ABSTRACT

WEBB, JACKSON TODD- A case study cost benefit analysis of deferred harvesting for an industrial loblolly pine plantation in eastern North Carolina. (Under the Direction of Dr. John King and Dr. Maricar Aguilos),

The use of deferred harvesting as a climate-smart forestry practice has been utilized to increase amounts of carbon dioxide stored within terrestrial forests, offsetting fossil fuel CO_2 emissions. Deferred harvesting is able to increase carbon storage through “deferring” or pushing back the age of harvest thus increasing the amount of time the forest has to store carbon dioxide (Carino & Biblis, 2002). As a widely used species throughout southeastern U.S forestry plantations, understanding the potential gains from deferring the harvest of loblolly pine is important to quantifying the environmental and ecological costs and benefits of this practice.

In this study, I modeled the biomass biomass accumulation (Mg/ha) of an industrial loblolly pine plantation located in Washington County, NC, using LobDSS to simulate deferring the age of harvest from 29 to 50 years of age, in 5-year increments. Over the course of the deferral period, aboveground biomass continuously increased over multiple management practice scenarios. To quantify potential economic benefits from engaging in a deferral program, breakeven carbon price and derived revenues were calculated. Derived values were compared to values calculated utilizing a range of real-world carbon prices. Breakeven carbon prices across multiple management scenarios ranged from less that \$1 to slightly more than \$3, but all remained considerably less than real world values. Additionally, landowner benefits increased through participation within offset programs, with correspondingly higher benefits when discount rates are lower than when they are heightened. While this study demonstrates potential benefits from landowner participation in deferred harvesting and carbon offset markets, additional research is needed to quantify these dynamics within Southeastern forest systems.

A case study of cost benefit analysis of deferred harvesting of an industrial loblolly pine plantation in eastern North Carolina

by
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DEDICATION

I dedicate this thesis to all my teachers, family, and friends: their knowledge and advocacy have given me the chance to pursue this research.

BIOGRAPHY

Jackson Todd Webb was born on June 19th, 2002 in Atlanta, GA to Elizabeth and Todd Webb. After getting his B.S in Ecology and Evolutionary Biology from Sewanee: The University of the South in 2023, Jackson pursued a M.S program in Forestry at North Carolina State University. While at NC State University, Jackson worked within the Tree Physiology and Ecosystem Science Lab group and was a Graduate Teaching Assistant for the College of Natural Resources. In his Master’s thesis, he focused on the effects of carbon offset markets on forest management scenarios in North Carolina.

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CHAPTER 1- Literature review on southern forest plantation management impact on carbon storage and economic implications

1. Introduction

The purpose of this literature review is to summarize and synthesize the current body of knowledge regarding the carbon storage dynamics of industrial loblolly pine (*Pinus taeda*) plantations in the coastal plain region of North Carolina, as well as the impact that the implementation that deferred harvesting may have on those dynamics. This review covers the topics of loblolly pine silviculture, carbon storage, forest carbon modeling, forest management, deferred harvesting, and carbon offset markets. Due to the increase in atmospheric carbon and the large potential for forest carbon storage within the southeastern United States, these topics are critical in understanding the future role the Southeast can play in climate change strategies.

My study sought to assess and quantify the aboveground carbon stored within the loblolly pine plantation present at Parker Tract, North Carolina, a coastal plain site that has been utilized for industrial pine plantations for several rotations. Industrial forest plantation prevalence throughout both North Carolina and the Southeast at large amplifies the degree to which research into the carbon storage potentials need to be studied. I modeled rotation length of loblolly pine at this site extended in five-year increments from the baseline length of 29 years towards the upper bound of 50 years, to quantify potential carbon storage levels at this site. This use of extended rotation lengths to increase the carbon stored within a forested area is known as deferred harvesting. This was conducted with the Loblolly Decision Support System (LobDSS), a forest growth and yield model for forest management (Amateis et al., 2001). LobDSS utilizes growth and yield equations for loblolly pine, in addition to both input site-specific characteristics and economic parameters such as timber product pricing, to simulate a rotation of loblolly pine based on these inputs. I then compared these biomass figures to observed biomass at Parker Tract to determine their validity. From these biomass figures, allometric equations were used to determine carbon stored in biomass.

Once carbon storage potential was determined, the economic impacts of this practice were analyzed. These were conducted through a cost-benefit analysis of the implementation of a deferred harvesting program funded through a voluntary carbon offset program. Benefits (revenue from harvesting timber products based on local timber product pricing as well as benefits from carbon offset payments) and costs (management and harvesting costs) were totaled for each of the 5-year increments between the baseline and year 50 to determine the optimal year in which to harvest to maximize revenue. This was conducted over multiple different site indicess, carbon pricing plans, and discount rates. My goal was to quantify the effects different economic factors can have on the implementation of a deferred harvesting program for industrial loblolly pine plantations. This study can assist landowners in making informed decisions regarding implementation of a deferred harvesting program for their land. Additionally, this study can serve as a baseline in which other studies can build on to quantify the implementation of deferred harvesting for other types of plantation forests under different economic conditions.

1.1 Forest land carbon storage and importance under heightened atmospheric carbon levels

Due to forested areas being natural ecosystems with high carbon dioxide absorption potential, these areas have been seen as critical towards supporting climate mitigation efforts. Carbon dioxide, an essential chemical building block necessary for the growth of loblolly pine, is stored throughout the stem, branches, and foliage of the tree as an integral makeup of its biomass. In addition to carbon dioxide making up a large part of the biomass of the tree, carbon dioxide plays an integral role in the photosynthetic process. At face value, an increased amount of atmospheric carbon would seem to be heavily beneficial to the growth rate of tree species, as an increased amount of atmospheric carbon means an increased amount of potential carbon for tree species to absorb in photosynthesis. However, this increase in available carbon for uptake is offset by the other effects of atmospheric carbon accumulation, such as increased global temperatures initiating stomatal closure (Slot et al., 2024). These heightened temperatures interfere with the tree's ability to conduct photosynthesis, therefore decreasing the ability for trees to grow, thus creating a feedback loop in which less carbon dioxide is stored within forested areas, causing more to be emitted into the atmosphere, leading to a further increase in global temperatures. Therefore, while climate change may increase total atmospheric carbon dioxide, boosting one aspect contributing to growth within tree species, this is offset by the other effects of climate change, creating a net decrease in the ability for forested areas to store carbon-dioxide, and more forested areas becoming carbon sources instead of carbon sinks.

A forest carbon sink is defined as a forested area that absorbs more carbon than it emits. Through the natural carbon cycling system that forested areas play a large part in, forests can act as a carbon sink, storing approximately 69% of terrestrial carbon (Hou et al., 2020). Not all the carbon stored in terrestrial systems is within the trees or aboveground. The majority of carbon stored within forested areas is stored belowground, however forest management can impact this carbon storage through management practices such as removing tree roots during site preparation or turning soil during harvesting (Gough & Seiler, 2004; G. G. Wang et al., 2012). This study has focused on aboveground carbon storage, however future studies examining belowground carbon dynamics would be useful in optimizing forest management in favor of increasing forest carbon.

