Holling, C. (1985). *Resilience of ecosystems: Local surprise and global change.* (J. G. Roederer & T. F. Malone, Eds.; No. 5; Issue 5, pp. 228–269). Cambridge University Press. https://iiasa.dev.local/

Hoover, C., Birdsey, R., Goines, B., Lahm, P., Fan, Y., Nowak, D., Prisley, S., Reinhardt, E., Skog, K., Skole, D., Smith, J., Trettin, C., & Woodall, C. (2014). Chapter 6: Quantifying Greenhouse Gas Sources and Sinks in Managed Forest Systems. *In: Eve, M.; Pape, D.; Flugge, M.; Steele, R.; Man, D.; Riley-Gilbert, M.; Biggar, S. Quantifying Greenhouse Gas Fluxes in Agriculture and Forestry: Methods for Entity-Scale Inventory. Tech. Bull. 1939. Washington, DC: U.S. Department of Agriculture, Office of the Chief Economist: 6-1-6.114.*, 6-6.114.

Huntsinger, L., & McCaffrey, S. (1995). A Forest for the Trees: Forest Management and the Yurok Environment, 1850 to 1994. *American Indian Culture and Research Journal*, *19*(4). https://escholarship.org/uc/item/7qn456xf

IPCC. (2023). *Summary for Policymakers* (1st ed.). Cambridge University Press. https://doi.org/10.1017/9781009325844

Ives, A. R., & Carpenter, S. R. (2007). Stability and Diversity of Ecosystems. *Science*, *317*(5834), 58–62.

Jarvis, P. G., & McNaughton, K. G. (1986). Stomatal Control of Transpiration: Scaling Up from Leaf to Region. In A. MacFadyen & E. D. Ford (Eds.), *Advances in Ecological Research* (Vol. 15, pp. 1–49). Academic Press. https://doi.org/10.1016/S0065-2504(08)60119-1

Jett, J. B., McKeand, S. E., & Weir, R. J. (1991). Stability of juvenile wood specific gravity of loblolly pine in diverse geographic areas. *Canadian Journal of Forest Research*. https://cdnsciencepub-com.prox.lib.ncsu.edu/doi/abs/10.1139/x91-148

Jokela, E. J., Dougherty, P. M., & Martin, T. A. (2004). Production dynamics of intensively managed loblolly pine stands in the southern United States: A synthesis of seven long-term experiments. *Forest Ecology and Management*, *192*(1), 117–130. https://doi.org/10.1016/j.foreco.2004.01.007

Jonker, J. G. G., van der Hilst, F., Markewitz, D., Faaij, A. P. C., & Junginger, H. M. (2018). Carbon balance and economic performance of pine plantations for bioenergy production in the Southeastern United States. *Biomass and Bioenergy*, *117*, 44–55. https://doi.org/10.1016/j.biombioe.2018.06.017

Josefsson, J., Widenfalk, L. A., Blicharska, M., Hedblom, M., Pärt, T., Ranius, T., & Öckinger, E. (2021). Compensating for lost nature values through biodiversity offsetting – Where is the evidence? *Biological Conservation*, *257*, 109117. https://doi.org/10.1016/j.biocon.2021.109117

Knoll, A. H. (2003). *Life on a Young Planet: The First Three Billion Years of Evolution on Earth*. Princeton University Press.

Körner, C. (2006). Plant CO2 responses: An issue of definition, time and resource supply. *New Phytologist*, *172*(3), 393–411. https://doi.org/10.1111/j.1469-8137.2006.01886.x

Kramer, P. J. (1950). Effects of wilting on the subsequent intake of water by plants. *American Journal of Botany*, *37*, 280–284.

Kunkel, K. E., Easterling, D. R., Ballinger, A., Bililign, S., Chamption, S. M., Corbett, D. R., Dello, K. D., Dissen, J., Lackmann, G. E., Luettich Jr., R. A., Perry, L. B., Robinson, W.

A., Stevens, L. E., Stewart, B. C., & Terando, A. J. (2020). *North Carolina Climate Science Report: Report Findings and Executive Summary* (North Carolina Climate Science Report, p. 233). North Carolina Insitute for Climate Studies.

Lammerant, J., Starkey, M., de Horde, A., Bor, A. M., Driesen, K., & Vanderheyden, G. (2021). *Critical assessment of biodiversity accounting approaches for businesses* (Update Report No. 3). EU Commission.

Lee, S. H., Calvo-Polanco, M., Chung, G. C., & Zwiazek, J. J. (2010). Role of aquaporins in root water transport of ectomycorrhizal jack pine (Pinus banksiana) seedlings exposed to NaCl and fluoride. *Plant, Cell & Environment*, *33*(5), 769–780. https://doi.org/10.1111/j.1365-3040.2009.02103.x

Levin, S. A. (1992). The Problem of Pattern and Scale in Ecology. *Ecology*, *73*(6), 1943.

Lindblom, C. E. (1977). *Politics and markets: The world's political economic systems*. Basic Books. https://catalog.lib.ncsu.edu/catalog/NCSU436682

Lindenmayer, D. B., Hulvey, K. B., Hobbs, R. J., Colyvan, M., Felton, A., Possingham, H., Steffen, W., Wilson, K., Youngentob, K., & Gibbons, P. (2012). Avoiding bio-perversity from carbon sequestration solutions. *Conservation Letters*, *5*(1), 28–36. https://doi.org/10.1111/j.1755-263X.2011.00213.x

Loehle, C., Miller, D. A., Kovach, A. I., Larsen-Gray, A. L., Akresh, M. E., McDonald, J. E., Cheeseman, A. E., King, D., Petzinger, S. M., & Kanter, J. (2024). Forest Management Is Key for Conserving Biodiversity and Providing Ecosystem Services in the United States. *Forests*, *15*(12), 2087. https://doi.org/10.3390/f15122087

Lorio, P. L. J., & Hodges, J. D. (1968). Oleoresin exudation pressure and relative water content of inner bark as indicators of moisture stress in loblolly pines. *Forest Science*, *14*, 392–398.

MacDougall, A., Gellner, G., Mccann, K., & Turkington, R. (2013). (PDF) Diversity loss with persistent human disturbance increases vulnerability to ecosystem collapse. *Nature*. https://doi.org/10.1038/nature11869

Margalef, R. (1963). On Certain Unifying Principles in Ecology. *The American Naturalist*, *97*(897), 357–374. https://doi.org/10.1086/282286

Matallana-Ramirez, L. P., Whetten, R. W., Sanchez, G. M., & Payn, K. G. (2021). Breeding for Climate Change Resilience: A Case Study of Loblolly Pine (Pinus taeda L.) in North America. *Frontiers in Plant Science*, *12*. https://doi.org/10.3389/fpls.2021.606908

McKeand, S. E., Jokela, E. J., Huber, D. A., Byram, T. D., Allen, H. L., Li, B., & Mullin, T. J. (2006). Performance of improved genotypes of loblolly pine across different soils, climates, and silvicultural inputs. *Forest Ecology and Management*, *227*(1), 178–184. https://doi.org/10.1016/j.foreco.2006.02.016

McQuillan, K. A., Hwang, T., & Martin, K. L. (2023). Extended growing seasons and decreases in hydrologic connectivity indicate increasing water stress in humid, temperate forests. *Agricultural and Forest Meteorology*, *338*, 109525. https://doi.org/10.1016/j.agrformet.2023.109525

Mehrabi, Z., Naidoo, R., Leung, B., Hargreaves, A. L., Greenberg, D. A., McGill, B., & Dornelas, M. (2022). Shifting baselines and biodiversity success stories. *Nature*, *601*(7894), E17–E19. https://doi.org/10.1038/s41586-021-03750-6

Miller, J. H., Zutter, B. R., Zedaker, S. M., Edwards, M. B., & Newbold, R. A. (2003). Growth and yield relative to competition for loblolly pine plantations to midrotation-a southeastern United States regional study. *Southern Journal of Applied Forestry*, *27*(4), 237–252.

Montague, C. (2022, January 18). *Systems Ecology*. https://www.oxfordbibliographies.com/display/document/obo-9780199830060/obo-9780199830060-0078.xml

N.C. Forest Service. (2025, January 9). *N.C. Forest Service—Wildland Urban Interface | NC Agriculture*. https://www.ncagr.gov/divisions/nc-forest-service/fire-control-and-prevention/wui

Neale, D. B., Wegrzyn, J. L., Stevens, K. A., Zimin, A. V., Puiu, D., Crepeau, M. W., Cardeno, C., Koriabine, M., Holtz-Morris, A. E., Liechty, J. D., Martínez-García, P. J., Vasquez-Gross, H. A., Lin, B. Y., Zieve, J. J., Dougherty, W. M., Fuentes-Soriano, S., Wu, L.-S., Gilbert, D., Marçais, G., … Langley, C. H. (2014). Decoding the massive genome of loblolly pine using haploid DNA and novel assembly strategies. *Genome Biology*, *15*(3), R59. https://doi.org/10.1186/gb-2014-15-3-r59

North Carolina Forest Service. (2024). *State and Private Forestry Fact Sheet: North Carolina 2024*.

Novak, L. D., Comer, C. E., Conway, W. C., Scognamillo, D. G., & Gay, R. D. (2016). *Nesting ecology of early-successional birds in restored longleaf and loblolly pine stands*. https://bioone.org/journals/the-wilson-journal-of-ornithology/volume-128/issue-2/wils-128-02-314-327.1/Nesting-ecology-of-early-successional-birds-in-restored-longleaf-and/10.1676/wils-128-02-314-327.1.full

Nowacki, G. J., & Abrams, M. D. (2008). The Demise of Fire and “Mesophication” of Forests in the Eastern United States. *BioScience*, *58*(2), 123–138. https://doi.org/10.1641/B580207

Odum, E. P. (1964). The New Ecology. *BioScience*, *14*(7), 14–16. https://doi.org/10.2307/1293228

Onwuchekwa, N. E., Zwiazek, J. J., Quoreshi, A., & Khasa, D. P. (2014). Growth of mycorrhizal jack pine (Pinus banksiana) and white spruce (Picea glauca) seedlings planted in oil sands reclaimed areas. *Mycorrhiza*, *24*(6), 431–441. https://doi.org/10.1007/s00572-014-0555-x

Orians, G. H. (1975). Diversity, stability and maturity in natural ecosystems. In W. H. van Dobben & R. H. Lowe-McConnell (Eds.), *Unifying Concepts in Ecology: Report of the plenary sessions of the First international congress of ecology, The Hague, the Netherlands, September 8–14, 1974* (pp. 139–150). Springer Netherlands. https://doi.org/10.1007/978-94-010-1954-5_11

Oswalt, S. N., Smith, W. B., Miles, P. D., & Pugh, S. A. (2019). *Forest Resources of the United States, 2017: A technical document supporting the Forest Service 2020 RPA Assessment* (No. WO-GTR-97; p. WO-GTR-97). U.S. Department of Agriculture, Forest Service. https://doi.org/10.2737/WO-GTR-97

Panshin, A. J., & de Zeeuw, C. (1980). *Textbook of wood technology* (4th ed.). McGraw-Hill.

Paquette, A., & Messier, C. (2010). The role of plantations in managing the world’s forests in the Anthropocene. *Frontiers in Ecology and the Environment*, *8*(1), 27–34. https://doi.org/10.1890/080116

Peitz, D. G., Tappe, P. A., Shelton, M. G., & Sams, M. G. (1999). Deer Browse Response to Pine-Hardwood Thinning Regimes in Southeastern Arkansas. *Southern Journal of Applied Forestry*, *23*(1), 16–20. https://doi.org/10.1093/sjaf/23.1.16

Perry, T. O., & Wang, C.-W. (1958). The Value of Genetically Superior Seed. *Journal of Forestry*, *56*(11), 843–845. https://doi.org/10.1093/jof/56.11.843

Peterson, D. L., Wolken, J. M., Hollingsworth, T. N., Giardina, C. P., Littell, J. S., Joyce, L. A., Swanston, C. W., Handler, S. D., Rustad, L. E., & McNulty, S. G. (2014). Regional Highlights of Climate Change. In D. L. Peterson, J. M. Vose, & T. Patel-Weynand (Eds.), *Climate Change and United States Forests* (pp. 113–148). Springer Netherlands. https://doi.org/10.1007/978-94-007-7515-2_6

Phaneuf, D. J., & Requate, T. (2016). *A Course in Environmental Economics: Theory, Policy, and Practice*. Cambridge University Press. https://doi.org/10.1017/9780511843839

Phillips, C. E. (2023). *Integrating Wildlife Management Goals into Quantitative Forest Planning.* https://www.lib.ncsu.edu/resolver/1840.20/40929

Pienaar, L. V. (1979). An Approximation of Basal Area Growth after Thinning Based on Growth in Unthinned Plantations. *Forest Science*, *25*(2), 223–232. https://doi.org/10.1093/forestscience/25.2.223

Pimm, S. L. (1984). *The Complexity and Stability of Ecosystems*. https://www.researchgate.net/publication/202000100_The_Complexity_and_Stability_of_Ecosystems

Pincebourde, S., Sanford, E., Casas, J., & Helmuth, B. (2012). Temporal coincidence of environmental stress events modulates predation rates. *Ecology Letters*. https://doi.org/10.1111/j.1461-0248.2012.01785.x

Pretzsch, H., del Río, M., Arcangeli, C., Bielak, K., Dudzinska, M., Ian Forrester, D., Kohnle, U., Ledermann, T., Matthews, R., Nagel, R., Ningre, F., Nord-Larsen, T., Szeligowski, H., & Biber, P. (2023). Competition-based mortality and tree losses. An essential component of net primary productivity. *Forest Ecology and Management*, *544*, 121204. https://doi.org/10.1016/j.foreco.2023.121204

Puettmann, K. J., Coates, K. D., & Messier, C. C. (2012). *A Critique of Silviculture: Managing for Complexity*. Island Press.

Puls, S. J., Cook, R. L., Baker, J. S., Rakestraw, J. L., & Trlica, A. (2024). Modeling wood product carbon flows in southern us pine plantations: Implications for carbon storage. *Carbon Balance and Management*, *19*(1), 8. https://doi.org/10.1186/s13021-024-00254-4

Rose, B. D. (2023). *Investigating the Role of Ectomycorrhizal Fungi in Salinity Tolerance and Root Carbon Allocation of Loblolly Pine in Response to Potassium Availability*. https://www.lib.ncsu.edu/resolver/1840.20/40844

Schmidtling, R. (2003). The Southern Pines During The Pleistocene. *4th*, *615*, 203–209.

Shephard, N. T., Joshi, O., Susaeta, A., & Will, R. E. (2021). A stand level application of efficiency analysis to understand efficacy of fertilization and thinning with drought in a loblolly pine plantation. *Forest Ecology and Management*, *482*, 118855. https://doi.org/10.1016/j.foreco.2020.118855

Shephard, N. T., Narine, L., Peng, Y., & Maggard, A. (2022). Climate Smart Forestry in the Southern United States. *Forests*, *13*(9), Article 9. https://doi.org/10.3390/f13091460

Sinclair, W. A. (1966). *Decline of hardwoods: Possible causes. 42*, 17–32.

Smith, W. D., & Strub, M. R. (1991). Initial Spacing: How Many Trees To Plant. In M. L. Duryea & P. M. Dougherty (Eds.), *Forest Regeneration Manual* (pp. 281–289). Springer Netherlands. https://doi.org/10.1007/978-94-011-3800-0_15

Sohngen, B., & Brown, S. (2008). Extending timber rotations: Carbon and cost implications. *Climate Policy*, *8*(5), 435–451. https://doi.org/10.3763/cpol.2007.0396

Stewart, J. F., Will, R. E., Robertson, K. M., & Nelson, C. D. (2015). Frequent fire protects shortleaf pine (Pinus echinata) from introgression by loblolly pine (P. taeda). *Conservation Genetics*, *16*(2), 491–495. https://doi.org/10.1007/s10592-014-0669-x

Stokes, B. J., & Watson, W. F. (1996). Plantation thinning systems in the Southern United States. *Problems and Prospects for Managing Cost Effective Early Thinnings; a Report from the Concerted Action Cost Effective Early Thinnings; AIR2-CT93-1538. Horsholm, Denmark: Danish Forest and Landscape Research Institute: 107-121.* https://research.fs.usda.gov/treesearch/209

Swain, D. L., Prein, A. F., Abatzoglou, J. T., Albano, C. M., Brunner, M., Diffenbaugh, N. S., Singh, D., Skinner, C. B., & Touma, D. (2025). Hydroclimate volatility on a warming Earth. *Nature Reviews Earth & Environment*, *6*(1), 35–50. https://doi.org/10.1038/s43017-024-00624-z

Tedersoo, L., Sepping, J., Morgunov, A. S., Kiik, M., Esop, K., Rosenvald, R., Hardwick, K., Breman, E., Purdon, R., Groom, B., Venmans, F., Kiers, E. T., & Antonelli, A. (2024). Towards a co-crediting system for carbon and biodiversity. *PLANTS, PEOPLE, PLANET*, *6*(1), 18–28. https://doi.org/10.1002/ppp3.10405

The South's fourth forest: Opportunities for the future (Miscellaneous Publication No. 24; p. 512). (1988). U.S. Department of Agriculture, Forest Service.

Theis, S., Ruppert, J. L. W., Roberts, K. N., Minns, C. K., Koops, M., & Poesch, M. S. (2020). Compliance with and ecosystem function of biodiversity offsets in North American and European freshwaters. *Conservation Biology*, *34*(1), 41–53. https://doi.org/10.1111/cobi.13343

TSVCM. (2021). *Taskforce on Scaling Voluntary Carbon Markets* (p. 156) [Final Report].

UNEP. (2023, December 7). *State of Finance for Nature 2023 | UNEP - UN Environment Programme*. https://www.unep.org/resources/state-finance-nature-2023

U.S. Department of Agriculture, Forest Service. (2023). *Future of America's Forests and Rangelands* (General Technical Report No. WO-102; Forest Service: 2020 Resources Planning Act Assessment).