Forested areas require large amounts of carbon dioxide uptake to grow and photosynthesize, however forests at the time of their establishment are more likely to be a net source of carbon, as the trees have not yet grown large enough to absorb enough carbon to offset the output by the ecosystem (Aguilos et al., 2022). Conversely, as the growth of trees begins to plateau into their maturity and become “old growth” their rate of absorption of carbon dioxide decreases. Therefore, while these aboveground old growth forested areas are important in terms of storing carbon dioxide for long periods of time, additional carbon dioxide from the atmosphere is not being absorbed, leading to the ecosystem becoming a net carbon source once again. This underscores the importance of forest management and rotation lengths in support of carbon management.

1.2 Impacts of forest management on carbon storage

Forest management practices can greatly impact the carbon storage dynamics within a forested area. Utilizing techniques such as strategic harvesting, thinning, altering rotation lengths, and genetic improvement of tree species has proven effective in increasing carbon stored as opposed to stands that experienced natural growth (Daigneault et al., 2022; Kolo et al., 2020). Additionally, when comparing the effects of forest management practices on stored carbon stocks between baseline management scenarios reflecting current management practices and management scenarios utilizing strategic increases of rotation lengths, the stands which utilized longer rotation lengths showed considerably higher carbon storage levels (Nunery & Keeton, 2010). Increasing knowledge regarding the effects of genotype choice by forest managers can be utilized to better manage forest carbon pools.

Loblolly pine, a species whose long-term growth and yield dynamics under a variety of site characteristics are well understood, stands out as an ideal species for forest carbon management. Typically, planted loblolly pine rotation lengths range from 20-30 years, depending largely on the type of timber product that the harvested timber will be utilized for (Maynor et al., 2021). This typical rotation period ends considerably before full maturity is reached by the tree, meaning that there is additional potential for growth at the time of harvest. Maturity for loblolly pines is reached around 50 years, so harvested trees could have from 20-30 additional years left of growth and carbon storage (USDA Forest Service, 1929). The effects of thinning, however, are not as well understood in the context of loblolly pine carbon storage, as thinning's effect on carbon storage is largely dependent on other site factors such as soil quality and other management decisions (Gonzalez-Benecke et al., 2011). Additionally, differing genotypes of loblolly pine have demonstrated additional carbon storage potential when compared to the currently utilized genotype within the majority of plantation forestry (Aspinwall et al., 2013). Therefore, due to the body of knowledge regarding the effects of management on loblolly pine, as well as its prevalence throughout the Southeast as a plantation crop, it stands out as a species well-suited for forest carbon management strategies.

1.3 Impacts, utilization, and costs of deferred harvesting

The majority of large acre private forested areas within the United States are planted and managed with the purpose of harvest ("Forest Ownership Statistics," 2012). While these harvested forests are critical in supplying the raw materials for forest product markets, the presence of harvesting within their current management regime limits their carbon storage potential. While harvesting can be critical in replacing old growth stands with diminished capacity to absorb carbon with younger stands with higher long-term carbon storage potential, the short-term effects of harvesting result in net carbon emissions (Gundersen et al., 2021; Luyssaert et al., 2008). In addition to emitting carbon at the time of harvest, young stands are unable to convert the carbon dynamics from a source to a sink for several years after stand establishment (Aguilos et al., 2022). Therefore, utilization of deferred harvesting serves as a “compromise” option to gain the benefits of both harvesting and non-harvesting options.

Deferred harvesting, instead of eliminating the use of harvesting, “defers” the harvest to increase rotation length, therefore increasing the amount of carbon stored in the additional time between the original harvest age and the deferred age (Carino & Biblis, 2002). Theoretically, the use of deferred harvesting addresses both issues identified with harvesting, as additional carbon is stored within forested areas for increased amounts of time, and timber materials are still gained. Additionally, emissions output by equipment utilized in harvesting are also deferred through deferring harvest.

However, there are several issues with deferred harvesting that prevents it from currently being widespread in its usage. First, to be effective in its stated goal of increasing storage, the additional rotation length added must store more carbon than the baseline rotation length. As specific site productivity strongly influences the carbon storage potential and rates of forested areas over time, deferred harvesting will vary both in its effectiveness and length for different scenarios (Puls et al., 2024). Second, as deferring harvest also defers the benefits for the landowner at the sale of harvested material, possibly to a less-advantageous time for the timber market (Baker et al., 2010). This can serve as a barrier for landowners who are dependent on historical rotation lengths for payments as their primary source of income, as well as increasing landowner certainty towards their benefits. Third, this can create a market-wide issue of demand shocks within the timber market, deferring the current supply of forest products, thus lowering the supply in the short term (Rossi et al., 2023). Therefore, while deferred harvesting can be an important tool to assist forest managers towards increasing carbon storage, its utilization is scenario dependent.

1.4 Use of carbon markets and carbon offsetting in support of deferred harvesting

To address the barriers to implementation inherent in deferred harvesting, the use of carbon offset programs serves as a useful financial framework in order to increase landowners' likelihood of participation. Carbon offset programs offer a solution through creating a framework linking net emitters to landowners engaging in pro-environmental behaviors, where the net emitter pays the landowner to continue engaging in their behavior, where that behavior “offsets” the carbon emissions emitted (van Kooten & Johnston, 2016). This framework and payments are maintained by third parties that oversee and verify the legitimacy of these behaviors, and their offsetting of emissions. This need for verification of offsetting measures underpins the relative success of each of these projects, as if additional carbon is not being stored, then all that is occurring is a payment from emitters to landowners with no tangible result. Therefore, the three metrics of additionality, permanence, and leakage are used in order to verify the legitimacy of carbon offset programs (Tahvonen & Rautiainen, 2017). Hypothetically, these markets serve as a win for all parties involved, as atmospheric carbon decreases, landowners generate more revenue when compared to their baseline, and emitters claim fewer overall emissions compared to their baseline.

Within forested ecosystems, the use of carbon offset programs in support of deferred harvesting has yielded largely positive results both in terms of increasing terrestrial carbon storage and landowner revenue (Mei, 2023a), however programs can be limited in their effectiveness due to macroeconomic drivers such as price (of both timber and carbon), land prices, and landowner willingness to engage with these markets (Kilgore et al., 2007; Mei, 2023b). As one of the most common forms of carbon pricing, the social cost of carbon bases the price of a ton of carbon on the abatement cost of that ton of carbon from entering the atmosphere (Hickey, 2023; Zhen et al., 2018). Therefore, as atmospheric carbon increases and the effects of increasing carbon dioxide in the atmosphere are more pronounced, the cost of this abatement increases over time, in turn increasing the price of carbon being stored.

In a vacuum, this is ideal for the growth of carbon markets, as this increases the return in value for landowners engaging with these markets, however abatement prices are balanced against the tumultuous prices of timber and land, as well as the specific management intentions of individual landowners. Alternative landowner strategies such as shorter or even baseline rotation lengths have relatively "shorter" returns as opposed to carbon markets (as deferral periods can range from 5-50 years) and therefore benefit from decreased risk for the landowner as well as decreased time until payment. For landowners whose entire revenue stream depends on a set rotation length, adding additional time until payment, even if marginal, can greatly harm them financially. Due to the quicker turnaround on the benefits for the landowner, these plans can be perceived by landowners as less "risky" then the deferred harvesting (Markowski-Lindsay et al., 2011). From the landowner's perspective adding ten additional years to the rotation adds ten additional years for incurring management costs, while also adding ten additional changes for timber prices to decrease (Layton & Siikamäki, 2009). Deferring harvesting additionally increases risks of loss of timber revenue through events such as fire, disease, or pests. When compared to the baseline management strategies implemented by forested landowners, the economic benefits of deferred harvesting have showed limited effectiveness in increasing landowner enrollment in these programs (Dickinson et al., 2012; Mathur et al., 2014).

1.5 State of carbon markets within United States

Within the United States, the usage of carbon offset markets has been and continues to be relatively decentralized, with little oversight from governmental institutions, however recent statewide and regional programs have effectively implemented these programs to great economic and environmental gain. The implementation of mandatory governmental programs both regulating and subsidizing the use of offset markets is a crucial prerequisite for these markets to be successful (Mei, 2023b). While Voluntary Carbon Markets (VCMs) can function without the presence of governmental programs supporting it, governmental programs have several benefits. First, these government programs can assist in verification that these programs are fulfilling the needed requirements of additionality, permanence, and leakage. While non-governmental organizations such as Verra specialize in this verification, the involvement of governmental institutions provides an additional degree of transparency towards the effectiveness of each program, as otherwise these programs can be “black boxes” where money changes hands between parties and the relative impact of a program is unknown (Siddique et al., 2024). Second, government involvement brings with it economic incentives such as subsidies, which can be critical in generating additional landowner benefits (Lederer, 2012). Third, institutions can help manually alter the price of carbon, preventing it from sudden shifts or shocks that may destabilize the program in its entirety, which can be seen with the example of the state of Washington’s carbon program (Pest, 2024).

Currently, no national carbon offset programs exist within the U.S, however participation in VCMs are numerous, as the implementation of these programs have proved vital in assisting in reducing statewide emissions. The largest example of this is California, which implemented a Cap and Trade system in 2013, that has reportedly assisted in the state decreasing its overall emissions since its implementation (“California Cap and Trade,” n.d.). This system, similar to programs implemented by the E.U and Quebec, creates a “cap” for carbon that can be emitted per carbon emitter, and allows emitters to “trade” carbon credits to offset their emissions, therefore decreasing their net emissions through funding pro-environmental behavior. This program serves as a cornerstone of California’s ambitious emissions reduction plan to reduce emissions to 40% below 1990 levels before 2030. However critics have noted that the program’s lack the ability to take into account the additional emissions occurring elsewhere due to emitters relocating the geographic location of their emissions (Bartram et al., 2022). The presence of leakage within this system speaks to both the barriers to effectiveness that face statewide, or regional carbon programs, as well as the need for larger, more robust programs that would be able to track and regulate this leakage.

The implementation of a national carbon program has faltered over the last decade. While implementation of carbon programs has largely been at the state level, eleven Northeastern states (and Pennsylvania as a participating member) joined together in 2005 to create the Regional Greenhouse Gas Initiative (RGGI) in order to promote environmental regulation and a shared carbon market between member states (“Regional Greenhouse Gas Initiative (RGGI),” n.d.). The RGGI has reported a net profit of $ 4.7 billion over the course of the program. While there have been talks about other states joining the initiative, little serious progress has been made in expanding other than adding Pennsylvania as an official member. The largest exception to this has been the RGGI’s potential expansion into the Southeastern United States, where the Virginia provides an opportunity to expand into this highly forested region.

1.6 Carbon markets within the state of North Carolina

In May of 2023, legislation that would lead to the formation of a state carbon offset program in North Carolina was rejected. Support for the formation of an offset trading program in North Carolina had been strong since 2021; however the legislation did not pass. This legislation would also have linked the prospective program to the Regional Greenhouse Gas Initiative (RGGI), which is an interstate cap-and-trade program specifically designed for offsets within the power sector (*USA - Regional Greenhouse Gas Initiative (RGGI) | International Carbon Action Partnership*, 2021). By planning to link up with the RGGI at the start of the program, North Carolina seemingly anticipated Washington's eventual link with the Western Climate Initiative, so the price of carbon within the power offset sector likely would not have ballooned due to external states within the Initiative keeping the price grounded. However, even with this price control measure, why would the formation not pass? While the failure of this legislation is recent and there has not been a plethora of research regarding the exact reasons for the failure of the legislation in North Carolina. A failure within offsets for another sector of North Carolina's economy may have planted this distrust.

The forestry sector of North Carolina is large, with the vast majority of forested land within the state being privately owned and managed (*NC_2021_FIA_Factsheet.Pdf*, 2021). Because of this, forest carbon offsetting through the Voluntary market within the state (as well as much of the forested South) had become highly popular, with one of the most valuable firms for brokering credits being NCX. NCX introduced a new methodology of accounting for these credits, by allowing for deferrals of harvesting annually, instead of other contracts that would have much longer deferral periods (Vanderschaaf, 2023). By lowering the barrier to entry to an annual commitment NCX was able to quickly become one of the most profitable offsetting firms. However, due to this "unorthodox" system of accounting for offsets, refused to verify NCX's accounting system due to a lack of provable additionality due to annual contracts. This led to a massive decrease in NCX's value, with opposition to offset markets seeing this as another case of offset brokers selling credits for unverifiable offsets that would actively hinder climate smart forestry efforts by promising emissions reductions when none may occur. Verra's lack of verification of NCX's in-house carbon accounting system put their offset structure into doubt, and few within the carbon offset sector wanted to work with an unverified firm. While NCX was not an organization based in North Carolina, the state's heavy reliance on the forest products industry certainly led to many North Carolinian eyes being on NCX during their fall. Additionally, the lack of verification for NCX's accounting system, while being the actual reason for NCX's loss in value, was not seen as the reason by large swaths of the public, who instead saw NCX as another venture capitalist bubble. In short, there were certainly many possible reasons for the failure of the institution of an offsetting program in North Carolina, with one of them possibly being the failure of NCX.