USDA Forest Service Northern Research Station. (2023, November 30). *Understanding the Wildland Urban Interface (1990-2020)*. ArcGIS StoryMaps. https://storymaps.arcgis.com/stories/6b2050a0ded0498c863ce30d73460c9e

Vogel, J. G., Bracho, R., Akers, M., Amateis, R., Bacon, A., Burkhart, H. E., Gonzalez-Benecke, C. A., Grunwald, S., Jokela, E. J., Kane, M. B., Laviner, M. A., Markewitz, D., Martin, T. A., Meek, C., Ross, C. W., Will, R. E., & Fox, T. R. (2022). Regional Assessment of Carbon Pool Response to Intensive Silvicultural Practices in Loblolly Pine Plantations. *Forests*, *13*(1), 36. https://doi.org/10.3390/f13010036

Wahlenberg, W. G. (1946). Longleaf pine: Its use, ecology, regeneration, protection, growth, and management. In *Charles Lathrop Pack Forestry Foundation, January 1946. 429 pp.* (p. 429). Charles Lathrop Pack Forestry Foundation. https://www.proquest.com/docview/58630679?pq-origsite=summon&sourcetype=Books

Wear, D. N., & Greis, J. G. (2002). Southern Forest Resource Assessment. *Gen. Tech. Rep. SRS-53. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 635 p.*, *053*. https://doi.org/10.2737/SRS-GTR-53

Weintraub, A., Church, R. L., Murray, A. T., & Guignard, M. (2000). Forest management models and combinatorial algorithms: Analysis of state of the art *. *Annals of Operations Research*, *96*(1), 271–285.

Weiskopf, S. R., Isbell, F., Arce-Plata, M. I., Di Marco, M., Harfoot, M., Johnson, J., Lerman, S. B., Miller, B. W., Morelli, T. L., Mori, A. S., Weng, E., & Ferrier, S. (2024). Biodiversity loss reduces global terrestrial carbon storage. *Nature Communications*, *15*(1), 4354. https://doi.org/10.1038/s41467-024-47872-7

Wertin, T. M., Mcguire, M. A., & Teskey, R. O. (2010). The influence of elevated temperature, elevated atmospheric CO2 concentration and water stress on net photosynthesis of loblolly pine (Pinus taeda L.) at northern, central and southern sites in its native range. *Global Change Biology*, *16*(7), 2089–2103. https://doi.org/10.1111/j.1365-2486.2009.02053.x

W.G. Wahlenberg. (1960). *Loblolly pine: Its use, ecology, regeneration, protection, growth, and management*. The School of Forestry: Duke University. https://hdl.handle.net/2027/mdp.39015006925997?urlappend=%3Bseq=9

Williams, R. J., Berlow, E. L., Dunne, J. A., Barabási, A.-L., & Martinez, N. D. (2002). Two degrees of separation in complex food webs. *Proceedings of the National Academy of Sciences of the United States of America*, *99*(20), 12913–12916. https://doi.org/10.1073/pnas.192448799

W.R. Mattoon. (1915). *Life history of shortleaf pine.* (Bulletin No. 244; p. 46). U.S. Department of Agriculture.

Zahner, R., & Whitmore, F. W. (1960). *Early Growth of Radically Thinned Loblolly Pine* (pp. 628–634). U.S. Department of Agriculture, Forest Service.

zu Ermgassen, S. O. S. E., Devenish, K., Simmons, B. A., Gordon, A., Jones, J. P. G., Maron, M., Schulte to Bühne, H., Sharma, R., Sonter, L. J., Strange, N., Ward, M., & Bull, J. W.

(2023). Evaluating the impact of biodiversity offsetting on native vegetation. *Global Change Biology*, *29*(15), 4397–4411. https://doi.org/10.1111/gcb.16801

Chapter 2: Quantifying the externalities associated with species-specific timber prescriptions on artificially regenerated loblolly pine plantations

Abstract

Planted pine forests play important roles in providing timber revenue and ecosystem services in the southeastern United States. Trade-offs between management objectives exist, but demonstrating quantitative links between forest stand characteristics and species-specific habitat quality requires models that are scaled appropriately. We identified 24 thinning regimes and 6 planting densities deemed suitable for increasing open-forest condition within loblolly pine plantations. With the identified thinning regimes as our guides, we developed 1,008 prescriptions and associated growth and yield tables for newly regenerated loblolly pine plantations aimed at increasing open-forest condition. We identified the combination of thinning regime and initial planting density that generated the highest mean open-forest habitat suitability index scores. Then, we updated the North Carolina Wildlife Resources Commission’s Woodstock model by replacing the original regenerated growth and yield tables with the growth and yield tables that generated the highest habitat suitability index scores. We ran both the original and updated Woodstock models for 100 years and determined that the updated growth and yield tables generated a higher total habitat suitability index score during the modeled horizon than the original growth and yield tables. Using the updated outputs, we developed a production possibilities frontier to demonstrate the tradeoffs between managing for species-specific habitat objectives and providing sustainable revenue generation. Ultimately, we provided additional evidence that thinning pine plantations often and to less than 11.5 m^2/ha (50 ft^2/ac) is critical to conservation of open-forest associates species.

Introduction

Forests play critical roles in providing goods and ecosystem services, but determining when, how, and where to manage complex objectives presents "wicked problems"(DeFries & Nagendra, 2017). For example, managing forests involves balancing science and values, integrates multiple disciplines, and can be influenced by many conflicting perspectives (Gray et al., 2023). Climate change, in concert with rapidly evolving political, economic, and social dimensions, presents additional confounding challenges for natural resource professionals attempting to plan for the future. Though, with appropriate planning and management, forests can produce wood products and provide habitat for terrestrial species in need of conservation (Campbell et al., 2015; Loehle et al., 2024; Stewart, 2022).

Forestry professionals often collaborate with experts in a variety of disciplines and frequently balance economic, social, and ecological objectives to develop management plans (Bengston, 1994; Daigneault & Favero, 2021; Vincent & Binkley, 1993). Although Western forestry has been critiqued for its emphasis on human preferences (Bennett, 2015; Himes & Dues, 2024; Huntsinger & McCaffrey, 1995; Puettmann et al., 2012), forest management plans now more often employ tools, multiple-value frameworks, and indicators that are not expressed solely in economic terms (Bengston, 1994).

Additionally, forest management planning to conserve focal species habitat requires assessment at the appropriate temporal and spatial scales (Gleick, 1987; Jarvis & McNaughton, 1986; Levin, 1992; Mandelbrot, 1982), clearly defined focal species (Morrison & Mathewson, 2015), and quantitative measures to connect extrapolated forest conditions and habitat requirements (Marzluff et al., 2002; Phillips, 2023). Loblolly pine (*Pinus taeda*) plantations in the southeastern United States offer excellent opportunities to examine and model the effects of silvicultural inputs on multiple ecosystem services, including timber revenue and species-specific habitat, over extended time horizons.

On many public lands, including those owned and managed by the North Carolina Wildlife Resources Commission (NCWRC), habitat creation through targeted management is the primary objective, while timber revenue is a secondary objective (NCWRC Forest Management and Optimization, 2022). In 2023, the NCWRC developed an approach to optimize management practices across 64,749 hectares (160,000 acres) of game land, of which approximately 17,534 hectares (43,329 acres) were loblolly pine forest (Phillips, 2023). In 2023, approximately 6% (~ $6.5 million USD) of the NCWRC's operating budget stemmed from yearly timber revenue. Hence, it is worth exploring management practices that optimize both habitat quality and cashflow from timber harvest.

The NCWRC built a constrained-optimization linear programming model and developed a novel method for calculating an index that represents the relative potential of a forest stand to provide habitat for a set of 16 focal species aggregated into three distinct species guilds: longleaf pine associates, open forest associates, and shrubland associates. Each guild contained five species. Ruffed grouse (*Bonasa umbellus*), the sixteenth species, was assigned to guild by itself.

The Woodstock model developed by Phillips (2023) encompassed 80,334 hectares (198,511 acres) of game lands across 4,550 timber stands managed by the NCWRC. The model was designed to run for 50 years, generate habitat for the focal species, and continuously supply timber (Phillips, 2023). NCWRC forestry staff assigned each managed stand as one of 15 timber regimes based on the desired future condition. Each regime was assigned specific treatments that could include thinning, final harvest, or no action. To ensure that stands would not be overstocked, the model allowed for thinning beyond the minimum basal area thinning trigger in the first three 5-year periods. Every stand was assigned two focal species guilds. The Shrubland Associates Guild was assigned to all stands and the second focal species guild was determined by managers based on geography, elevation, and timber regime. For example, stands above 460 m (1,509 ft) mean sea level (msl) were assigned the Ruffed Grouse and Shrubland Associates Guild. The piedmont contained 50.1% of the modeled stands, whereas the mountains and coastal plain accounted for 26.3% and 23.6%, respectively (Phillips, 2023).

Loblolly pine prescriptions in the model were assumed to be continuously propagated and artificially regenerated (Phillips, 2023). For regenerated loblolly pine stands, the model allowed one initial planting density 1,074 trees/ha (435 trees/ac) and four prescriptions. Ultimately, Phillips (2023) demonstrated that alternative objectives can be achieved within the framework of wildlife management oriented silvicultural prescriptions, associated trade-offs between habitat management and revenue generation goals are not constant, and consequential dividends can be realized in each objective with modest marginal opportunity costs.

Our first objective was to develop and test silvicultural prescriptions aimed at increasing species-specific habitat in loblolly pine plantations on North Carolina game land. We accomplished this by calculating the open-forest habitat suitability index scores for each silvicultural regime. Next, we inserted the highest performing regenerated growth and yield tables into a Woodstock model developed by NCWRC. We compared the pertinent original model outputs with those of the updated model to provide NCWRC staff with additional context and data to make informed management decisions.

Methods

Prescription Development

We conducted a literature review and conferred with the NCWRC to develop silvicultural prescriptions that would be within the NCWRC's operational capacity, would not reduce a stand's capability of producing timber products, and would promote forest structural conditions that meet the needs of open-forest focal species (Levin, Chapter 1). We identified six feasible planting densities: 896 trees/ha (363 trees/ac), 978 trees/ha (396 trees/ac), 1,074 trees/ha (435 trees/ac), 1,195 trees/ha (484 trees/ac), 1,344 trees/ha (544 trees/ac), 1,536 trees/ha (622 trees/ac) and seven site indexes (60, 70, 80, 90, 100, 110, and 120, at a base age of 25) that reflected loblolly plantation sites owned and managed by the NCWRC. We chose pre-thinning basal area triggers and post-thinning basal area targets of 20.7 m^2/ha and 9.2 m^2/ha (90 ft^2/ac and 40 ft^2/ac), respectively (Table 2.1). Each initial planting density reflected realistic planting densities for intensively managed loblolly pine plantations in the piedmont and coastal plain physiographic regions of North Carolina.

Simulating in FVS

Each thinning operation was actuated when the simulated stand reached a certain basal area m^2/ha (ft^2/ac) and ceased when the stand was thinned to a lower specified basal area. We generated growth and yield tables with the United States Forest Service Forest (USFS) Vegetation Simulator (FVS) model and the associated graphical user interface (GUI). We supplied the keyword component files (the user-defined set of instructions) and the requisite tree data file. The tree data file contained stands that were almost identical, only differing by way of site index. The GUI allowed us to choose any combination of stands when simulating. Using keyword component files, we permitted FVS to thin stands no more than 3 times during a simulation. For example, Thinning Regime 1 (Table 2.1) would initiate a thin from below when the basal area of a simulated stand reached 20.7 m^2/ha (90 ft^2/ac). The simulator would continue to thin from below until the stand had basal area of 13.8 m^2/ha (60 ft^2/ac).

We first applied the aforementioned thinning triggers and targets to simulated regenerated stands at each planting density, and each stand was simulated for 100 years at each of the seven site indexes. For instance, a regenerated stand in Thinning Regime 1 that was replanted with 896 seedlings was simulated with a site index of 60, 70, 80, 90, 100, 110, and 120. Therefore, FVS generated a growth and yield table at each site index for a total of 7 site indexes. An identical process occurred for simulated stands that were replanted at densities of 896 trees/ha (363 trees/ac), 978 trees/ha (396 trees/ac), 1,074 trees/ha (435 trees/ac), 1,195 trees/ha (484 trees/ac), 1,344 trees/ha (544 trees/ac), 1,536 trees/ha (622 trees/ac). As each planting density was simulated 7 times, and there were six planting densities, each thinning regime was modeled to generate 42 growth and yield tables. In total, 24 thinning regimes, each generating 42 growth and yield tables, provided 1,008 growth and yield tables from which to choose. As each growth and yield table represented one unique combination of site index, planting density, and thinning regime, we termed each a prescription.

We adapted an existing NCWRC keyword component file using an R (R Core Team, 2023) script to include the TPA and thinning instructions for each FVS run. To ensure that FVS would be able to simulate three thinning operations during the length of the rotation, we set the length of each run to 100 years in FVS. Shortening the rotation length to, for example, 50 years may not allow simulated stands to reach certain basal area triggers, thereby potentially excluding one or more thinning operations. Additionally, longer rotation lengths were chosen to produce higher value timber products. We programmed FVS to generate growth and yield data every five years, which resulted in a total of 20 periods. In cases where FVS did not generate data, we used a script in RStudio to replace NA values with zeroes. Missing data only occurred in Period 0 and was expected. For example, basal area triggers were not met at any point in Period 0 as the stands had not been planted for more than 5 years.

We created a script in R to calculate the open-forest condition score generated by each growth and yield table. At the end of each 5-year period, vegetation metrics (% canopy cover, total basal area, % midstory, and % of total basal area of oak > 10") were evaluated individually and assigned scores of 1 if in Best condition, 0.5 if in Good condition, and 0 if in Poor condition (Phillips, 2023). Hence, the maximum score during each period was 4 and the highest possible cumulative total score for each growth and yield table was 80 points over the 20 periods. We calculated the mean and median open-forest condition scores and standard deviation for each growth and yield table. Note that we did not include fire return interval as part of this calculation, as we felt that its inclusion was not feasible as part of this method.

Woodstock Preparation and Implementation

Woodstock is a planning system that projects growth, development and management over time (Remsoft Inc., 2024). The software utilizes linear programming (LP) to allocate limited resources to competing activities and optimize a single objective function to find an optimal solution (Remsoft Inc., 2024). LP permits users to create and test efficient alternatives to complex problems in forestry and natural resource management. We chose to adapt the original NCWRC Woodstock model (hence forth referred to as the original model, while we refer to the adapted model as the updated model). Specifically, Woodstock finds an optimal solution (if one exists) by scanning three separate models which make up the whole: biological, management, and optimization. The biological model contains forest stand attributes and associated growth and yield data, while the management model includes the decisions and outcomes related to the areas of interest to the modeler. The optimization model specifies the user-defined objective function and model constraints that guide Woodstock to find a solution. We identified each growth and yield table that was specific to artificially regenerated to loblolly pine, and we inserted growth and yield tables associated with the thinning regime and planting density combination that generated the highest mean open-forest condition scores at each of the 7 site indexes mentioned previously. Simply replacing the original growth and yield tables (which featured a 20.7 m^2/ha (90 ft^2/ac) basal area thinning trigger, basal area thinning target of 13.8 m^2/ha (60 ft^2/ac), and a planting density of 1,074 trees/ha or 435 trees per acre) with those generated by the highest performing thinning regime and planting combination is not sufficient to allow Woodstock to scan and incorporate the new yield tables. We adapted the updated yield tables to match the format of the original growth and yield tables. We included updated growth and yield tables that simulated the highest scoring thinning regime and planting density combination that were unthinned, thinned once, thinned twice, and thinned three times. In this case, Woodstock requires yield tables that feature unthinned stands. Each loblolly pine stand slated for artificial regeneration must undergo a clearcut regeneration harvest before it can be replanted. Woodstock will not implement a clearcut harvest if it does not find yield tables that are unthinned, as NCWRC programmed the model to transition clearcut stands to stands that are unthinned or, “just grown”. Intuitively, we know that a clearcut and replanted stand, in practice, might be able to undergo a first thinning after some period of time. As it was programmed, the model must identify a stand that has transitioned from clearcut to unthinned. Only once

Woodstock has transitioned a clearcut stand to an unthinned stand can it opt to transition a stand from unthinned (or "just grow") to a stand thinned once. Additionally, we ran these FVS simulations at not 7, but 14 site indexes. In the model, some stands slated for continuously propagated loblolly pine had measured site indexes such as 65, 75, 85, etc. Including the NCWRC's original regenerated growth and yield tables with site indexes in increments of 10 would result in exclusion of these stands. Although the NCWRC included many such stands in the model, failure on our part to include matching growth and yield tables meant that while Woodstock knew the excluded stands exist, it would not have the requisite yield data to include these stands in the modeled scenario. Put simply, excluded stands are ignored. If stands are ignored in the updated model, model outputs would not be comparable to those of the original model. A valuable comparison between both the original model and the updated model is not possible if the models do not project outputs from the same spatially explicit stands. Although we replaced the NCWRC model's original regenerated growth and yield tables, we mimicked the structure of the yield tables (which were constructed to capture each regenerated pine stand in site increments of 5) to ensure loblolly pine stands at every site index would be scanned and considered.