This perceived "failure" of NCX, while creating a barrier to the creation of a statewide carbon market, was unable to end the momentum of VCMs within the state. Several other carbon accounting companies such as Bluesource, Finite Carbon, and Forest Carbon Works, have been successful in establishing VCM programs with forested landowners. These VCMs primarily are utilized by forest landowners with smaller acreage size, typically family or non-corporate owned, as the majority of forest land within the state is owned by this demographic (*About NC Forest Products*, n.d.). While participation within this demographic of landowners is crucial to increasing carbon stored, assessing the effects of deferred harvesting and carbon offset programs in the context of larger, industrial landowners is critical to promoting climate smart forestry practices.

1.7 Gaps in current literature

The current body of literature relating to industrial loblolly pine plantations, carbon offset programs, and the use of deferred harvesting in support of carbon storage is robust, however limited in the examination of the interactions between these concepts. Specifically, there is a lack of case studies examining these questions. This is largely due to the lack of long-term (ages 30-50) growth and yield measurements for planted loblolly pine. While this study combines both measured and modeled data to gain a precise model of carbon storage dynamics, sites that lack a robust set of measurements largely must rely on growth and yield models as well as allometric equations to determine carbon stored. Therefore, studies comparing long-term datasets for loblolly pine with growth and yield models are crucial to expanding the current body of knowledge. Additionally, better refining forest carbon models is critical to determining the effectiveness of carbon management programs, therefore improving growth and yield models to better represent carbon storage is needed (H.-J. Wang et al., 2012). While this study seeks to fill these gaps, this case study is limited in its scope, both geographically and ecologically, as only one site with one species is considered. A greater number of case studies would provide a greater amount of data to better inform forest carbon management practices moving forward.

CHAPTER 2- Case study of the impacts of deferred harvesting on long-term carbon biomass storage within an industrial loblolly pine plantation

2.1 Introduction

In response to increasing atmospheric carbon dioxide levels over the past century, forest-based climate mitigation strategies are in high demand, especially those that do not negatively impact the market for forest products (Baker et al., 2010; Puls et al., 2024). Thus, finding forest-based management strategies that fit the needs of forest managers from both environmental and economic perspectives is crucial. One of the proposed management strategies to meet these management goals has been that of deferred harvesting, which has been shown to have the potential to increase amounts of carbon dioxide accumulated into forested areas (Carino & Biblis, 2002). This higher potential for carbon accumulation is due to the increased length of rotation in between harvests, "deferring" harvest until a stand has accumulated additional carbon exceeding the baseline rotation length.

The length of the deferral period required to accumulate additional carbon dioxide, however, is dependent on several factors that each impact the growth rates of trees (Birdsey et al., 2023; Xie et al., 2023). In order to determine the optimum rotation length for additionality, managers need to both understand and quantify these factors, as well as have effective and accurate methods of modeling growth rates (H.-J. Wang et al., 2012). Forest growth models vary in terms of scale (spatial and temporal), preference towards determining factors of growth, species, and output, as well as their varying levels of uncertainty (Harmon, 2001; Smith & Heath, 2022).

Within the context of North Carolina forest managers, the Forest Productivity Cooperative's (FPC) Loblolly Decision Support System (LobDSS) serves as one of the most widely used growth and yield prediction models for loblolly pine, the most common Southeastern plantation forestry species (Peay et al., 2022).

LobDSS is a stand-simulator model built around the FASTLOB 3.1 growth and yield model developed by Virginia Tech's Forest Productivity Cooperative (Amateis et al., 2001). LobDSS utilizes user input factors to determine growth and yield over time, with outputs including metrics needed for long-term forest management, such as aboveground biomass by year. This aboveground biomass output is highly important. While LobDSS itself does not have the feature of simulating carbon dioxide content present in stands, the use of allometric equations to determine the carbon content based on biomass estimations allows for the use of LobDSS for simulating forest growth and yield for management for both timber production and carbon (Gonzalez-Benecke et al., 2011; Kim et al., 2020).

These models can be run for up to rotations of 50 years, longer than the usual plantation rotation length of loblolly pine within the coastal plain of North Carolina, which is typically closer to 25-year rotations, with variation occurring due to specific management goals requiring shorter or longer rotations (Albaugh et al., 2012; Maynor et al., 2021). Loblolly pine possesses the potential to continue growing well after this age, with this harvest age being chosen due to financial constraints on the forest manager, however the potential for growth to persist for each individual tree is dependent on site specific factors (Chappelle & Nelson, 1964). A study examining the forest carbon dynamics of long-rotation loblolly pine plantations is required to determine the potential benefits of deferred harvesting within this context. This study has sought to quantify the carbon dioxide accumulation over a 50-year period within an industrial loblolly pine plantation located within North Carolina's coastal plains.

2.2 Objectives and hypothesis

In this study, I investigated the accumulation of aboveground biomass within an industrial loblolly pine plantation located in the coastal plain region of North Carolina utilizing LobDSS to simulate growth rates over an extended rotation period. These models were calibrated to observe aboveground biomass measurements taken at the study site over a 27-year period. This study will be utilized to inform North Carolina forest managers of alternative management strategies to current baseline strategies, especially in the cases in which managers are managing in favor of climate mitigation.

The driving question for the study was will the increase in carbon dioxide stored in aboveground biomass due to deferred harvesting continuously increase through the deferral period or will it “level off” or plateau over time? To address this question, I hypothesize that the above-ground biomass will continuously increase over the deferral period, leading to a continuous increase in carbon stored within this stand.

2.3 Methods

2.3.1 Study site

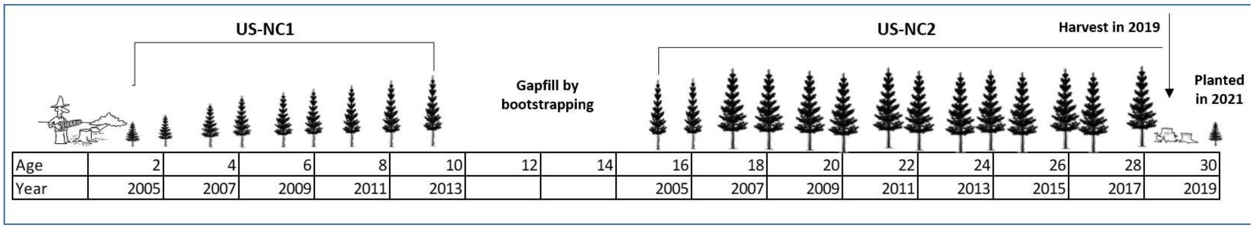
The study site for this experiment is located at the Parker Tract loblolly pine plantation located on the North Carolina coastal plain, with the nearest municipality being Plymouth, Washington County, NC, USA (35°48'32"N 76°40'41"W, Figure 1). This site is an operationally historically managed loblolly pine plantation, with plantation forestry being the dominant use of the site for many decades. The areas consists of a flat, loamy soil with poor drainage and an elevation of 8 m above sea level (Middleton et al., 2017). This site is currently managed by Weyerhaeuser Co. in collaboration with NC State University, and the US Forest Service, with many of the site improvements (such as drainage, canals, and regular management) being provided by these organizations. Similarly, historic measurements of forest growth, water vapor, and flux tower monitoring of atmospheric carbon dioxide have been gathered at this site for more than 30 years.

This site has been managed by Weyerhaeuser for the purpose of industrial loblolly pine plantation production since the acquisition of the site. Therefore, our dataset reflects management practices commonly practiced by forest managers. As this is a poorly drained coastal plain site. Bedding, weed control, phosphorus fertilization, and hardwood control were implemented at planting. Elemental nitrogen fertilization of 150 lbs/acre occurred at age 15 with additional phosphorus treatments occurring at this same time. Additionally, thinning at age 19, which will be reflected in all experimental treatments.

Figure 1. Aerial photograph taken of Parker Tract, Washington County, NC. Photo taken using Google Earth at the coordinates 35°48'32"N 76°40'41". Yellow line reflects borders of Parker Tract, where everything within is considered within the study site. Google Earth was accessed on 2/15/2025. Photograph does not reflect the state of the site when measurements were taken.

2.3.2 Vegetation data

Biometric data used to create a baseline management scenario of the conditions at Parker Tract, NC were gathered over a 27-year period. Data gathering methods were summarized in (Aguilos et al., 2020), with the same measurements of age (years), height, (m), and dbh (cm) being used within this study. Vegetation plots were measured using 13 plots of 7-meter radiuses that were randomly chosen within the footprint of the flux tower present at Parker Tract. Plots were measured yearly to construct the long-term dataset. Chrono-sequencing was utilized to determine the growth dynamics throughout years 2-27 of the 29-year long rotation (Figure 2). Years 0-2 and 28 and 29 were not measured within the original study was not measured for biometric data. Two study plots were used, with one being measured through ages 2-9 (NC1), and the other planted in 1990 being measured through its ages 15-27 years (NC2) (Figure 1). Identical management and preparation strategies were undertaken at the same ages in CC1 as they had been applied to NC2 to replicate the growth dynamics present in NC2.



Age	2	4	6	8	10	12	14	16	18	20	22	24	26	28	30
Year	2005	2007	2009	2011	2013			2005	2007	2009	2011	2013	2015	2017	2019

Figure 2. Chronosequence data visualization of vegetation data over US-NC1 and US-NC2. Plots were managed identically to match NC1 early rotation growth dynamics to NC2 dynamics.

2.3.3 Bootstrapping analysis

Between the two data sets of NC1 and NC2, a gap is present in the chronosequence data from ages 10 to 14. To determine values for the gap, linear interpolation bootstrapping was used to gap-fill this data to determine a continuous dataset for 27 years. Bootstrapping parameters were similar to those present within Cruz et al., 2020, with the differences being that our bootstrap consisted of 1000 interactions with a prediction interval of 99% (Efron, 1979). These bootstrapped values were used to determine early rotation dbh values to inform aboveground biomass allometric equations. These early rotation values were used to construct a 28-year growth curve that was compared to the first 28 years of growth within simulated growth models to inform a linear regression model.

2.3.4 Height equations

Within the measured NC1 height data, gaps in collected data were present from ages 10-14 and 28. To determine height values during this period, height equations present in (Pienaar & Shiver, 1980) for poorly drained North Carolina coastal plains sites were utilized. The height equation utilized is:

$$H_t = 114.4[1 - \exp(-0.05507 \times t)]^{1.43550}$$

where H_t is height at age t (m). These height values were used to gap-fill collected data and inform aboveground biomass allometric equations.

2.3.5 Aboveground biomass allometric equations

Within this study, aboveground biomass allometric equations have been utilized to both fill gaps within missing historically observed data as well as determine the carbon dioxide content within aboveground biomass of modeled stands over time. The use of allometric equations to model aboveground biomass over time was necessary to determine the amount of aboveground biomass present at the site throughout its rotational period of 29-years, to better refine LobDSS simulations around these observed measurements. To model these aboveground biomass dynamics over time, the equations within (Gonzalez-Beneke et al., 2014) were utilized. The equation utilized to estimate total living branch biomass (represented as BRANCH) is:

$$BR5 = e_1 \times (dbh^{e_2}) \times (e^{e_3 \times dbh}) \times (H^{e_4}) \times (AGE^{e_5})$$

with BR5 being the total aboveground branch biomass (kg), e_{1-5} being parameter estimate coefficients, dbh being the diameter outside bark at 1.37 m height (cm), H being the total height of the tree (m), and AGE being the tree age (years). The equation used to estimate total living needles biomass (represented as FOLIAGE) was:

$$F5 = e_1 \times (dbh^{e_2}) \times (e^{e_3 \times dbh}) \times (H^{e_4}) \times (AGE^{e_5})$$

with F5 being the total living needles biomass (kg), e_{1-5} being parameter estimate coefficients, dbh being the diameter outside bark at 1.37 m height (cm), H being the total height of the tree (m), and AGE being the tree age (years). The equation used to estimate total above stump over bark biomass (represented as STEM) was:

$$S5 = e_1 \times (dbh^{e_2}) \times (H^{e_3}) \times (AGE^{e_4})$$

with S5 being the total living needles biomass (kg), e_{1-4} being parameter estimate coefficients, dbh being the diameter outside bark at 1.37 m height (cm), H being the total height of the tree (m), and AGE being the tree age (years). Once the totals for BRANCH, FOLIAGE, and STEM were estimated, these were summed to determine the total aboveground biomass for each year in kg/m^2. These totals in kg/m^2 were then converted to Mg/ha using the following conversion equation:

$$Mg/ha = ((kg/m^2)1000) \times 10000$$

where kg/m^2 is kilograms per meters squared and Mg/ha is megagrams per hectare. As these equations are to estimate aboveground biomass at the tree level, estimations were then multiplied by the number of trees within the stand for each year to determine the total aboveground biomass values of the stand for each year. The number of trees for each year was determined using tree survey data over the same 27-year period as height, dbh, and age data was gathered. This allowed for gradual stand-level overstory competitive dynamics to be considered, with a considerably smaller number of high-biomass trees being present within the stand at the end of the 27-year period than at the beginning. Thinning at year 19 additionally decreased both total aboveground biomasses accumulated, and number of trees present within the stand.

Comparison of aboveground biomass data derived from observed vs. gap-filled data can be found within Figure 3. Observed data has at least one source of measured data used to calculate aboveground biomass, whereas gap filled data was calculated using both the (Pienaar & Shiver, 1980) height equation as well as the bootstrapping techniques to derive dbh values. The only points where data is entirely gap-filled are ages 10-14 and age 28, with bootstrapping not being used to calculate age 29 aboveground biomass as this is the age in which harvesting occurred.