NCWRC's Woodstock Model: Objective Function, Base Model, and Their Novel Habitat Suitability Index

For habitat-first modeling (MaxHabitat), we modified the objective function to prioritize generating the greatest combined sum of each habitat index during the modeled horizon. While the focus of this work is open-forest condition generated on artificially regenerated loblolly pine stands, we chose to use the NCWRC's Habitat Suitability Index (HSI) as the primary objective in the model's objective function. Developed by Phillips et al. (2023), the index is determined by summing the calculated species-specific habitat score and the Shrubland Associates score. Each species-specific habitat score is found by assigning a score of 0, 0.5, or 1 (representing Poor, Good, or Best, respectively) for each guild. Once the scores were assigned, the mean score was determined by dividing the periodic sum by the number of metrics. As each stand was evaluated for the Shrubland Associates Guild and the Open Forest Guild, the total habitat index is the sum of both scores. To account for variations in stand size, the objective function calculations for each total habitat index are weighted by the area (ha/ac) of the represented stand. For example, a

2-hectare stand that earned a score of 0.5 for each open-forest condition metric would earn a score of 2.0 points (0.5+0.5+0.5+0.5), and the mean score would be assessed as 0.5 points. This score would be multiplied by the stand hectarage (2) and the first half of the score comes to 1 point. Next, the Shrubland Associates score, which features 4 characteristics in the matrix, would be calculated. In this example, the same 2-hectare (5-acre) stand was found to have a score of 1 point for each characteristic in the matrix. The mean score for this stand would be 1 point, and multiplying the mean score by the acreage/hectarage gives a Shrubland Associates score of 2 points. Both the open-forest condition score and Shrubland Associates score would then be summed to determine the total HSI score for this particular 2- hectare (5-acre) stand. Each stand would be calculated in this way, at the end of every period, with differences only arising from the stand area and secondary assigned species guild. While loblolly pine plantations make up a substantial part of the NCWRC's game land portfolio, solely optimizing artificially regenerated loblolly pine in the objective function would be antithetical to the NCWRC's mission. Moreover, optimizing only a portion of the total land base in the model would not offer a realistic simulation, and therefore, not be in the interest of the Commission. As stated above, each stand, when any (or all) of the HSIs are optimized in the objective function, as programmed by the Commission, are evaluated for two focal species guilds (Shrubland Associates Guild and a secondary guild). Decoupling the scores associated the Shrubland and secondary guild would fundamentally alter the HSI and undermine one of the goals of this work. Ill-advised specificity, as this would certainly have been, represents a pitfall we wanted to avoid.

Next, we ran the updated Woodstock model once with MaxHabitat as the objective and once with MaxCashflow as the objective. We then ran separate simulations with the original Woodstock model: one to prioritize MaxHabitat and one to prioritize MaxCashflow. This method allowed us to compare the original and updated MaxHabitat/MaxCashflow model outputs with one another. We kept both the original NCWRC model's 30% even-flow cashflow (changes in revenue cannot exceed a 30% variation from period to period) and ending inventory constraints. The Model's periodic cashflow and ending inventory constraints ensure the modeled revenue streams remain stable, and the final standing volume is greater than the mean standing volume spanning the last 14 periods. We did not compare the updated MaxCashflow model to the original MaxCashflow model. While it may be useful in the future to compare the changes in

MaxCashflow and MaxHabitat models with more targeted artificially regenerated loblolly pine growth and yield tables, that was outside the scope of this work.

Production Possibilities Frontier Development

To better understand the tradeoffs between MaxHabitat and MaxCashflow in the updated Model, we composed a set of simulations that optimized both objectives simultaneously. Rather than use acreage/hectarage in Best or Good condition, as in Phillips et al. (2023), we opted to evaluate habitat using the sum of HSI values from each species-specific guild. We determined the upper and lower limits of the production possibilities frontier by running the MaxHabitat and MaxCashflow models without cashflow constraints. The maximum revenue generated by the unconstrained MaxCashflow model represented the upper limit, while the maximum revenue generated by the unconstrained MaxHabitat model represented the lower level. We found the difference between the two amounts and divided the result by 5, as we had chosen to simulate the ensuing MaxCashflow and MaxHabitat models 5 times each. For example, if the revenue generated by MaxCashflow was \$40,000,000, and \$10,000,000 for MaxHabitat, the difference between the two models would be \$30,000,000. Dividing this number by 5 generates a value of \$6,000,000. Therefore, each simulation would be run with cashflow constraints of \$34,000,000, \$28,000,000, \$22,000,000, \$16,000,000, and \$10,000,000. Once the cashflow constraint intervals were determined using the above method, we modified the optimization model for the MaxHabitat and MaxCashflow model separately. With the upper and lower cashflow limits established, we constructed two objective functions: one with the combined maximum sum of portfolio wide HSI values + Cashflow (MaxHabitat), and the other with the minimum sum of portfolio wide HSI values (MaxCashflow). We ran both the MaxHabitat and MaxCashflow models with the same revenue constraints. At the end of each model run we, for MaxCashflow and MaxHabitat, plotted the output total HSI value on a graph as the x value and constrained total revenue as the y value.

Results and Discussion

Identifying the highest performing thinning regime and planting density combination

The highest mean open-forest condition score (45.29) was generated by Thinning Regime 15 (Table 2.2) when regenerated with (896 seedlings/ha) 363 seedlings (hereafter referred to as 15-363), which instructed FVS to thin from 18.4 m^2/ha (80 ft^2/ac) to 9.2 m^2/ha (40 ft^2/ac) zero, one, two, or three times during the 100-year simulation period. The lowest mean open-forest condition score (29.57) was generated by Thinning Regime 11 when regenerated with 622 seedlings, which instructed FVS to thin to 13.8 m^2/ha (60 ft^2/ac) when the stand reached 18.4 m^2/ha (80 ft^2/ac). The resulting scores from all 1,008 prescriptions can be found in Appendix A. Thinning Regime 15 also generated the highest mean open-forest condition with 45.30 points. This calculation included the scores from each growth and yield table at each planting density and site index for a total of 42 regenerated growth and yield tables (Table 2.3). Thinning Regime 11 also posted the lowest total mean score for the open forest condition (32.20).

The median total combined open-forest condition score was 40.91. No Thinning Regime in Quartile 1 and 2 that generated open-forest condition scores below the median featured a third basal area thinning target of 11.5 m^2/ha (50 ft^2/ac) or greater (Table 2.3). On the other hand, three and six thinning regimes in Quartiles 1 and 2 did feature second and first thinning targets of 11.5 m^2/ha (50 ft^2/ac) or greater, respectively. We conducted a Pearson's correlation coefficient test in R to measure the linear relationship between the mean open-forest condition scores and each thinning trigger and target. Thinning triggers 1, 2, and 3 shared the same correlation coefficient, -0.0048. The variables Thin 1 BA Target, Thin 2 BA Target, Thin 3 BA Target returned correlation coefficients of -0.8216, -0.9488, and -0.9431, respectively. Negative values represent that the relationship between two variables is inversely correlated, while positive values represent that the relationship between two variables is positively correlated.

Open-forest condition outputs on artificially regenerated loblolly pine stands

The updated Woodstock MaxHabitat model generated 46 hectares (114,722 acres) in "Best" condition on artificially regenerated loblolly pine plantations (Table 2.4, Figure 2.1), while the original MaxHabitat model generated 47 hectares (117,389 acres) in "Best" condition. On the

other hand, the updated MaxHabitat model generated 655,232 (Table 2.5, Figure 2.2) hectares (1,619,115 acres) in “Good” condition, whereas the original MaxHabitat model generated 634,217 hectares (1,567,185 acres) in “Good” condition. As for the hectarage in "Poor" condition, the updated MaxHabitat model generated 172,044 hectares (425,130 acres). The original MaxHabitat model produced 192,041 hectares (474,457 acres) in “Poor” condition (Table 2.6, Figure 2.3). The updated MaxHabitat model generated a higher total suitability score than the original MaxHabitat model by a margin of 3,890 points (Table 2.7, Figure 2.4).
The updated MaxHabitat model produced better open forest HSI scores on artificially regenerated loblolly pine stands than the original MaxHabitat model, but the percentage increase in HSI was small (0.3%). The updated model underperformed in terms of generating hectares in "Best" condition, in which the original model produced 2.3% more such hectarage. The updated model generated approximately 3.2% more "Good" hectarage than the original model, while also producing 11% fewer hectares in "Poor" condition.

Cashflow, Removals, and Carbon

The updated MaxHabitat model generated less cashflow on artificially regenerated loblolly pine stands than the original MaxHabitat model by a margin of $9,217,963 (Table 2.8, Figure 2.5). From a model wide perspective, the updated MaxHabitat model generated less cashflow on all stands than the original MaxHabitat model by a margin of $9,556,179 (Table 2.9, Figure 2.6). The updated MaxHabitat thinned 3,546 fewer acres during the modeled horizon than the original MaxHabitat model (Table 2.10, Figure 2.7). On the other hand, the updated MaxHabitat harvested 20,634 more acres during the modeled horizon than the original MaxHabitat model (Table 2.11, Figure 2.8).

The Woodstock model calculates total stored carbon as an outcome by summing total stand carbon and carbon stored in harvested wood products that persists for 100 years. The updated MaxHabitat stored fewer tons of carbon on artificially regenerated loblolly pines stands by a margin of 5,478,719 tons as compared to the original MaxHabitat model (Table 2.12, Figure 2.9). The original model thinned 4.9% more hectarage of artificially regenerated loblolly pine, and final harvests increased 68.2% in the updated model. The updated model produced 3.6% less cashflow from removals and stored 1.1% less carbon than the original model.

As timber removal, revenue generation, and carbon storage are inextricably linked (Puls et al. 2024), we surmise that the updated model's underperformance as compared to the original model, in terms of carbon stored and revenue generation, was caused by the 4.9% decrease in thinned hectares. Trees left on the stand after a thinning action often elicit a "thinning response", profiting from a decrease in pine-to-pine competition. Such a crop-tree-release encourages the growth of standing trees into sawtimber, which both generates higher cashflow outcomes and stores more carbon in terms of biomass than pulpwood or chip'n'saw. Moreover, although the updated model saw a 68.2% increase of hectares in which final harvests took place, the volume and proportion of product classes removed on each hectare as compared to the original MaxHabitat model play a disproportionate role in shaping the revenue and carbon storage outputs. In other words, while it is useful to know *how many* more/less land units were harvested, it is far more important to know *what* and *how much* was removed.

Production Possibilities Frontier

MaxCashflow run without constrained cashflow generated a maximum sum of $451,681,419, whereas MaxHabitat (also run without constrained cashflow) generated a maximum sum of $292,978,205 in undiscounted revenue. After finding the difference between each model's maximum revenue output ($158,703,214), we calculated the increment at which we would run each model ($31,740,642). In this case, we ran each model with cashflow constraints of $451,681,419, $419,940,777, $388,200,134, $356,459,491, $324,718,848, and $292,978,205 (Table 2.13, Figure 2.10).

The updated MaxHabitat model included a constraint so as to limit horizon-length revenue to a maximum of $451,681,419, and at this constraint the updated MaxHabitat model produced a total HSI output of 3,739,726. When constrained to produce no more than $419,940,777, the updated MaxHabitat model generated a total HSI output of 3,876,017. We divided $31,740,642 by 136,290, the difference in total HSI between the constrained runs. Thus, we determined that to produce a total HSI output of 3,876,017, rather than 3,739,726, if the goal is to maximize habitat, one does so at a cost of $233 per point of MaxHabitat (HSI).

Conclusions and Limitations

Testing each thinning regime and planting density combination showed that the combination of frequent and heavy thinning, as expected, generated the highest open-forest condition HSI scores. As Thinning Regime 15 featured a basal area thinning target of 9.2 m^2/ha (40 ft^2/ac), assertions that thinning to 11.5 m^2/ha (50 ft^2/ac) to prioritize open-forest condition are conservative (Levin, Chapter 1) seem to be supported. In calculating the correlation coefficients between the mean open-forest condition (HSI) scores and each thinning trigger and target variable we were able to identify significant inverse relationships between each thinning target and the open-forest condition scores. Thinning Regime 15 was the most aggressive thinning regime, and it performed as expected. As basal area is a plausible corollary for stand stem density, it is reasonable to infer that the more aggressive thinning regimes removed more stems, therefore allowing more photosynthetically active radiation to pass through the canopy and hit the ground, thereby stimulating the growth of forbs and understory plants. Thinning Regimes 1, 6, and 11, which all featured basal area thinning targets of 13.8 m^2/ha (60 ft^2/ac) at each thinning action, generated the lowest respective scores (34.32, 33.17, 32.20). It should also be noted that Thinning Regimes 1, 6, and 11 also featured only one respective basal area thinning trigger. Thinning Regime 1 thinning actions are triggered at 11.5 m^2/ha (50 ft^2/ac), Thinning Regime 6 thinning actions are triggered at 19.5 m^2/ha (85 ft^2/ac), and Thinning Regime 11 thinning actions are triggered at 18.4 m^2/ha (80 ft^2/ac).

When integrated into the updated Woodstock model, we were able to observe that the inclusion of the higher performing artificially regenerated growth and yield tables did have a tangible effect on the total quantity of hectares in “Best”, “Good”, and “Bad” condition. Increasing the total number of hectarage in “Best” and “Good” condition was the goal. We did not expect that hectarage in “Best” condition would decrease, while the increase in “Good” hectarage was anticipated. Although hectares in “Best” condition decreased, hectarage in “Poor” condition saw a substantial decrease. Any decrease in “Poor” hectares must be accompanied by an increase in “Best” and “Good” acres. As the decrease in “Best” hectares was unanticipated, we must more closely examine individual stands throughout the model horizon to better understand how the condition of hectares in the updated model differs from those in the original at a finer scale.

The objective function, though, did not intend to optimize hectarage in “Best” or “Good” condition. Rather, we chose to optimize for the sum of HSI scores on every *stand*. While hectares are uniform in size, the modeled stands exhibit substantial variations in size. Moreover, when optimizing for the sum of HSI scores in the objective function the model multiplies each stand’s HSI score by the size of the stand. The updated model did generate a higher sum HSI score on artificially regenerated loblolly pine stands than the original model, but it is possible that Woodstock, given the native constraints and new regenerated growth and yield tables, optimized the sum HSI score by prioritizing stands that are larger, and therefore weighted more heavily. In comparison to the original model, the updated model thinned 3,546 hectarage of artificially regenerated pine stands. While it is important to concede that our initial thinning regime tests were aspatial, we can surmise that the updated model’s proclivity to thin fewer hectares caused, in part, at least, the decrease in “Best” hectares. In other words, the updated model was able to outperform the original model in terms of open-forest HSI by increasing the HSI score on some stands but decreasing the HSI score on others. Additional investigation is surely required to flesh out this assumption. We must compare, on a stand-by-stand basis, how the silvicultural actions were implemented (Appendix B).

This work provides a useful case study for any landowner or forest manager hoping to balance habitat and revenue objectives on artificially regenerated loblolly pine plantations, but it exhibits key limitations. We were not able to incorporate fire return interval into our initial tests. Without including the last metric for calculating open-forest condition HSI scores, the calculation is inherently incomplete. It is also important to note that the Commission as of yet has not defined a clear set of values for determining how the condition of each acre/hectare (“Best”, “Good’, and “Poor”) relates to one another. In other words, we do not know how much better one hectare in “Best” condition is compared to one hectare in “Good” condition. With this work as a case study, we cannot adequately determine whether the increase of acres in “Good” condition, accompanied by the decrease of acres in “Poor” condition, justifies the loss of acres in “Best” condition.

We were able to show that implementing more precise growth and yield data increased species-specific habitat measures. Additionally, we were able to provide more evidence that thinning pine plantations to below 11.5 m^2/ha (50 ft^2/ac) is more advantageous if the goal is to generate open-forest condition.

Works Cited

Bengston, D. N. (1994). Changing forest values and ecosystem management. *Society & Natural Resources*, *7*(6), 515–533. https://doi.org/10.1080/08941929409380885

Bennett, B. M. (2015). *Plantations and Protected Areas: A Global History of Forest Management*. https://direct.mit.edu/books/monograph/2293/Plantations-and-Protected-AreasA-Global-History-of

Campbell, T. N., Jones, P. D., Demarais, S., & Ezell, A. W. (2015). Vegetation Communities in Intensively Established Loblolly Pine Plantations at Crown Closure. *Journal of Forestry*, *113*(3), 298–307.

Daigneault, A., & Favero, A. (2021). Global forest management, carbon sequestration and bioenergy supply under alternative shared socioeconomic pathways. *Land Use Policy*, *103*, 105302. https://doi.org/10.1016/j.landusepol.2021.105302

DeFries, R., & Nagendra, H. (2017). Ecosystem management as a wicked problem. *Science*, *356*(6335), 265–270.

Gleick, J. (1987). *Chaos*. Viking Penguin Inc.

Gray, A. N., Pelz, K., Hayward, G. D., Schuler, T., Salverson, W., Palmer, M., Schumacher, C., & Woodall, C. W. (2023). Perspectives: The wicked problem of defining and inventorying mature and old-growth forests. *FOREST ECOLOGY AND MANAGEMENT*, *546*, 121350. https://doi.org/10.1016/j.foreco.2023.121350

Himes, A., & Dues, K. (2024). Relational forestry: A call to expand the discipline's institutional foundations. *Ecosystems and People*. https://www.tandfonline.com/doi/abs/10.1080/26395916.2024.2365236

Huntsinger, L., & McCaffrey, S. (1995). A Forest for the Trees: Forest Management and the Yurok Environment, 1850 to 1994. *American Indian Culture and Research Journal*, *19*(4). https://escholarship.org/uc/item/7qn456xf

Jarvis, P. G., & McNaughton, K. G. (1986). Stomatal Control of Transpiration: Scaling Up from Leaf to Region. In A. MacFadyen & E. D. Ford (Eds.), *Advances in Ecological Research* (Vol. 15, pp. 1–49). Academic Press. https://doi.org/10.1016/S0065-2504(08)60119-1

Levin, S. A. (1992). The Problem of Pattern and Scale in Ecology. *Ecology*, *73*(6), 1943.

Loehle, C., Miller, D. A., Kovach, A. I., Larsen-Gray, A. L., Akresh, M. E., McDonald, J. E., Cheeseman, A. E., King, D., Petzinger, S. M., & Kanter, J. (2024). Forest Management Is Key for Conserving Biodiversity and Providing Ecosystem Services in the United States. *Forests*, *15*(12), 2087. https://doi.org/10.3390/f15122087

Mandelbrot, B. B. (1982). *The Fractal Geometry of Nature*. W.H. Freeman and Company.

Marzluff, J. M., Millspaugh, J. J., Ceder, K. R., Oliver, C. D., Withey, J., McCarter, J. B., Mason, C. L., & Comnick, J. (2002). Modeling Changes in Wildlife Habitat and Timber Revenues in Response to Forest Management. *Forest Science*, *48*(2), 191–202. https://doi.org/10.1093/forestscience/48.2.191

Morrison, M. L., & Mathewson, H. A. (2015). *Wildlife habitat conservation: Concepts, challenges, and solutions*. Johns Hopkins University Press.