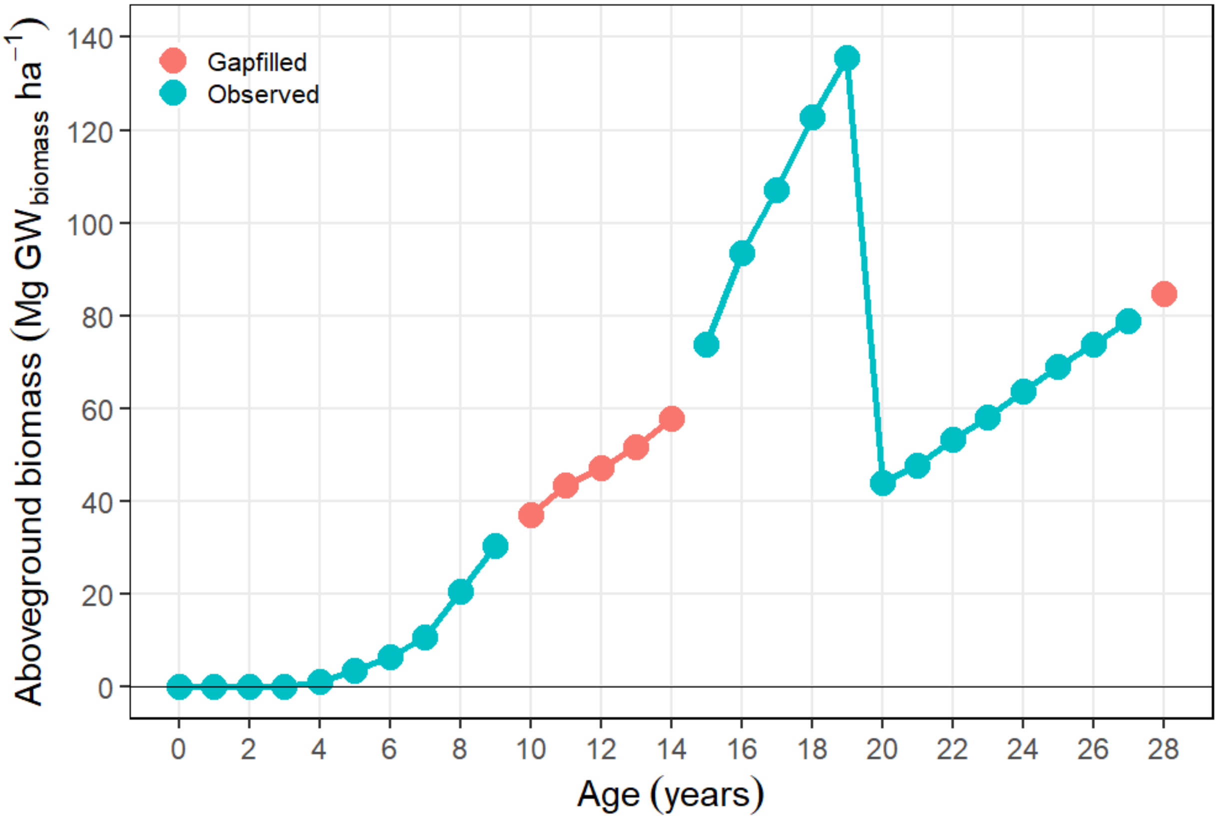


Figure 3. Green weight aboveground biomass (Mg/ha) over 28-year period for loblolly pine plantation ages 0-28 located in Washington County, NC. Chrono-sequencing was used to

compare aboveground biomass of site NC1 (ages 0-14) and NC2 (ages 0-27). Gap-filling was used in years 10-14 and 28. Year 19 experienced a post-thinning aboveground biomass decrease from 135.5 Mg/ha to 43.77 Mg/ha. Figure created using R faceting.

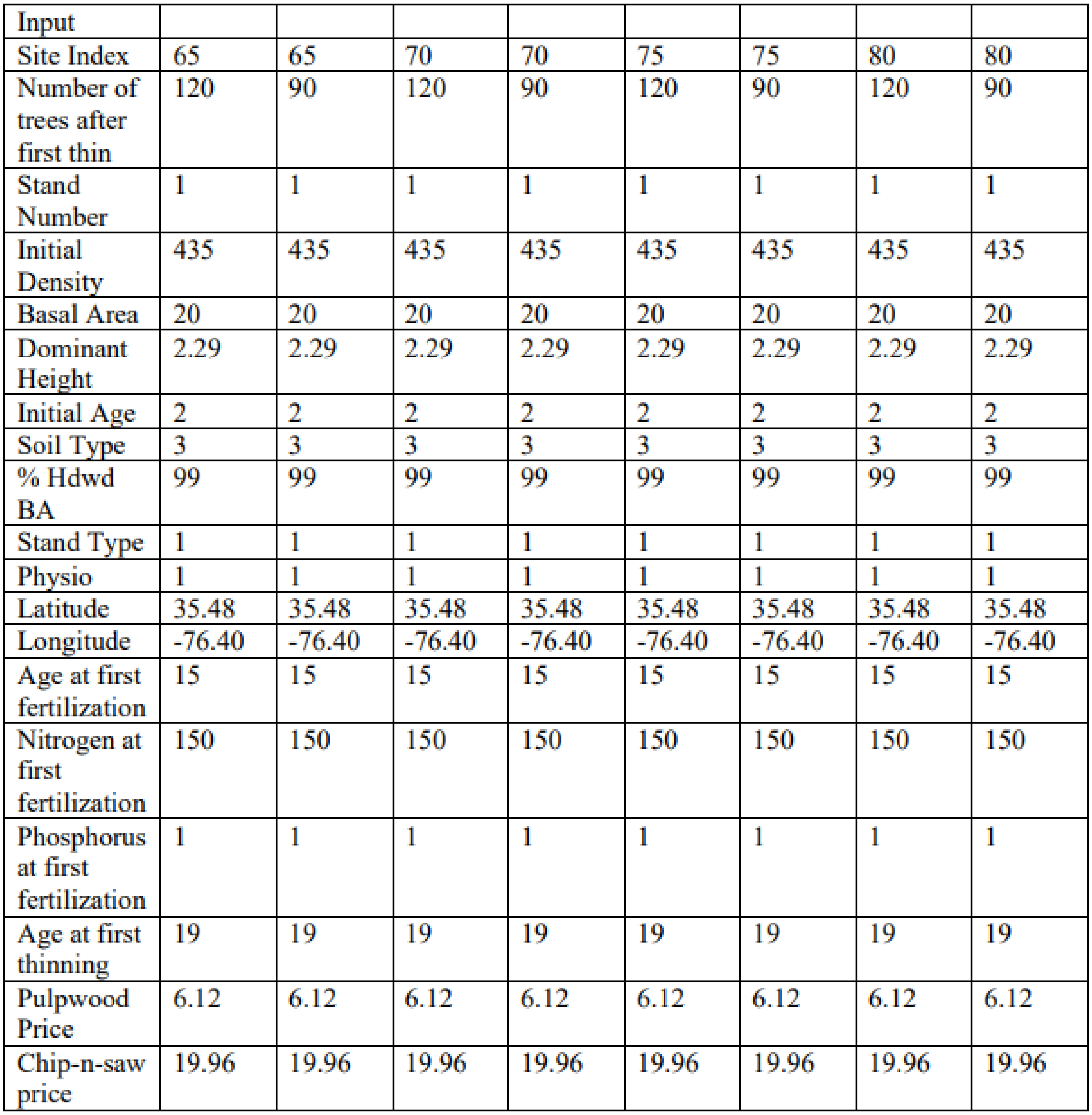
2.3.6 LobDSS (Loblolly Decisions Support System)