Phillips, C. E. (2023). *Integrating Wildlife Management Goals into Quantitative Forest Planning.* https://www.lib.ncsu.edu/resolver/1840.20/40929

Puettmann, K. J., Coates, K. D., & Messier, C. C. (2012). *A Critique of Silviculture: Managing for Complexity*. Island Press.

Puls, S. J., Cook, R. L., Baker, J. S., Rakestraw, J. L., & Trlica, A. (2024). Modeling wood product carbon flows in southern us pine plantations: Implications for carbon storage. *Carbon Balance and Management*, *19*(1), 8. https://doi.org/10.1186/s13021-024-00254-4

R Core Team. (2023). _*R: A Language and Environment for Statistical Computing*_ [Computer software]. R Foundation for Statistical Computing. https://www.R-project.org

Remsoft Inc. (2024). *Modeling Fundamentals: Learning to Model Efficiently and Accurately in Woodstock.*

Stewart, D. G. (2022). *Effects of Thinning Intensity, Prescribed Fire, and Herbicide on Wildlife Habitat in Mid-Rotation Loblolly Pine Stands* [M.Sc., Auburn University]. https://www.proquest.com/docview/2866084237/abstract/3905B6931A74C24PQ/1

Vincent, J. R., & Binkley, C. S. (1993). Efficient Multiple-Use Forestry May Require Land-Use Specialization. *Land Economics*, *69*(4), 370–376. https://doi.org/10.2307/3146454

Table 2.1 Each thinning regime with associated basal area (BA, ft^2/ac) triggers and targets.

Thinning Regime	Thin 1 BA Trigger	Thin 1 BA Target	Thin 2 BA Trigger	Thin 2 BA Target	Thin 3 BA Trigger	Thin 3 BA Target
1	90	60	90	60	90	60
2	90	55	90	55	90	55
3	90	50	90	50	90	50
4	90	45	90	45	90	45
5	90	40	90	40	90	40
6	85	60	85	60	85	60
7	85	55	85	55	85	55
8	85	50	85	50	85	50
9	85	45	85	45	85	45
10	85	40	85	40	85	40
11	80	60	80	60	80	60
12	80	55	80	55	80	55
13	80	50	80	50	80	50
14	80	45	80	45	80	45
15	80	40	80	40	80	40
16	90	60	90	55	90	50
17	90	55	90	50	90	45
18	90	50	90	45	90	40
19	85	60	85	55	85	50
20	85	55	85	50	85	45
21	85	50	85	45	85	40
22	80	60	80	55	80	50
23	80	55	80	50	80	45
24	80	50	80	45	80	40

Table 2.2 The open-forest condition score generated from growth and yield tables in Thinning Regime 15 at 363 trees per acre at planting. The mean score was greater than any other thinning regime/planting density combination.

Site Index	Habitat Score
60	42.5
70	44
80	44.5
90	47.5
100	47.5
110	48
120	46.5

Table 2.3 Each thinning regime with mean total combined open-forest condition (HSI) scores the scores are in descending order.

Thinning Regime	Mean Total Combined Open-Forest Condition Score
15	45.30
24	44.14
14	43.68
10	43.58
21	43.36
9	43.10
5	42.85
18	42.27
4	41.85
20	41.19
17	41.04
23	41.00
8	40.82
3	40.52
13	39.70
16	38.39
2	37.98
19	37.77
22	37.11
7	36.99
12	36.42
1	34.32
6	33.17
11	32.20

Table 2.4 The updated MaxHabitat model generated 2,667 fewer acres in "Best" condition on artificially regenerated loblolly pine stands.

Period	Original MaxHabitat	Updated MaxHabitat
0	1,050	1,050
1	4,283	3,975
2	7,567	6,188
3	8,911	9,042
4	6,905	7,342
5	5,961	6,523
6	3,934	3,913
7	3,480	3,740
8	4,402	4,441
9	6,149	5,884
10	6,392	5,824
11	5,703	5,555
12	5,542	5,375
13	6,322	6,121
14	6,494	6,222
15	6,132	6,445
16	5,958	5,722
17	6,187	5,693
18	5,723	5,448
19	6,164	5,912
20	4,130	4,307
Total	117,389	114,722

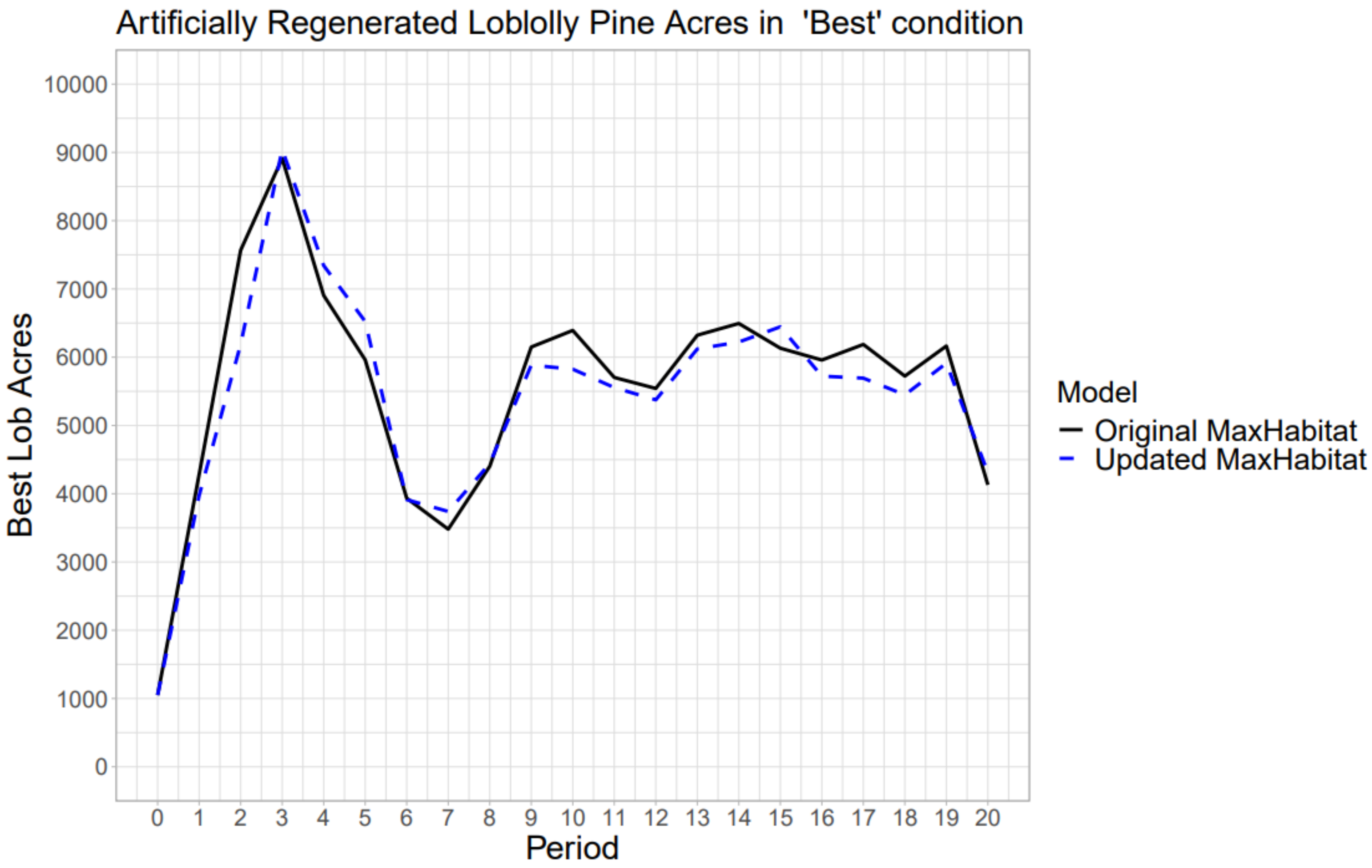

Figure 2.1 The updated MaxHabitat model generated 2,667 fewer acres in "Best" condition on artificially regenerated loblolly pine stands during the model horizon.

Table 2.5 The updated MaxHabitat model generated 51,930 more acres in “Good” condition on artificially regenerated loblolly pine stands.

	Period	Original MaxHabitat	Updated MaxHabitat
	0	59,002	61,184
	1	64,283	67,303
	2	68,128	71,811
	3	73,169	74,811
	4	74,084	73,579
	5	74,007	72,108
	6	72,549	74,076
	7	71,322	74,505
	8	74,220	77,288
	9	80,460	81,491
	10	80,314	79,941
	11	79,887	80,062
	12	78,935	82,444
	13	80,332	81,933
	14	81,131	79,922
	15	78,609	78,061
	16	76,037	77,617
	17	75,859	81,066
	18	76,227	84,363
	19	75,648	84,349
	20	72,982	81,201
Total		1,567,185	1,619,115

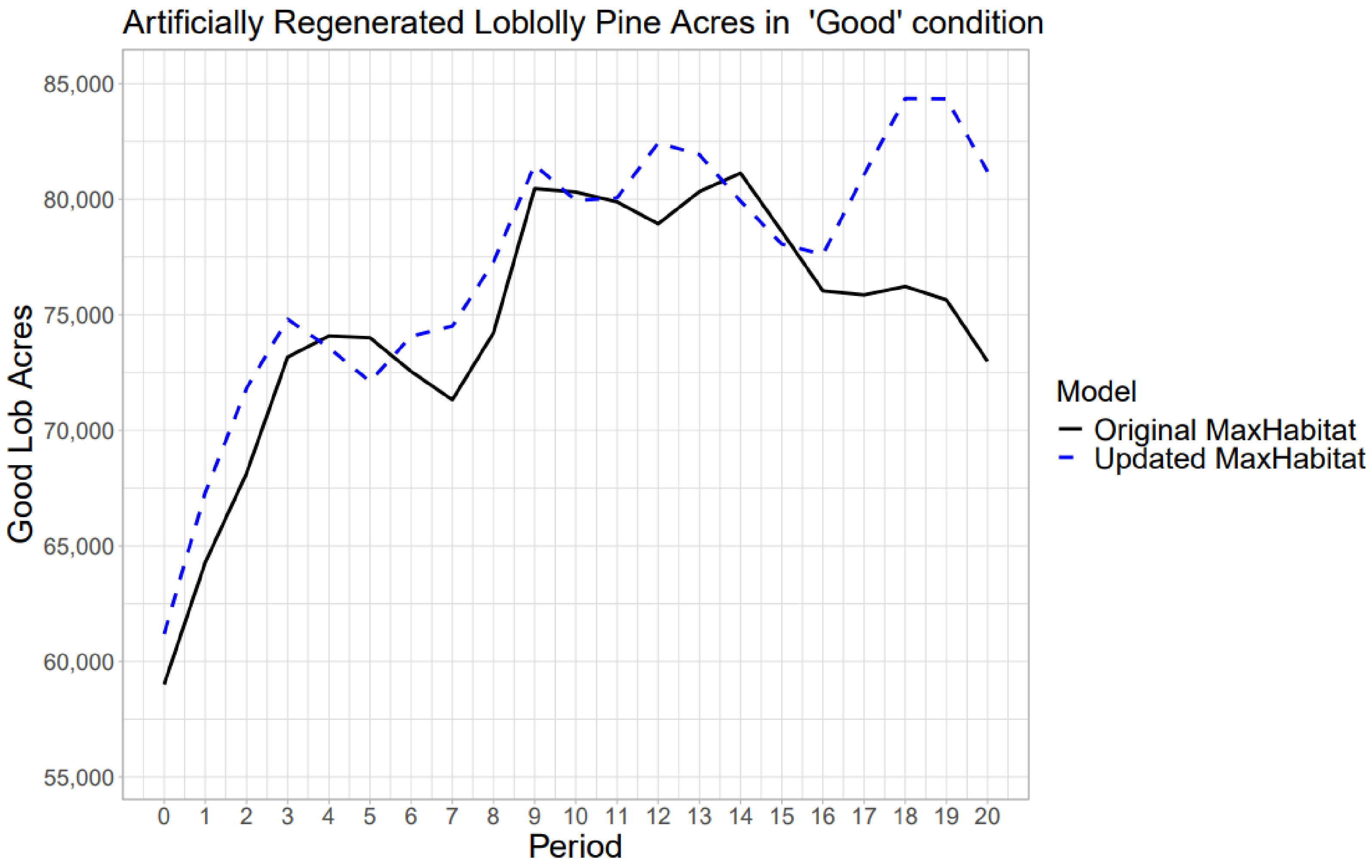

Figure 2.2 The updated MaxHabitat model generated 51,930 more acres in “Good” condition on artificially regenerated loblolly pine stands during the model horizon.

Table 2.6 The updated MaxHabitat model generated 49,327 fewer acres in "Poor" condition on artificially regenerated loblolly pine stands.

Period	Original MaxHabitat	Updated MaxHabitat
0	42,759	40,577
1	34,245	31,533
2	27,116	24,812
3	20,731	18,959
4	21,822	21,884
5	22,843	24,157
6	26,328	24,818
7	28,009	24,561
8	24,189	21,013
9	16,202	15,370
10	16,105	17,037
11	17,221	17,237
12	18,334	15,014
13	16,157	14,766
14	15,186	16,673
15	18,070	18,272
16	20,816	19,420
17	20,765	16,080
18	20,861	13,075
19	20,999	12,558
20	25,699	17,314
Total	474,457	425,130

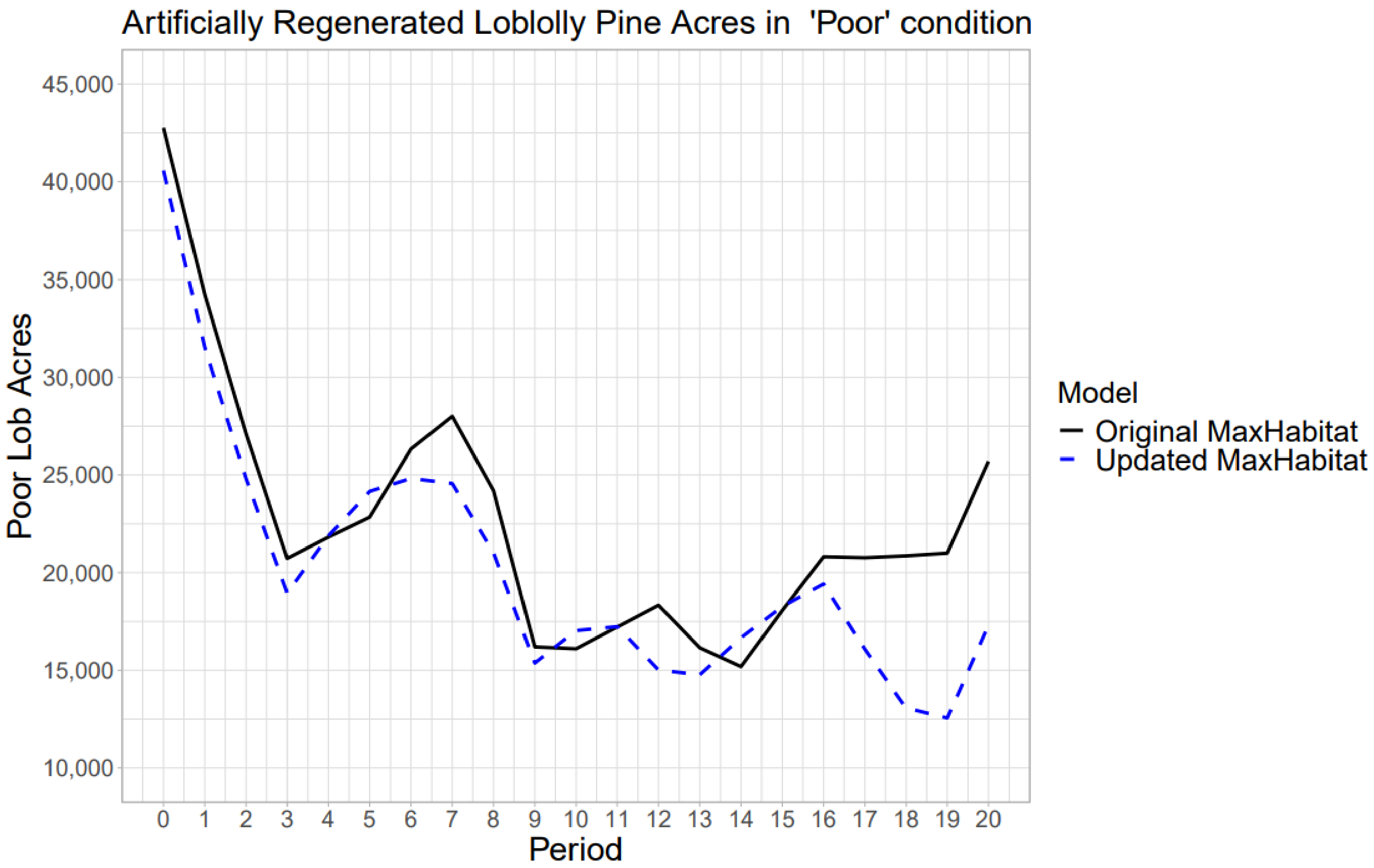

Figure 2.3 The updated MaxHabitat model generated 49,327 fewer acres in “Poor” condition on artificially regenerated loblolly pine stands during the model horizon.

Table 2.7 On artificially regenerated loblolly pine plantations the updated MaxHabitat model generated a higher total habitat suitability score than the original MaxHabitat model by a margin of 3,890 points.

Period	Original MaxHabitat	Updated MaxHabitat
0	49,751	50,489
1	53,444	53,891
2	56,511	56,500
3	58,933	59,313
4	57,553	57,542
5	56,529	56,247
6	54,505	55,133
7	54,245	55,178
8	56,730	57,258
9	60,070	59,462
10	60,214	58,951
11	60,018	59,521
12	59,918	59,830
13	60,411	59,679
14	60,489	59,447
15	59,382	59,140
16	58,645	58,666
17	59,225	59,598
18	58,910	60,109
19	59,151	60,726
20	57,347	59,190
Total	1,211,980	1,215,870

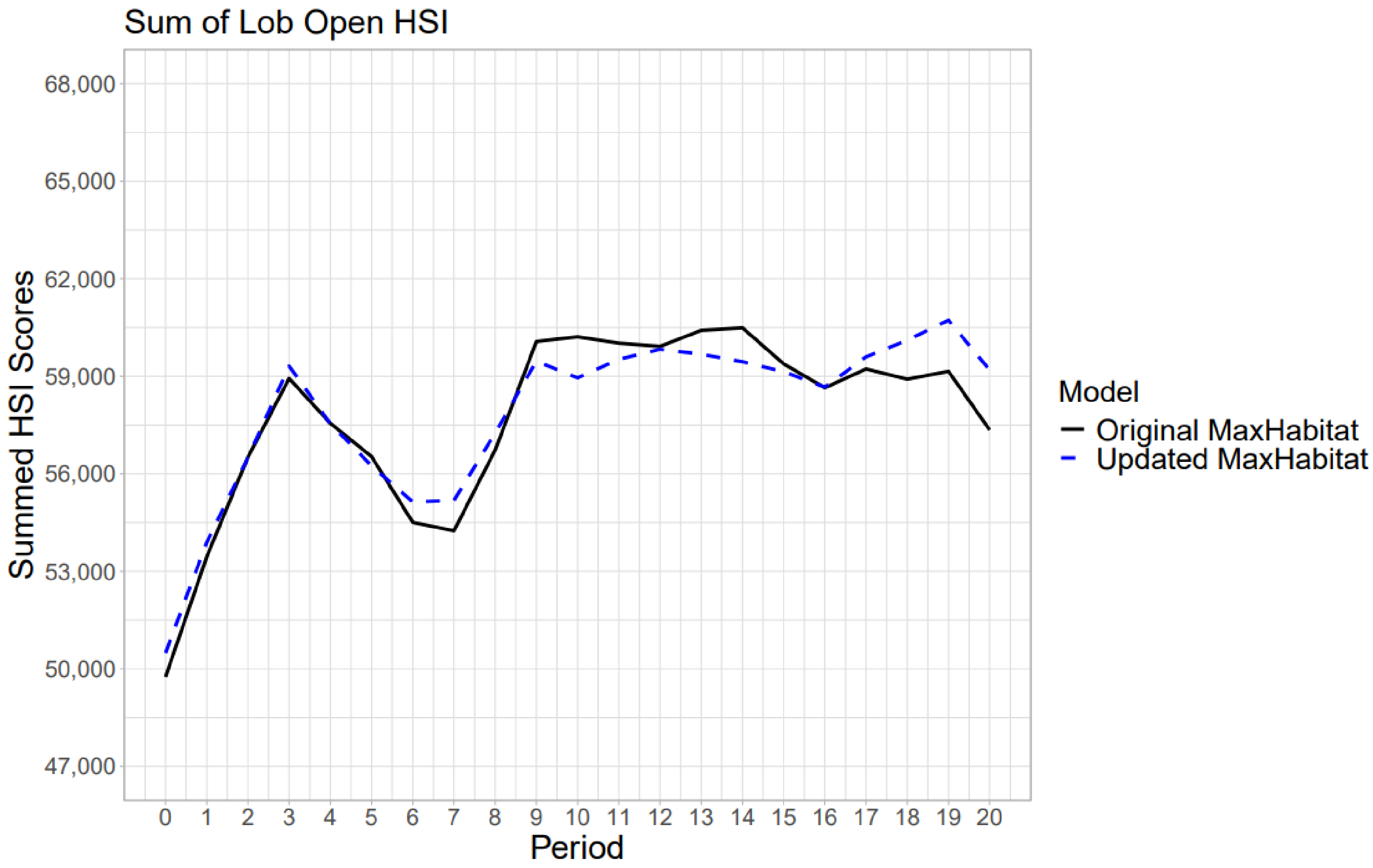

Figure 2.4 The updated MaxHabitat model generated a higher total habitat suitability score than the original MaxHabitat model by a margin of 3,890 points during the model horizon.

Table 2.8 The updated MaxHabitat model generated less cashflow on artificially regenerated loblolly pine stands than the original MaxHabitat model by a margin of $9,217,963.

Period	Original MaxHabitat	Updated MaxHabitat
0	0	0
1	15,642,448	15,883,183.50
2	15,792,699	15,878,754.90
3	17,141,976	16,433,892.60
4	17,238,551	17,372,465.70
5	17,168,406	17,461,542.40
6	16,236,147	16,361,555.10
7	15,029,715	11,969,708.00
8	16,973,843	13,877,867.60
9	14,986,654	12,878,141.00
10	12,480,685	12,302,091.30
11	11,256,469	10,114,774.40
12	7,306,479	7,538,858.80
13	11,558,443	11,147,867.20
14	12,200,442	11,927,291.70
15	12,277,673	12,324,613.90
16	11,631,371	11,566,196.40
17	8,587,248	8,678,785.10
18	8,728,172	8,188,367.80
19	8,214,035	8,956,232.90
20	9,999,161	10,370,464.10
Total	260,450,617	251,232,654

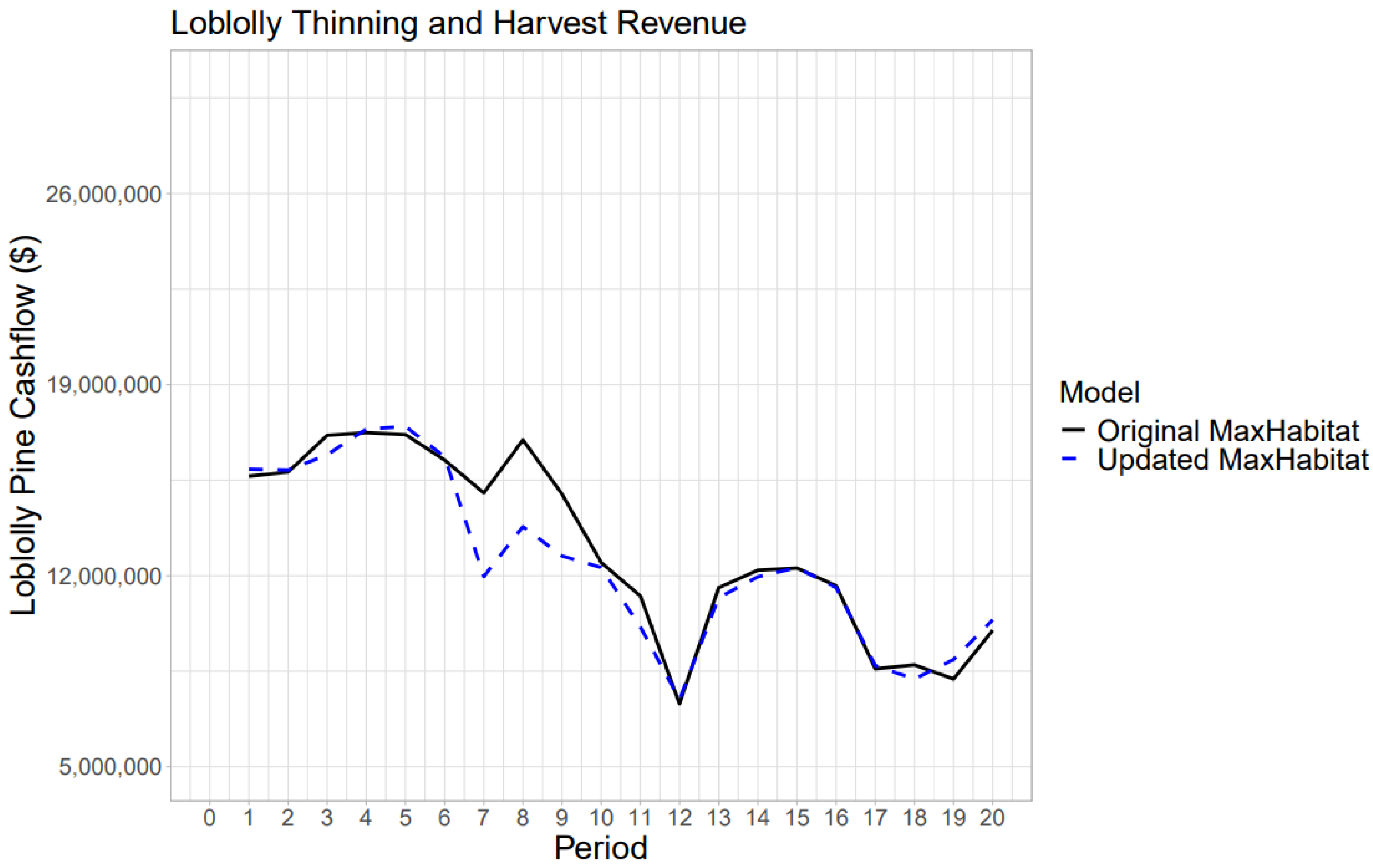

Figure 2.5 The updated MaxHabitat model generated less cashflow on artificially regenerated loblolly pine stands than the original MaxHabitat model by a margin of $9,217,963 during the model horizon.

Table 2.9 The updated MaxHabitat model generated less cashflow on all stands than the original MaxHabitat model by a margin of $9,556,179.

Period	Original MaxHabitat	Updated MaxHabitat
0	0	0
1	18,476,335	18,392,625
2	18,476,335	18,392,625
3	18,476,335	18,392,625
4	18,476,335	18,392,625
5	18,476,335	18,392,625
6	18,476,335	18,392,625
7	16,016,168	12,874,837
8	17,535,987	14,331,182
9	15,856,434	13,793,229
10	12,933,435	12,874,837
11	12,933,435	12,874,837
12	12,933,435	12,874,837
13	12,933,435	12,874,837
14	12,933,435	12,874,837
15	12,933,435	12,874,837
16	12,933,435	12,874,837
17	12,933,435	12,874,837
18	12,933,435	12,874,837
19	12,933,435	12,874,837
20	12,933,435	12,874,837
Total	302,534,384	292,978,205

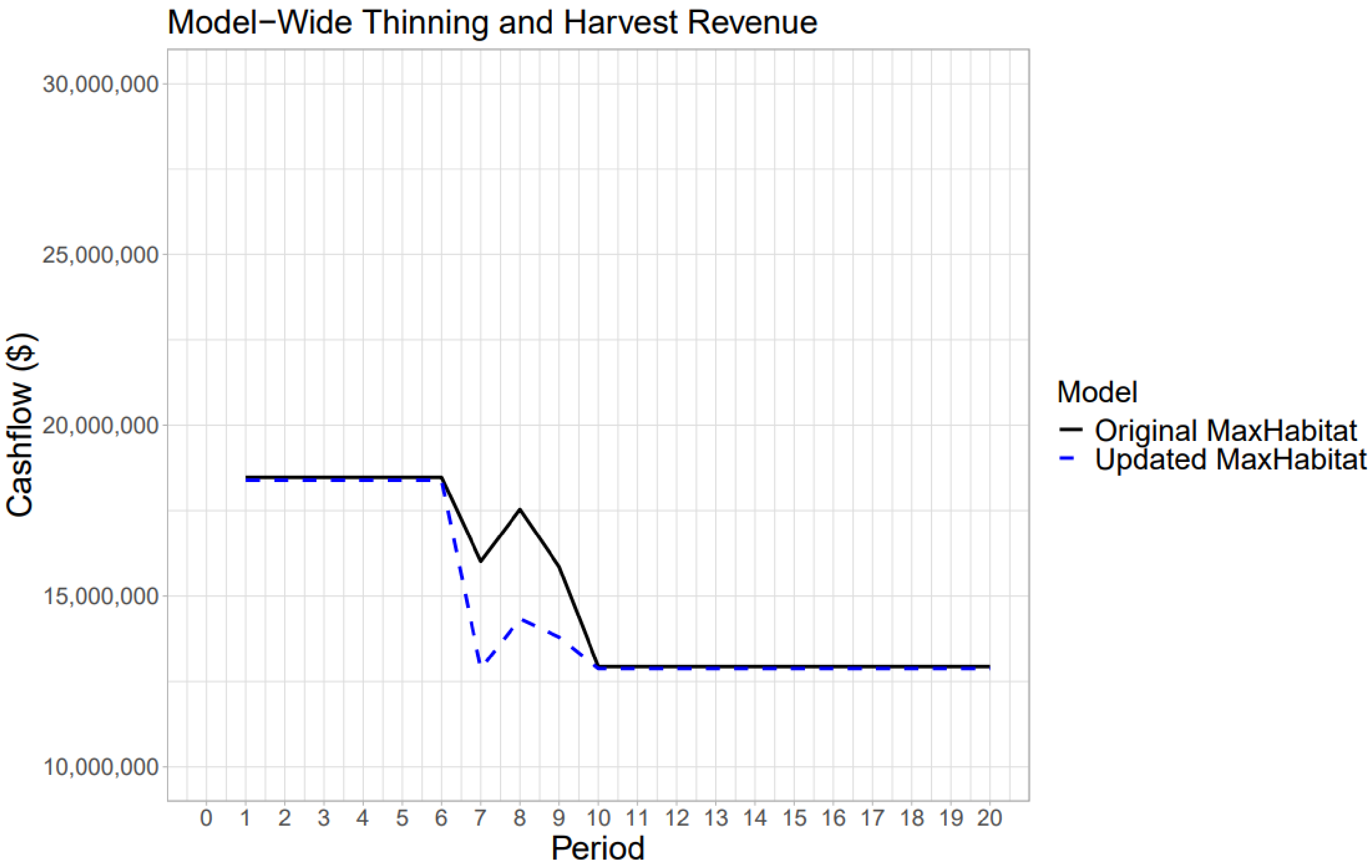

Figure 2.6 The updated MaxHabitat model generated less cashflow on all stands than the original MaxHabitat model by a margin of $9,556,179.

Table 2.10 The updated MaxHabitat thinned 3,546 fewer acres during the modeled horizon than the original MaxHabitat model.

	Period	Original MaxHabitat	Updated MaxHabitat
	0	0	0
	1	6,594	6,646
	2	8,142	6,734
	3	9,173	9,125
	4	2,190	1,258
	5	2,005	1,161
	6	2,310	1,178
	7	2,441	1,550
	8	6,706	5,731
	9	9,457	8,717
	10	1,881	1,539
	11	4,289	2,536
	12	2,805	1,178
	13	4,506	1,988
	14	1,831	2,335
	15	1,530	2,997
	16	2,092	1,803
	17	1,410	1,608
	18	1,812	2,731
	19	608	3,991
	20	50	3,480
Total		71832	68286

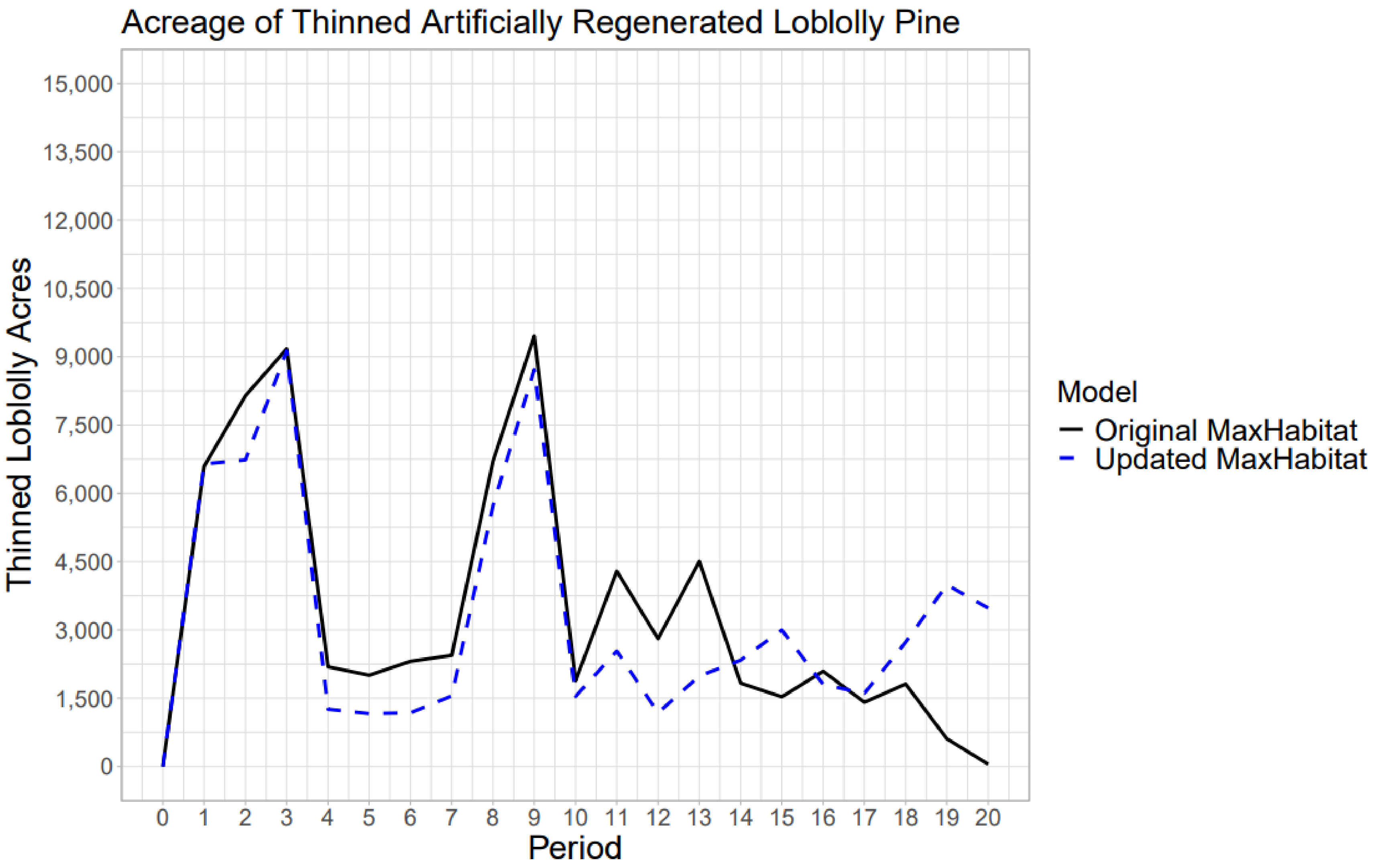

Figure 2.7 The updated MaxHabitat thinned 3,546 fewer acres during the modeled horizon than the original MaxHabitat model.