The Forest Productivity Cooperative's Loblolly Decision Support System (LobDSS) serves as an important growth and yield model for industrial forest landowners. LobDSS was developed throughout the 1990s and 2000s and refined through several papers, with the current form of the model (FASTLOB 3.1) serving as the version utilized since 2014. FASTLOB is a loblolly pine growth and yield model, with LobDSS serving as a user interface overlay for wider accessibility of this model for understanding loblolly growth dynamics over extended periods of time. Within the context of this study, LobDSS provides an opportunity to model potential aboveground biomass accumulations over extended rotation periods, without dedicating the resources or the time that is required of an experimental planting. The user interface of LobDSS allows for the input of determining factors for the model run, with the interface separating the factors into the following headers of Stand information, Stand management, Costs, Products, and Establishment and First Year treatments. After these factors are input, rotation length in years can be chosen. However, for this study, the header and contents of Costs were not utilized so that financial analyses could be done on the back end to account for factors that LobDSS is not able to consider (such as payments from carbon offset programs).

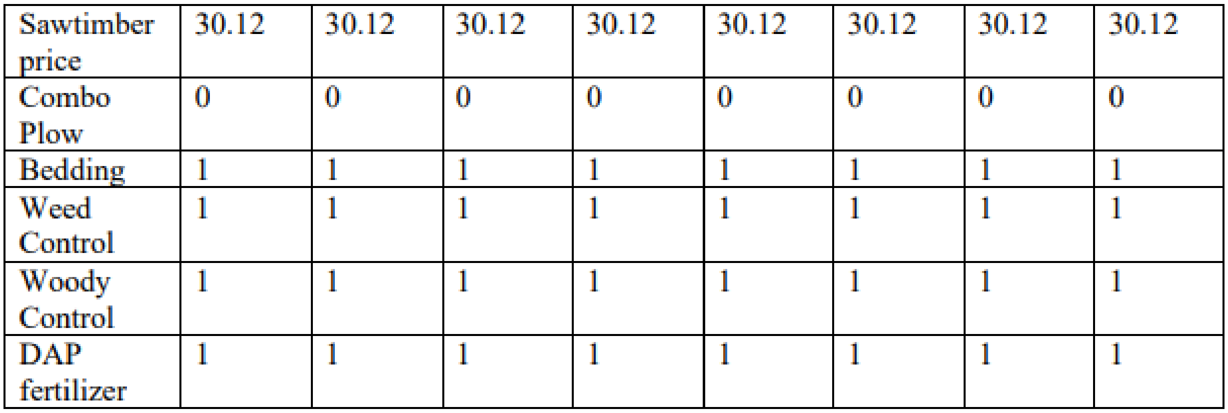
To model the effects of extended rotation ages on the loblolly pine stands, eight different treatments options were devised to best understand the potential growth and yield at this site. Differing factors between these treatments are the Site Index (SI), as well as the level of thinning (that being the number of trees per acre remaining after thinning). These treatments were SI values of 65, 70, 75, and 80, and thinning intensities of 120 and 90 trees remaining post-thinning.

These treatments are shown within Table 1, with each SI treatment having two sub-treatments of each thinning intensity.

Table 1. Inputs used to simulate growth and yield using Loblolly Decision Support System (LobDSS). Information used to determine range of Site Index is derived from (Pienaar & Shiver, 1980). Management scenarios, decisions, and geographic information are derived from recommendations from WeyCo., and were cross-referenced through (Middleton et al., 2017). Financial information is derived from (*Quarterly Price Report*, 2024).



Input								
Site Index	65	65	70	70	75	75	80	80
Number of trees after first thin	120	90	120	90	120	90	120	90
Stand Number	1	1	1	1	1	1	1	1
Initial Density	435	435	435	435	435	435	435	435
Basal Area	20	20	20	20	20	20	20	20
Dominant Height	2.29	2.29	2.29	2.29	2.29	2.29	2.29	2.29
Initial Age	2	2	2	2	2	2	2	2
Soil Type	3	3	3	3	3	3	3	3
% Hdwd BA	99	99	99	99	99	99	99	99
Stand Type	1	1	1	1	1	1	1	1
Physio	1	1	1	1	1	1	1	1
Latitude	35.48	35.48	35.48	35.48	35.48	35.48	35.48	35.48
Longitude	-76.40	-76.40	-76.40	-76.40	-76.40	-76.40	-76.40	-76.40
Age at first fertilization	15	15	15	15	15	15	15	15
Nitrogen at first fertilization	150	150	150	150	150	150	150	150
Phosphorus at first fertilization	1	1	1	1	1	1	1	1
Age at first thinning	19	19	19	19	19	19	19	19
Pulpwood Price	6.12	6.12	6.12	6.12	6.12	6.12	6.12	6.12
Chip-n-saw price	19.96	19.96	19.96	19.96	19.96	19.96	19.96	19.96



Sawtimber price	30.12	30.12	30.12	30.12	30.12	30.12	30.12	30.12
Combo Plow	0	0	0	0	0	0	0	0
Bedding	1	1	1	1	1	1	1	1
Weed Control	1	1	1	1	1	1	1	1
Woody Control	1	1	1	1	1	1	1	1
DAP fertilizer	1	1	1	1	1	1	1	1

The range in SI values for this site represents a range of possible SI values for a North Carolina loblolly pine coastal Plain site with poor drainage (Carmean et al., 1989). The variation in remaining trees/acre reflects the two possibilities for the site: The first (being the thinning level of 120, is the thinning level reported by Weyerhaeuser in their management of the site; Second, the thinning level of 90 was included to closer fit the bootstrapped aboveground biomass values post-thinning. Therefore, to include both possibilities, and to represent a larger range of loblolly pine forest managers, both treatments were included within the study. Aside from these eight differing factors, all other inputs within the user interface were held the same throughout all treatments. The inputs for model runs are shown in Figure 2. An input present on the LobDSS User Interface not present on this table represents an input that was not altered to influence growth dynamics; therefore, these remaining inputs were left as their default settings within LobDSS.