Table 2.11 The updated MaxHabitat harvested 20,634 more acres during the modeled horizon than the original MaxHabitat model.

Period	Original MaxHabitat	Updated MaxHabitat
0	0	0
1	245	721
2	387	1281
3	198	131
4	1126	2067
5	1018	2672
6	2928	2732
7	1957	2042
8	774	822
9	223	1719
10	605	3637
11	1060	2372
12	415	1701
13	231	2670
14	600	3086
15	2144	2906
16	3446	3663
17	327	1692
18	612	397
19	597	527
20	1033	3722
Total	19926	40560

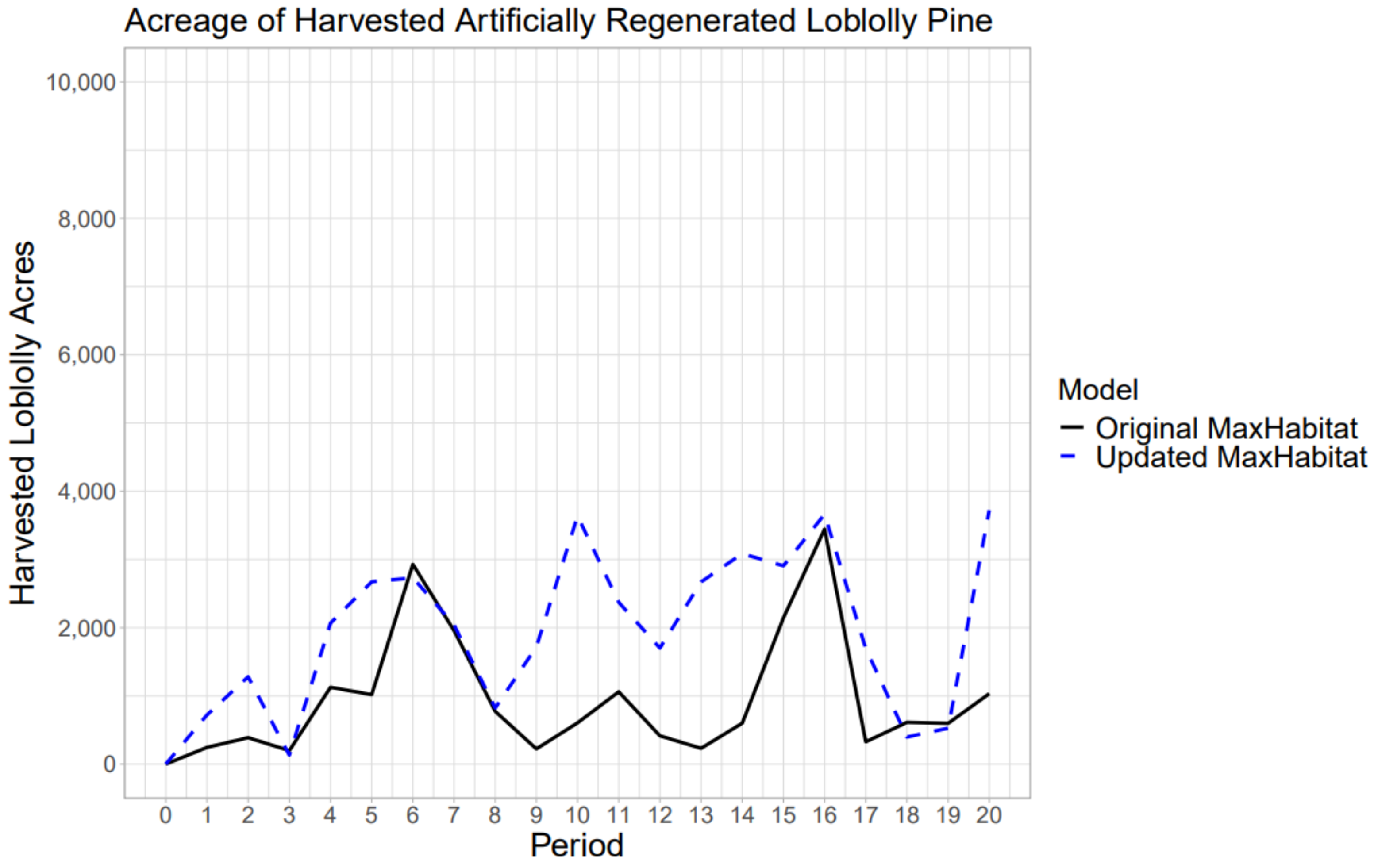

Figure 2.8 The updated MaxHabitat harvested 20,634 more acres during the modeled horizon than the original MaxHabitat model.

Table 2.12 The updated MaxHabitat stored fewer tons of carbon by a margin of 5,478,719 tons as compared to the original MaxHabitat model. Stored carbon is the summed tally of above/below standing carbon and carbon that persists in harvested wood products for 100 years.

Period	Original MaxHabitat	Updated MaxHabitat
0	20,495,928	20,448,529
1	21,678,016	21,473,972
2	22,316,889	21,968,631
3	22,759,967	22,319,117
4	23,088,419	22,588,472
5	23,417,134	22,900,874
6	23,621,954	23,165,369
7	23,906,836	23,485,477
8	24,210,825	23,918,417
9	24,494,505	24,189,195
10	24,399,823	24,041,437
11	24,150,680	23,775,926
12	23,805,826	23,499,581
13	23,814,489	23,514,822
14	23,676,465	23,447,461
15	23,590,356	23,468,657
16	23,475,758	23,379,786
17	23,323,593	23,263,507
18	23,223,042	23,229,588
19	23,154,678	23,148,436
20	23,084,224	22,983,434
Total	489,689,407	484,210,688

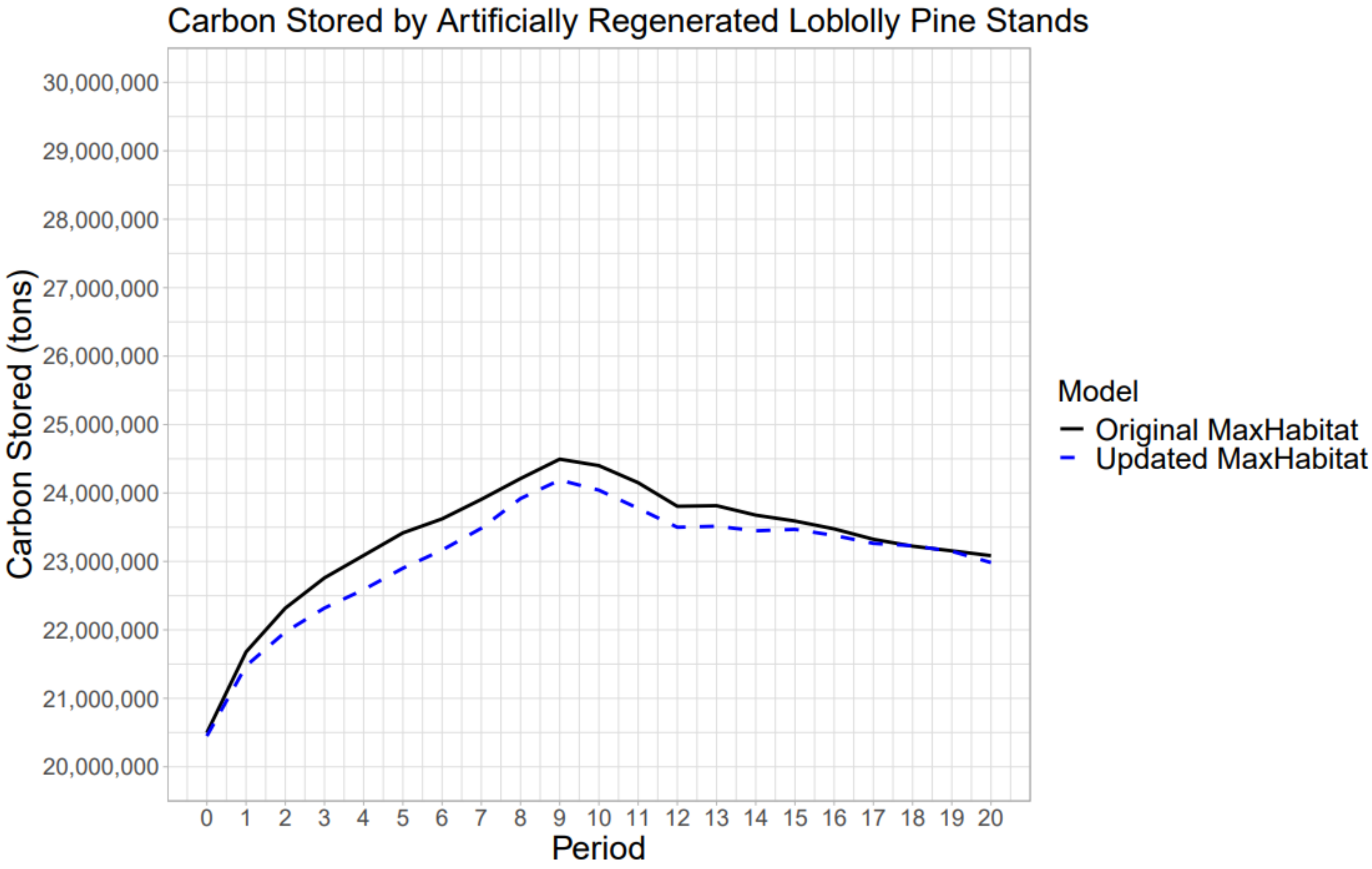

Figure 2.9 The updated MaxHabitat stored fewer tons of carbon by a margin of 5,478,719 tons as compared to the original MaxHabitat model. Stored carbon is the summed tally of above/below standing carbon and carbon that persists in harvested wood products for 100 years.

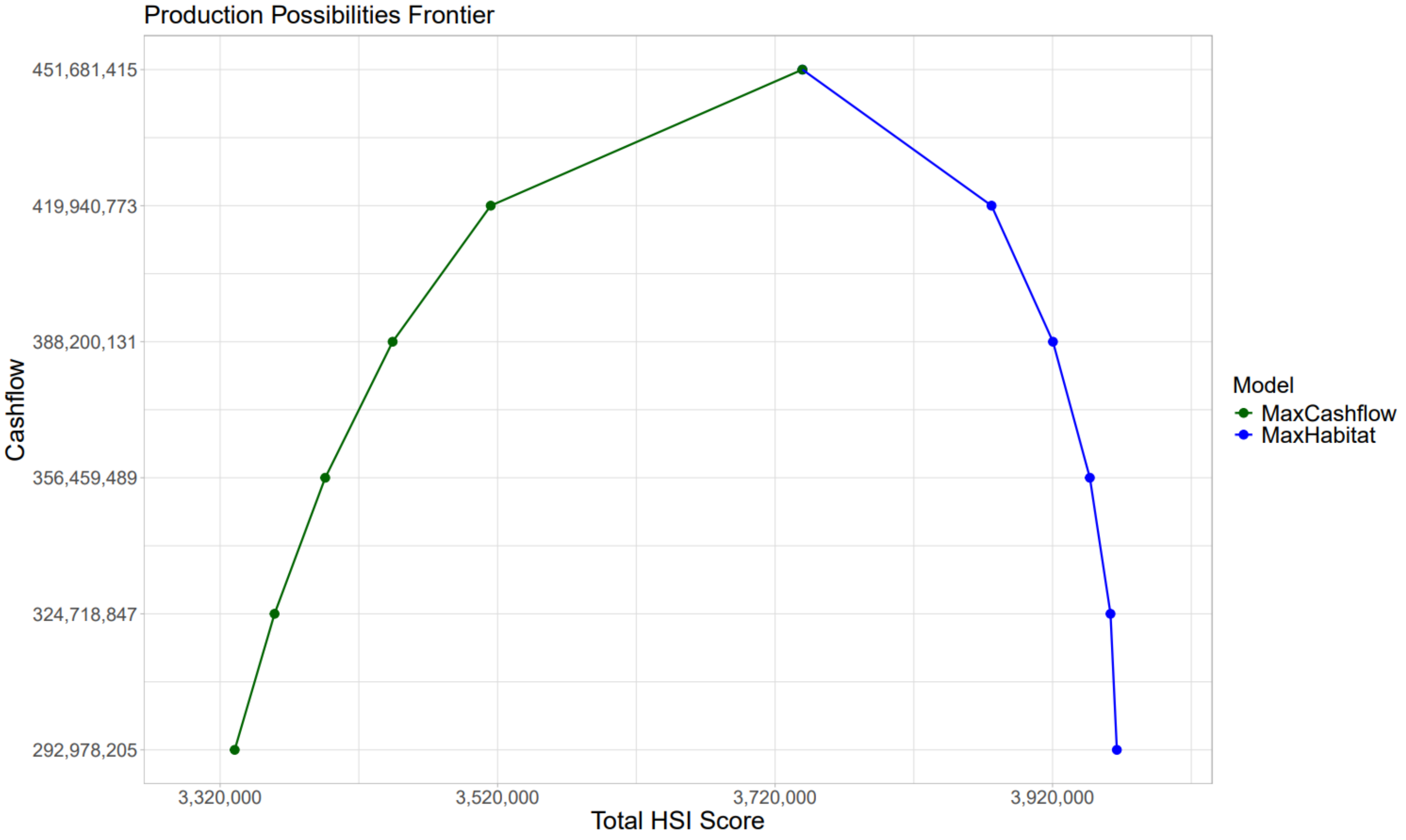

Figure 2.10 The green dots and associated line refer to constrained model runs that were optimized for MaxCashflow, while the blue dots and associated line represent MaxHabitat as the primary objective. When constrained at the same cashflow intervals (in this case $31,740,642) we can compare how cashflow and HSI relate to one another in terms of productive tradeoffs. For MaxCashflow, cashflow generation at higher constrained intervals increases model wide HSI scores. On the other hand, when MaxHabitat is the primary objective, revenue generation diminishes the model's productive capacity in terms of HSI.

Table 2.13 For both the updated MaxCashflow and MaxHabitat model, we calculated the total HSI at the same constrained revenue intervals. Where each model is constrained to generate no more than $451,681,419, the MaxHabitat model generates 59 more HSI points than the updated MaxCashflow model.

Revenue	Total HSI (MaxCashflow)	Total HSI (MaxHabitat)	Total HSI Difference (MaxCashflow)	MaxCashflow Opportunity Cost ($/point)	Total HSI Difference (MaxHabitat)	MaxHabitat Opportunity Cost ($/point)
451,681,419	3,739,668	3,739,726				
419,940,777	3,515,059	3,876,017	224,609	141	136,290	233
388,200,135	3,444,360	3,920,277	70,699	449	44,260	717
356,459,493	3,395,762	3,946,880	48,598	653	26,604	1,193
324,718,851	3,359,225	3,961,759	36,537	869	14,878	2,133
292,978,209	3,330,518	3,966,349	28,707	1,106	4,591	6,914

Appendix A: Cashflow and HSI Results for each Prescription

Thinning Regime	TPA	SINDEX	HSI	Cashflow
15	363	110	48	2519.17
15	622	100	48	2323.28
15	363	90	47.5	1909.53
15	363	100	47.5	2268.28
15	396	90	47.5	1974.77
15	396	120	47.5	2910.28
15	435	120	47.5	2918.87
15	484	120	47.5	2918.87
15	544	90	47	2057.29
15	544	110	47	2690.23
15	622	90	47	2023.72
10	622	120	46.5	2558.96
15	363	120	46.5	3333.97
15	396	100	46.5	2700.77
15	396	110	46.5	3028.07
15	435	90	46.5	2111.83
15	435	100	46.5	2642.34
15	484	90	46.5	2111.83
15	484	100	46.5	2642.34
15	544	120	46.5	3069.97
15	622	120	46.5	2558.96
5	622	120	46.5	2833.42
15	435	110	46	3042.62
15	484	110	46	3042.62
15	544	100	46	2730.32
15	622	80	46	1691.93
15	622	110	46	2835.46
24	435	120	46	2496.61
10	363	110	45.5	3214.39
10	363	120	45.5	3496.24
10	396	100	45.5	2875.62
10	396	110	45.5	3219.26
10	435	100	45.5	2812.12
14	363	110	45.5	2413.59
14	396	100	45.5	2056.2
21	363	120	45.5	3253.01
21	396	110	45.5	2773.91
24	363	100	45.5	1660.99
24	363	120	45.5	2491.75

24	396	100	45.5	1747.07
24	396	110	45.5	2052.95
24	435	90	45.5	1527.53
24	435	100	45.5	1796.94
24	435	110	45.5	2092.82
24	484	90	45.5	1567.99
24	622	100	45.5	2015.84
9	396	100	45.5	2056.2
10	435	110	45	3182.43
10	484	90	45	2650.32
10	484	100	45	2977.98
10	484	120	45	3598.04
10	544	100	45	2889.76
14	363	90	45	1797.24
14	363	100	45	1856.06
14	363	120	45	2655.19
14	396	110	45	2486.76
14	435	90	45	1856.59
14	435	100	45	2044.11
14	435	110	45	2427.54
14	435	120	45	2723.58
14	484	90	45	2001.46
14	484	120	45	2858.81
15	544	80	45	1637.54
18	363	110	45	2998.63
18	396	110	45	2995.35
18	435	100	45	2543.6
18	622	100	45	2735.31
21	363	110	45	2788.06
21	435	100	45	2543.6
21	622	90	45	1864
21	622	100	45	2735.31
24	363	90	45	1520.81
24	363	110	45	2060.22
24	396	90	45	1502.36
24	396	120	45	2371.73
24	484	110	45	2138.73
24	484	120	45	2563.64
24	544	100	45	1766.99
24	622	90	45	1612.86
4	363	110	45	2627.21
4	396	110	45	2759.06
4	435	100	45	2516.37
4	622	90	45	2191.58
9	363	110	45	2627.21
9	396	110	45	2486.76

9	622	90	45	2191.58
10	435	90	44.5	2666.97
10	544	110	44.5	3381.54
14	396	90	44.5	1882.47
14	396	120	44.5	2787.67
14	484	100	44.5	2120.26
14	484	110	44.5	2482.33
14	544	90	44.5	1971.73
14	544	100	44.5	2122.21
14	544	110	44.5	2499.35
14	622	90	44.5	1973.7
14	622	100	44.5	2345.64
15	363	80	44.5	2249.45
18	363	120	44.5	3495.76
18	396	120	44.5	3354.57
18	435	120	44.5	3566.9
18	484	120	44.5	3593.16
18	622	120	44.5	2310.8
21	396	90	44.5	2179.64
21	396	100	44.5	2402.53
21	396	120	44.5	3354.57
21	435	90	44.5	2217.96
21	435	110	44.5	2947.51
21	435	120	44.5	3320.44
21	484	90	44.5	2261.7
21	484	120	44.5	3327.12
24	363	80	44.5	1928.73
24	435	80	44.5	2085.81
24	544	110	44.5	2125.42
24	622	80	44.5	1241.29
4	435	90	44.5	2258.82
4	484	90	44.5	2352.89
4	544	90	44.5	2172.91
4	622	100	44.5	2583.63
5	363	110	44.5	3364.26
5	363	120	44.5	3704.82
5	396	110	44.5	3399.31
5	435	100	44.5	2951.3
9	363	100	44.5	2530.39
9	363	120	44.5	2950.18
9	396	90	44.5	2101.81
9	396	120	44.5	2787.67
9	435	90	44.5	2048.9
9	435	100	44.5	2252.19
9	435	120	44.5	2967.04
9	484	90	44.5	2161.94

9	484	100	44.5	2120.26
9	484	110	44.5	2482.33
9	484	120	44.5	3038.6
9	544	90	44.5	2172.91
9	544	100	44.5	2389.41
9	622	100	44.5	2345.64
10	363	100	44	2971.48
10	396	90	44	2579.49
10	396	120	44	3607.14
10	435	120	44	3643.29
10	544	90	44	2704.94
10	544	120	44	3713.96
10	622	90	44	2696.52
10	622	100	44	3140.19
10	622	110	44	3354.18
14	363	80	44	1827.09
14	544	120	44	2920.74
15	363	70	44	1833.47
15	396	70	44	1845.29
15	435	70	44	1930.8
15	435	80	44	2339.93
15	484	70	44	1930.8
15	484	80	44	2339.93
18	435	90	44	2382.1
18	435	110	44	3206.32
18	484	90	44	2445.51
18	484	110	44	3111.47
18	544	90	44	2325.05
18	544	100	44	2584.03
18	544	110	44	3165.47
18	622	90	44	2504.12
18	622	110	44	3157.78
21	363	90	44	2308.83
21	363	100	44	2811.08
21	484	100	44	2486.01
21	484	110	44	2868.98
21	544	90	44	2325.05
21	544	100	44	2584.03
21	622	110	44	3157.78
24	396	70	44	1278.03
24	396	80	44	1911.78
24	435	70	44	1256.83
24	484	100	44	2195.56
24	544	90	44	1744.12
24	544	120	44	2741.49
24	622	110	44	2404.01

4	363	120	44	3552.07
4	484	120	44	3218.73
4	544	110	44	2887.19
5	363	100	44	1883.68
5	396	100	44	1943.97
5	435	110	44	3363.03
5	484	90	44	2771.12
5	484	100	44	3146.85
5	484	120	44	3778.2
5	544	100	44	3058.52
9	435	110	44	2641.8
9	544	110	44	2702.32
9	544	120	44	3149.88
10	363	90	43.5	1625.81
10	484	110	43.5	3439.62
10	544	80	43.5	2295.62
10	622	80	43.5	2238.22
14	396	70	43.5	1439.08
14	435	80	43.5	1836.87
14	622	80	43.5	1631.33
14	622	110	43.5	2686.66
15	622	70	43.5	1948.81
17	363	120	43.5	3267.91
18	484	100	43.5	2729.05
21	363	80	43.5	2067.46
21	435	80	43.5	2239.73
21	544	110	43.5	2933.46
21	544	120	43.5	3427.62
21	622	80	43.5	1915.74
21	622	120	43.5	1928.71
24	363	70	43.5	1314.29
24	484	80	43.5	2164.98
24	544	80	43.5	1286.76
24	622	70	43.5	1602.77
24	622	120	43.5	1928.71
4	484	100	43.5	2835.98
4	622	110	43.5	2888.87
4	622	120	43.5	2685.81
5	363	90	43.5	1625.81
5	396	90	43.5	1723.91
5	544	110	43.5	3558.53
9	363	80	43.5	1981.33
9	396	70	43.5	1574.11
9	435	70	43.5	1675.22
9	622	110	43.5	2888.87
9	622	120	43.5	2427.62

10	363	70	43	1271.22
10	396	60	43	1013
10	435	70	43	1034.05
10	435	80	43	2433.31
14	363	70	43	1467.68
14	396	60	43	1325.17
14	435	70	43	1538.82
14	484	80	43	1926.63
14	622	70	43	1473.62
15	396	60	43	1013
17	396	120	43	2703.28
18	363	100	43	2996.85
18	396	100	43	3089.64
18	544	120	43	3651.83
18	622	80	43	2086.11
20	396	100	43	1822.36
21	396	70	43	1687.31
21	396	80	43	2088.43
21	435	70	43	1723.15
21	544	80	43	1544.65
21	622	70	43	1734.19
24	484	70	43	1227.67
4	396	120	43	3761.35
4	435	120	43	3795.9
4	484	110	43	3420.47
4	544	100	43	2926.27
4	622	80	43	1802.93
5	363	80	43	1480.2
5	396	120	43	3791.48
5	435	70	43	1311.24
5	435	80	43	1520.14
5	435	120	43	3844.33
5	622	100	43	3268.25
9	484	80	43	2068.57
9	622	80	43	1802.93
10	363	60	42.5	1008.4
10	363	80	42.5	2391.69
10	396	80	42.5	1230.7
10	622	70	42.5	2040.91
14	363	60	42.5	1500.33
14	396	80	42.5	1932.5
14	544	80	42.5	1487.16
15	363	60	42.5	1008.46
15	396	80	42.5	2314.42
17	435	120	42.5	2491.7
17	484	120	42.5	2654.46

17	622	100	42.5	2644.57
18	363	80	42.5	2203.55
18	435	80	42.5	2378.07
18	484	80	42.5	2324.13
20	396	70	42.5	1186.18
20	435	80	42.5	1617.26
20	435	120	42.5	2491.7
20	484	120	42.5	2654.46
21	484	80	42.5	2324.13
23	363	80	42.5	1454.34
23	396	70	42.5	1186.18
23	435	80	42.5	1617.26
23	484	110	42.5	1877.25
24	363	60	42.5	1405.21
24	396	60	42.5	1452.28
24	544	70	42.5	1412.59
3	363	110	42.5	2529.99
3	396	110	42.5	2594.31
4	435	110	42.5	3255.81
5	396	80	42.5	1521.51
5	435	90	42.5	2884.94
5	484	80	42.5	1597.66
5	484	110	42.5	3579.33
5	544	80	42.5	1611.4
5	622	80	42.5	2360.95
8	363	120	42.5	2826.9
8	396	110	42.5	2279.42
9	396	80	42.5	1932.5
9	544	80	42.5	1683.12
10	396	70	42	2007.25
10	484	70	42	2051.44
13	435	80	42	1641.01
14	484	70	42	1555.9
15	544	70	42	2003.2
17	363	110	42	2136.88
17	396	100	42	2967.21
17	435	110	42	2917.42
17	484	100	42	2523.49
17	484	110	42	2166.21
17	622	90	42	1661.99
17	622	110	42	2369.95
18	396	80	42	2239.46
18	435	70	42	1833.95
18	622	70	42	1848.38
20	363	80	42	1671.93
20	363	90	42	2413.89

20	363	110	42	2136.88
20	363	120	42	2395.02
20	396	90	42	1556.32
20	435	70	42	1196.54
20	484	110	42	2166.21
20	544	120	42	2756.7
20	622	90	42	1661.99
20	622	110	42	2369.95
23	363	120	42	2063.12
23	396	80	42	1531.06
23	435	70	42	1196.54
23	484	120	42	2291.26
3	363	120	42	3070.12
3	396	120	42	2851.72
3	435	100	42	2179.32
3	484	110	42	2536.82
3	622	90	42	2044.08
3	622	100	42	2346.73
4	396	100	42	3166.26
4	544	120	42	3813.02
5	363	60	42	1182.59
5	396	60	42	1189.57
5	396	70	42	1494.96
5	544	90	42	2907.83
5	544	120	42	3994.93
5	622	70	42	1349.14
5	622	90	42	2922.54
5	622	110	42	3588.73
8	363	110	42	2271.69
8	396	120	42	2851.72
8	435	90	42	1872.23
8	484	110	42	2536.82
9	435	80	42	2315.53
9	484	70	42	1555.9
10	435	60	41.5	1022.22
10	484	80	41.5	2502.81
10	544	60	41.5	1131.18
13	363	80	41.5	1712.28
13	363	120	41.5	2062.94
14	484	60	41.5	1571.96
14	544	60	41.5	1591.21
14	544	70	41.5	1607.7
14	622	120	41.5	1762.83
15	435	60	41.5	1022.22
15	484	60	41.5	1022.22
15	544	60	41.5	1734.94

17	363	80	41.5	2107.95
17	363	90	41.5	2578.4
17	363	100	41.5	2735.09
17	396	90	41.5	2380.07
17	396	110	41.5	2183.14
17	435	80	41.5	2241.85
17	435	100	41.5	2468.25
17	544	90	41.5	1653.58
17	544	100	41.5	2656.38
17	544	110	41.5	2253.98
18	544	80	41.5	2305.64
20	363	100	41.5	2735.09
20	396	80	41.5	1739.99
20	396	110	41.5	2183.14
20	396	120	41.5	2358.88
20	435	100	41.5	1990.89
20	435	110	41.5	2151.98
20	484	80	41.5	1615.45
20	544	90	41.5	1653.58
20	544	100	41.5	1884.97
20	544	110	41.5	2253.98
20	622	100	41.5	2034.33
21	363	60	41.5	1504.58
21	363	70	41.5	1981.98
21	544	60	41.5	1584.09
21	544	70	41.5	1821.35
23	363	70	41.5	1137.07
23	363	100	41.5	1548.25
23	363	110	41.5	1794.73
23	396	100	41.5	1481.62
23	396	110	41.5	1846.8
23	396	120	41.5	2358.88
23	435	90	41.5	1327.65
23	435	100	41.5	1633.59
23	484	80	41.5	1615.45
23	622	90	41.5	1408.27
23	622	100	41.5	1710.75
24	484	60	41.5	1523.4
24	544	60	41.5	1584.09
3	363	100	41.5	2614.65
3	396	100	41.5	2736.75
3	435	80	41.5	2011.02
3	435	110	41.5	2515.09
3	435	120	41.5	3033.64
3	484	90	41.5	1993.98
3	484	120	41.5	3110.79

3	544	100	41.5	2254.48
4	363	100	41.5	3193.5
5	363	70	41.5	1451.36
5	484	70	41.5	1331.91
5	544	60	41.5	1131.18
5	544	70	41.5	1395.18
8	363	80	41.5	1712.28
8	363	90	41.5	1912.46
8	363	100	41.5	2396.3
8	396	90	41.5	1670.68
8	396	100	41.5	2075.44
8	435	80	41.5	1822.76
8	435	100	41.5	1941.51
8	435	110	41.5	2515.09
8	484	90	41.5	1993.98
8	484	120	41.5	2842.41
8	544	100	41.5	2254.48
8	544	120	41.5	2782.62
8	622	100	41.5	2100.02
9	363	60	41.5	1578.38
9	363	90	41.5	2620.4
9	622	70	41.5	1990.54
10	484	60	41	1080.95
10	544	70	41	2114.73
13	363	100	41	1544.12
13	396	80	41	1581.51
13	484	80	41	1708.09
13	484	100	41	2057.2
14	435	60	41	1555.86
16	363	90	41	1808.88
17	396	70	41	1845.7
17	435	90	41	1588.32
17	484	90	41	1818.59
17	544	120	41	3479.65
17	622	120	41	2061.7
18	396	90	41	2970.98
18	484	70	41	1804.61
19	363	90	41	1808.88
20	435	90	41	1588.32
20	484	90	41	1553.46
20	484	100	41	1836.08
20	622	70	41	1700.2
21	484	70	41	1804.61
23	363	60	41	1065.18
23	396	60	41	1062.17
23	435	110	41	1844.79

23	484	90	41	1293.14
23	484	100	41	1528.29
23	544	90	41	1357.2
23	544	110	41	1906.72
24	435	60	41	1523.46
3	435	90	41	2075.11
3	544	90	41	2043.95
3	544	110	41	2681.33
3	544	120	41	3041.93
3	622	110	41	2709.36
4	363	60	41	994.38
4	435	80	41	2422.14
5	435	60	41	1208.85
8	363	70	41	1635.24
8	396	80	41	1770.89
8	435	120	41	2745.34
8	484	100	41	2057.2
8	544	90	41	1823.26
8	622	110	41	2454.36
13	363	60	40.5	1157.32
13	363	70	40.5	995.78
13	396	60	40.5	1187.97
13	396	70	40.5	997.8
13	435	70	40.5	983.43
13	435	90	40.5	1175.61
13	484	90	40.5	1203.52
15	622	60	40.5	1656.17
16	363	100	40.5	2158.36
16	363	120	40.5	2583.62
16	396	100	40.5	2209.44
17	396	80	40.5	2121.58
17	435	70	40.5	1803.35
17	484	80	40.5	2223.57
17	622	80	40.5	1409.06
18	544	70	40.5	1968.7
20	363	70	40.5	1802.92
20	484	70	40.5	1220.89
20	544	70	40.5	1273.59
20	622	80	40.5	1409.06
21	484	60	40.5	1620.59
23	363	90	40.5	1266.09
23	396	90	40.5	1262.47
23	435	120	40.5	2123.09
23	484	70	40.5	1220.89
23	544	70	40.5	1096.33
23	544	120	40.5	2342.46

23	622	110	40.5	2033.27
24	622	60	40.5	1463.53
3	363	80	40.5	1858.72
3	363	90	40.5	2578.82
3	396	80	40.5	1916
3	396	90	40.5	2646.1
3	484	100	40.5	2339.45
3	622	70	40.5	1654.95
3	622	80	40.5	1652.44
4	363	90	40.5	2713.78
4	396	90	40.5	2784.45
4	435	70	40.5	2123.15
4	622	70	40.5	2105.05
5	484	60	40.5	1269.93
8	396	70	40.5	1405.34
8	435	70	40.5	1471.31
8	484	80	40.5	1868.61
8	544	110	40.5	2398.9
8	622	70	40.5	1493.37
8	622	80	40.5	1652.44
8	622	90	40.5	1478.68
9	484	60	40.5	1660.85
9	544	60	40.5	1682.69
10	622	60	40	1181.72
13	396	110	40	1702.96
13	396	120	40	1908.34
13	435	60	40	1177.71
13	435	120	40	2002.39
13	484	120	40	2016.22
16	396	90	40	1810.45
16	435	80	40	1565.87
16	435	100	40	1899.24
17	363	60	40	1493.28
17	396	60	40	1563.22
17	484	70	40	1849.6
17	544	80	40	2247.97
17	622	70	40	1856.41
18	363	90	40	2945.47
19	363	100	40	1883.81
19	435	80	40	1565.87
2	363	120	40	2768.11
2	396	100	40	2500.17
20	363	60	40	1385.77
20	396	60	40	1446.1
20	544	80	40	1338.22
21	396	60	40	1796.28

21	435	60	40	1621.96
21	622	60	40	1561.81
23	484	60	40	1083.78
23	544	60	40	1183.68
23	622	70	40	1053.73
23	622	80	40	1142.82
3	435	70	40	1605.89
3	484	80	40	2046.99
3	622	120	40	1792.6
4	363	70	40	1356.59
4	363	80	40	2392.11
5	622	60	40	1181.72
7	363	90	40	2010.22
8	363	60	40	1274.59
8	396	60	40	1521.67
8	622	120	40	1792.6
9	435	60	40	1654.9
9	544	70	40	2010.4
13	363	90	39.5	1106.81
13	484	60	39.5	1262.62
13	484	70	39.5	1098.33
13	544	60	39.5	1261.26
13	544	110	39.5	1720.78
13	622	60	39.5	1261.26
13	622	110	39.5	1720.78
14	622	60	39.5	1583.48
16	435	70	39.5	1261.73
16	484	100	39.5	1895.29
17	363	70	39.5	1915.97
17	435	60	39.5	1505.32
19	363	60	39.5	1074.46
19	363	70	39.5	1316.63
2	363	80	39.5	1800.49
2	363	90	39.5	2183.24
2	363	100	39.5	2306.62
2	396	90	39.5	1988.68
2	435	80	39.5	1866.92
2	622	100	39.5	2141.69
20	435	60	39.5	1505.32
20	622	120	39.5	1669.89
22	363	80	39.5	1283.33
23	435	60	39.5	1373.47
23	544	80	39.5	1055
23	544	100	39.5	1540.71
23	622	120	39.5	1669.89
3	363	60	39.5	1568.87

3	396	60	39.5	1608.38
3	396	70	39.5	2027.54
3	484	70	39.5	1532.84
3	544	80	39.5	2004.16
4	396	60	39.5	1139.7
4	484	60	39.5	1108.55
4	484	70	39.5	2122.4
4	484	80	39.5	2530.41
4	544	60	39.5	1138.73
7	363	100	39.5	2306.62
8	435	60	39.5	1287.34
8	484	70	39.5	1532.84
8	544	70	39.5	1549.27
13	363	110	39	1584.03
13	396	100	39	1302.12
13	435	100	39	1360.17
13	544	70	39	1140.81
13	544	100	39	1317.49
13	544	120	39	2044.69
13	622	70	39	1140.81
13	622	100	39	1317.49
13	622	120	39	2044.69
16	363	60	39	1364.07
16	363	70	39	1703.33
16	363	80	39	1499.07
16	396	60	39	1386.91
16	396	70	39	1787.63
16	396	80	39	1566.69
16	396	120	39	2579.06
16	484	90	39	1565.63
16	544	90	39	1645.61
17	484	60	39	1596.9
17	544	70	39	1782.87
18	363	70	39	1238.85
18	396	60	39	1883.23
19	363	80	39	1499.07
19	363	120	39	2127.94
19	396	60	39	1026.23
19	396	70	39	1026.3
19	396	80	39	1566.69
19	435	70	39	1041.79
19	622	70	39	1050.2
2	396	120	39	2312.9
2	435	100	39	2171.07
2	435	110	39	2387.02
2	435	120	39	2317.01

2	484	80	39	1925.86
2	484	100	39	2106.85
20	484	60	39	1467.09
20	544	60	39	1491.23
22	363	60	39	909.85
22	363	120	39	2127.94
22	396	60	39	1026.23
22	396	70	39	1026.3
22	396	80	39	1343.64
22	435	70	39	1041.79
22	435	80	39	1328.94
22	484	80	39	1447.42
22	622	70	39	1050.2
23	622	60	39	1115.11
3	363	70	39	2035.23
4	396	70	39	1353.36
4	396	80	39	2534.31
4	435	60	39	1088.46
4	544	70	39	2120.66
4	544	80	39	2633.78
7	363	80	39	1286.48
8	484	60	39	1380.81
8	544	60	39	1381.54
9	363	70	39	2044.06
9	396	60	39	1708.36
12	435	80	38.5	1285.7
13	396	90	38.5	1083.79
13	435	110	38.5	1586.17
13	484	110	38.5	1642.14
13	544	90	38.5	1286.58
13	622	90	38.5	1286.58
16	435	90	38.5	1627.42
16	435	120	38.5	2607.5
16	484	80	38.5	1636.1
16	544	60	38.5	1428.75
16	544	120	38.5	2734.32
16	622	70	38.5	1245.04
16	622	90	38.5	1698.71
17	544	60	38.5	1609.1
18	396	70	38.5	1215.92
19	396	90	38.5	1255.81
19	484	60	38.5	1184.24
19	484	80	38.5	1636.1
2	363	70	38.5	1558.57
2	363	110	38.5	1961
2	396	60	38.5	1320.27

2	396	70	38.5	1540.08
2	396	80	38.5	1774.92
2	435	70	38.5	1476.18
2	544	100	38.5	2201.64
2	544	120	38.5	2802.42
22	363	70	38.5	898.34
22	363	90	38.5	1230.42
22	396	90	38.5	1255.81
22	484	60	38.5	1008.93
3	544	70	38.5	1692.69
7	363	70	38.5	1558.57
7	396	60	38.5	1175.4
7	435	80	38.5	1476.56
9	622	60	38.5	1689.57
12	363	60	38	930.14
12	363	70	38	832.41
12	363	100	38	1309.93
12	396	60	38	826.84
16	435	60	38	1416.57
16	484	60	38	1472.19
16	484	120	38	2324.7
16	544	80	38	1696.48
17	622	60	38	1583.11
18	363	60	38	1899.49
18	435	60	38	966.57
18	484	60	38	1957.17
19	435	60	38	1048.08
19	435	120	38	2272.1
19	484	90	38	1274.4
19	484	120	38	2324.7
19	544	60	38	1118.02
19	544	70	38	1048.46
2	363	60	38	1263.38
2	484	70	38	1558.59
2	484	110	38	1935.81
2	622	70	38	1590.9
22	363	100	38	1506.69
22	435	60	38	912.6
22	435	120	38	2272.1
22	484	90	38	1274.4
22	484	120	38	2324.7
22	544	60	38	971.7
22	544	70	38	1048.46
7	363	60	38	1137.65
7	396	80	38	1448.18
7	622	70	38	1411.7

8	544	80	38	1228.66
8	622	60	38	1357.08
1	396	70	37.5	1460.64
12	363	120	37.5	1947.41
12	435	120	37.5	2002.91
12	484	120	37.5	2180.58
13	544	80	37.5	942.65
13	622	80	37.5	942.65
16	396	110	37.5	1943.5
16	484	70	37.5	1253.47
16	484	110	37.5	1966.86
16	544	70	37.5	1264.39
16	622	110	37.5	2399.66
18	544	60	37.5	1996.7
19	396	100	37.5	1558.32
19	396	110	37.5	1943.5
19	396	120	37.5	2199.14
19	484	110	37.5	1966.86
19	622	90	37.5	1417.41
2	484	60	37.5	1264.79
2	484	120	37.5	2180.58
2	544	70	37.5	1394.78
2	544	80	37.5	1942.44
20	622	60	37.5	1459.6
22	396	100	37.5	1558.32
22	396	110	37.5	1943.5
22	396	120	37.5	2199.14
3	435	60	37.5	1669.15
3	484	60	37.5	1748.44
3	544	60	37.5	1773.45
4	622	60	37.5	1778.74
7	363	120	37.5	1947.41
7	435	120	37.5	2002.91
7	484	60	37.5	1264.79
7	484	120	37.5	2180.58
7	544	60	37.5	1264.79
7	544	120	37.5	2180.58
1	363	60	37	1132.35
1	363	70	37	1398.15
1	363	90	37	1612.6
1	396	60	37	1155.62
12	363	80	37	1080.44
12	396	70	37	835.63
12	396	100	37	1311.92
12	396	120	37	1972.77
12	435	60	37	1191.75

12	435	70	37	865.32
12	484	60	37	801.75
12	484	80	37	1383.87
12	484	110	37	1631.64
12	544	60	37	891.6
16	363	110	37	1793.3
16	435	110	37	2243.43
16	622	100	37	1766.35
19	363	110	37	1793.3
19	435	100	37	1501.64
19	544	90	37	1337.39
19	544	120	37	2354.24
19	622	100	37	1766.35
2	484	90	37	1460.93
2	622	110	37	2207.72
22	363	110	37	1793.3
22	435	100	37	1501.64
22	544	90	37	1337.39
22	544	120	37	2354.24
3	622	60	37	1798.03
7	396	70	37	835.63
7	396	100	37	1311.92
7	396	120	37	1972.77
7	435	60	37	1191.75
7	435	70	37	865.32
7	484	70	37	1061.94
7	484	80	37	1383.87
7	484	110	37	1631.64
7	544	70	37	1061.94
7	544	80	37	1383.87
7	544	110	37	1631.64
1	396	90	36.5	1675
1	435	60	36.5	1180.17
12	363	90	36.5	1109.23
12	363	110	36.5	1595.58
12	396	80	36.5	1186.13
12	396	110	36.5	1751.67
12	435	100	36.5	1357.72
12	544	70	36.5	942.79
12	622	70	36.5	925.85
12	622	90	36.5	1313.43
12	622	100	36.5	1565.93
16	544	110	36.5	2248.25
16	622	80	36.5	1192.58
19	435	90	36.5	1321.97
19	484	70	36.5	994.34

19	484	100	36.5	1537.02
19	544	110	36.5	1934.29
19	622	80	36.5	1192.58
19	622	110	36.5	2069.09
2	396	110	36.5	1751.67
2	435	60	36.5	1353.13
2	435	90	36.5	1440.46
2	544	60	36.5	1445.72
2	622	90	36.5	1313.43
22	435	90	36.5	1321.97
22	484	70	36.5	994.34
22	484	100	36.5	1537.02
22	544	110	36.5	1934.29
7	363	110	36.5	1595.58
7	396	110	36.5	1751.67
7	435	100	36.5	1357.72
7	622	90	36.5	1313.43
7	622	100	36.5	1565.93
1	484	60	36	1228.94
1	544	60	36	1184.29
11	363	60	36	805.1
12	435	90	36	1142.18
12	484	70	36	878.24
12	484	90	36	1165.95
12	544	110	36	1737.37
12	544	120	36	2107.08
16	544	100	36	1601.7
18	622	60	36	2084.55
19	435	110	36	1907.56
19	544	100	36	1601.7
19	622	60	36	1130.88
2	544	90	36	1277.68
2	544	110	36	1737.37
2	622	60	36	1242.19
22	435	110	36	1907.56
22	544	100	36	1601.7
22	622	60	36	944.88
22	622	100	36	1446.5
6	363	60	36	805.1
6	363	90	36	1396.85
7	435	90	36	1142.18
7	435	110	36	1701.01
7	484	90	36	1165.95
7	544	90	36	1165.95
7	622	60	36	1242.19
1	363	100	35.5	1687.7

12	396	90	35.5	1152.91
12	435	110	35.5	1382.6
12	484	100	35.5	1320.71
12	544	90	35.5	1000.26
12	544	100	35.5	1356.69
12	622	110	35.5	1887
16	622	60	35.5	1497.19
16	622	120	35.5	1701.89
19	622	120	35.5	1701.89
2	622	80	35.5	1272.09
22	484	110	35.5	1640.55
6	363	100	35.5	1687.7
7	396	90	35.5	1152.91
7	484	100	35.5	1320.71
7	544	100	35.5	1320.71
7	622	110	35.5	1887
1	363	120	35	1955.8
1	396	100	35	1792.81
11	396	60	35	772.29
12	622	60	35	849.83
12	622	80	35	999.86
19	544	80	35	1145.09
6	363	70	35	1033.93
6	396	60	35	772.29
7	622	80	35	999.86
1	363	80	34.5	1140.43
1	363	110	34.5	1621.64
1	396	110	34.5	1711.79
1	484	110	34.5	1770.34
1	484	120	34.5	2142.11
11	484	60	34.5	872.92
6	363	80	34.5	1140.43
6	396	70	34.5	893.02
6	484	60	34.5	872.92
1	396	120	34	1986.29
1	435	70	34	877.12
1	435	80	34	1257.33
1	435	90	34	1175.26
1	435	120	34	2126.36
1	622	100	34	1555.92
11	363	80	34	885.13
11	435	60	34	797.97
11	435	80	34	1040.43
11	544	60	34	839.96
2	622	120	34	1498.66
22	622	110	34	1227.32

6	396	90	34	1155.36
6	396	120	34	1986.29
6	435	60	34	797.97
6	435	70	34	877.12
6	435	80	34	1257.33
6	544	60	34	839.96
6	622	100	34	1555.92
7	622	120	34	1498.66
1	396	80	33.5	1195.92
1	435	100	33.5	1416.66
1	435	110	33.5	1825.74
1	484	80	33.5	1353.3
1	484	90	33.5	1244.67
1	484	100	33.5	1326.36
1	544	80	33.5	1423.33
1	544	90	33.5	1231.28
1	544	100	33.5	1411.39
1	544	110	33.5	1799.79
1	622	60	33.5	1259.59
1	622	70	33.5	986.54
11	363	100	33.5	1055.14
11	363	120	33.5	1562.76
11	396	70	33.5	602.66
11	435	70	33.5	612.9
11	435	120	33.5	1769.62
11	484	80	33.5	1105.9
12	544	80	33.5	985.44
22	622	90	33.5	874.54
6	363	120	33.5	1562.76
6	396	80	33.5	1195.92
6	435	100	33.5	1416.66
6	435	120	33.5	1769.62
6	484	80	33.5	1353.3
6	484	100	33.5	1326.36
6	544	90	33.5	1231.28
6	622	70	33.5	986.54
1	484	70	33	865.11
1	544	120	33	2182.54
1	622	90	33	1304.69
1	622	110	33	1855.33
11	363	70	33	542.92
11	363	110	33	1244.93
11	396	80	33	948.72
11	396	120	33	1597.43
11	435	90	33	847.58
11	484	110	33	1439.31

11	622	70	33	692.23
6	363	110	33	1244.93
6	435	90	33	847.58
6	484	70	33	865.11
6	484	110	33	1439.31
6	622	110	33	1855.33
1	544	70	32.5	921.74
11	363	90	32.5	819.26
11	396	110	32.5	1326.19
11	484	70	32.5	595.31
11	484	90	32.5	894.85
11	484	120	32.5	1755.23
11	544	110	32.5	1414.63
22	622	80	32.5	636.96
6	396	110	32.5	1326.19
6	484	90	32.5	894.85
6	484	120	32.5	1755.23
6	544	70	32.5	921.74
6	544	110	32.5	1414.63
11	396	90	32	762.75
11	396	100	32	1044.38
11	435	100	32	1053.41
11	435	110	32	1426.64
11	484	100	32	965.32
11	622	100	32	1197.53
22	544	80	32	659.6
6	396	100	32	1044.38
6	435	110	32	1426.64
6	622	60	32	866.8
6	622	90	32	983.75
1	622	80	31.5	1062.2
11	544	70	31.5	647.81
12	622	120	31.5	1052.47
1	622	120	31	1541.87
11	544	90	31	856.11
11	544	120	31	1772.91
11	622	60	31	638.71
6	544	120	31	1772.91
11	544	100	30.5	1062.06
6	544	100	30.5	1062.06
22	622	120	30	898.19
6	544	80	30	703.06
6	622	80	30	745.95
11	622	90	29	785.47
6	622	120	29	1067.06
11	622	110	28.5	1089.19

11	622	80	27	526.75
11	622	120	26.5	792.69
11	544	80	26	562.56

Appendix B: Loblolly Pine stands with associated thins

Stand	Game Land	Site Index	P1TH1	P1TH2	P1TH3	P2TH1	P2TH2	P2TH3	P3TH1	P3TH2	P3TH3	TH1	TH2	TH3
20017096	Butner-Falls of Neuse	95			Yes						Yes	Yes	Yes	Yes
20017164	Butner-Falls of Neuse	95										Yes	Yes	Yes
20017304	Butner-Falls of Neuse	95												
20017470	Butner-Falls of Neuse	80			Yes						Yes	Yes	Yes	Yes
20018396	Caswell	90			Yes						Yes	Yes	Yes	Yes
20018418	Caswell	95									Yes	Yes		
20018448	Caswell	105			Yes						Yes	Yes	Yes	Yes
20018493	Caswell	80			Yes						Yes	Yes	Yes	Yes
20018494	Caswell	100			Yes						Yes	Yes	Yes	Yes
20018636	Caswell	100										Yes	Yes	Yes
20018824	Caswell	70										Yes	Yes	
20019010	Embro	125			Yes						Yes	Yes	Yes	Yes
20019015	Embro	105			Yes						Yes	Yes	Yes	Yes

20019030	Embro	90	Yes	Yes	Yes	Yes	Yes
20019069	Embro	90	Yes	Yes	Yes	Yes	Yes
20019114	Embro	115	Yes	Yes	Yes	Yes	Yes
20019126	Embro	95	Yes	Yes	Yes	Yes	Yes
20020299	Jordan	85			Yes	Yes	Yes
20020511	Jordan	90	Yes	Yes	Yes	Yes	Yes
20025005	Sandy Creek	90	Yes	Yes	Yes	Yes	Yes
20025007	Sandy Creek	110	Yes	Yes	Yes	Yes	Yes
30011062	Angola Bay	125	Yes	Yes	Yes	Yes	Yes
30011075	Angola Bay	125	Yes	Yes	Yes	Yes	Yes
30011082	Angola Bay	115	Yes	Yes	Yes	Yes	Yes
30011117	Angola Bay	120	Yes	Yes	Yes	Yes	Yes
30012019	Bertie	100	Yes	Yes	Yes	Yes	Yes
30012025	Bertie	100	Yes	Yes	Yes	Yes	Yes
30012033	Bertie	100	Yes	Yes	Yes	Yes	Yes
30012044	Bertie	85	Yes	Yes	Yes	Yes	Yes
30012050	Bertie	95	Yes	Yes	Yes	Yes	Yes
30014004	Carteret County	75	Yes	Yes	Yes	Yes	Yes

30014005	Carteret County	70	Yes	Yes	Yes	Yes	Yes
30014007	Carteret County	80	Yes	Yes	Yes	Yes	Yes
30015032	Chowan Swamp	125	Yes	Yes	Yes	Yes	Yes
30015162	Chowan Swamp	95	Yes	Yes	Yes	Yes	Yes
30015240	Chowan Swamp	90	Yes	Yes	Yes	Yes	Yes
30015322	Chowan Swamp	115	Yes	Yes	Yes	Yes	Yes
30020115	Juniper Creek	110	Yes	Yes	Yes	Yes	Yes
30020173	Juniper Creek	90	Yes	Yes	Yes	Yes	Yes
30020193	Juniper Creek	110	Yes	Yes	Yes	Yes	Yes
30020213	Juniper Creek	115	Yes	Yes	Yes	Yes	Yes
30020297	Juniper Creek	115	Yes	Yes	Yes	Yes	Yes
30020169	Juniper Creek	90	Yes	Yes	Yes	Yes	Yes
30023014	Rocky Run	95	Yes	Yes	Yes	Yes	Yes
30023015	Rocky Run	70	Yes	Yes	Yes	Yes	Yes
30023017	Rocky Run	75	Yes	Yes	Yes	Yes	Yes
30025222	Suggs Mill Pond	105	Yes	Yes	Yes	Yes	Yes
30026015	Van Swamp	115	Yes	Yes	Yes	Yes	Yes
30026018	Van Swamp	110	Yes	Yes	Yes	Yes	Yes

30026034	Van Swamp	110	Yes	Yes	Yes	Yes	Yes
30026057	Van Swamp	125	Yes	Yes	Yes	Yes	Yes
30026066	Van Swamp	110	Yes	Yes	Yes	Yes	Yes
30026082	Van Swamp	110	Yes	Yes	Yes	Yes	Yes
30026093	Van Swamp	115	Yes	Yes	Yes	Yes	Yes
30028004	Whitehall Plantation	100	Yes	Yes	Yes	Yes	Yes
30028005	Whitehall Plantation	95	Yes	Yes	Yes	Yes	Yes