2.3.7 Carbon modeling using the LobDSS

LobDSS does not produce carbon content present in aboveground biomass, however we used allometric equations to derive this carbon content value from aboveground biomass. Aboveground biomass values for each year were converted to tons/acre and then converted to carbon. Within this study, aboveground standing biomass was assumed to be 48.5% C, so in order to determine the carbon content within aboveground biomass, the output provided by LobDSS was multiplied by .485 (King et al., 2007).

2.4 Results

2.4.1 Comparison of observed and modeled aboveground biomass

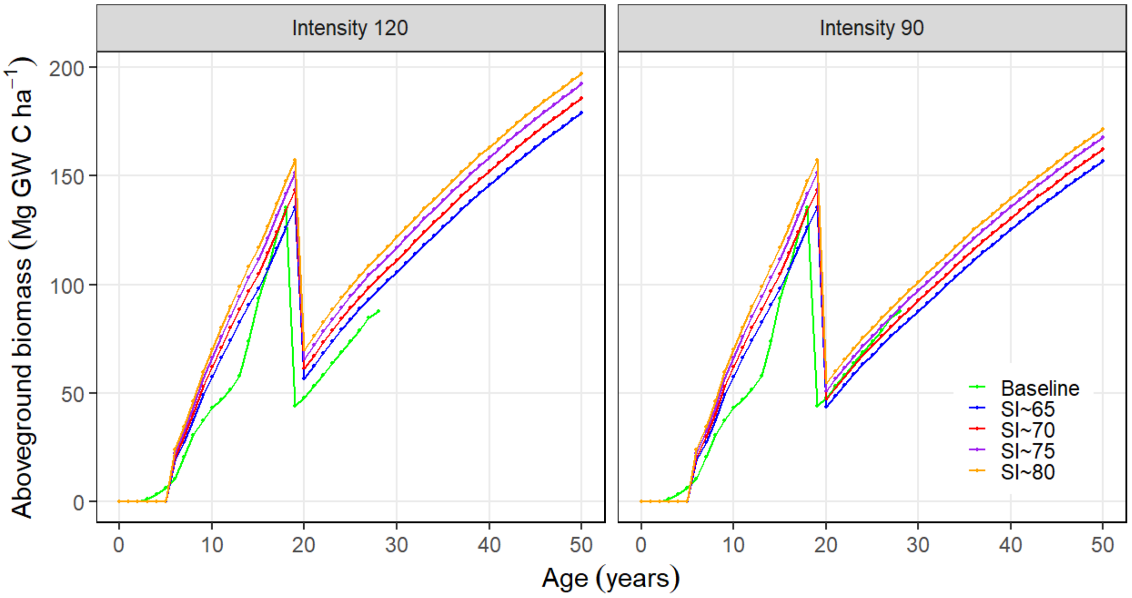


Figure 4. Comparison of aboveground biomass (Mg/ha) over multiple site indices (65, 70, 75, 80) and thinning treatments (120 and 90) over a 50-year period within an industrial loblolly pine plantation within Washington County, NC. Baseline treatment refers to observed aboveground biomass over 28-year period. Thinning occurs at year 19 within all treatments. Figure created using R studio faceting.

Across all SI and thinning treatments, all modelled aboveground biomass treatments increased continuously over the 50-year period (Figure 4). Thinning in year 19 is present within all treatments, however thinning is more pronounced in treatments with thinning intensity of 90 trees/acre, with aboveground biomass values for the rest of the period being lower than values present within simulations with thinning intensity of 120 trees/acre. Baseline treatment is held constant throughout both thinning intensities.

2.4.2 Linear regression analyses

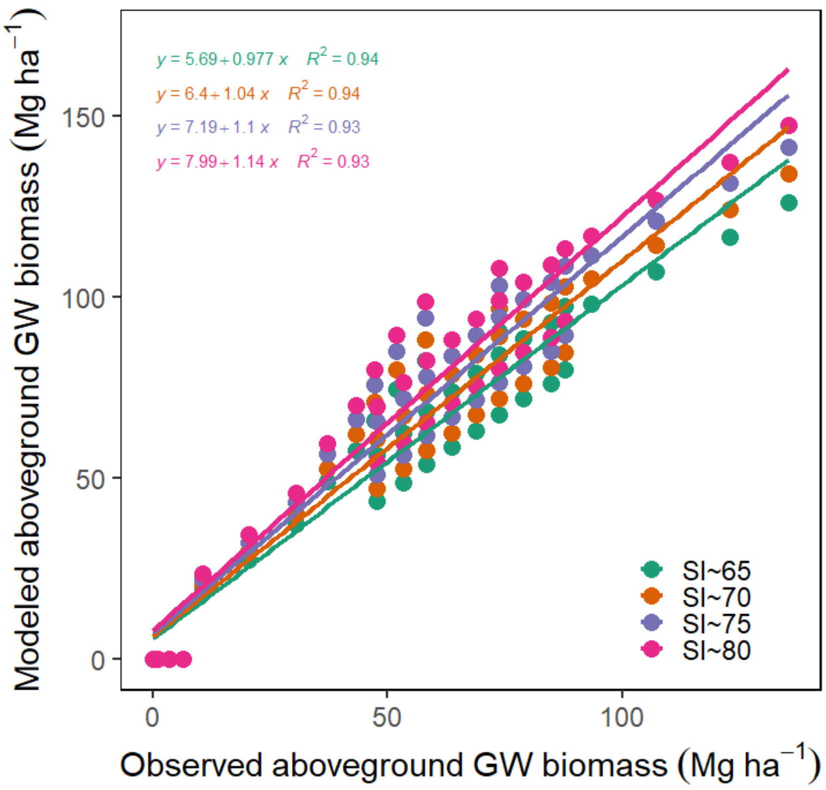


Figure 5. Regression Analysis comparing all aboveground biomass (Mg/ha) simulations of differing site indices (65, 70, 75, 80) to observed aboveground biomass (Mg/ha) data for an industrial loblolly pine plantation in Washington County, NC. Figure created using R Studio faceting.

Across all treatments, linear regression analyses conducted comparing the regressions of the observed aboveground biomass and the modelled runs produced statistically significant R^2values (Figure 5). Scenarios with SI values of 65 and 70 contain R^2 values of 0.94, while scenarios with SI values of 75 and 80 contain R^2 values of 0.93. Values present at and near (0,0) are present throughout all management scenarios, as LobDSS is ineffective at simulating growth and yield for the first four years of rotation period (Peay et al., 2022).

2.5 Discussion

2.5.1 Comparison of observed and modeled aboveground biomass

Throughout all treatments, modeled aboveground biomass increased continuously, supporting my first hypothesis of continuous growth. That the biomass will continue to continuously increase during the period. Additionally, throughout all models the aboveground biomass dynamics are statistically significant, with the slope for each growth curve showing a positive correlation with the observed data. Therefore, the models developed to simulate growth and yield for this site are highly accurate, with R^2 values of 0.93 or 0.94 demonstrating high levels of statistical significance (Figure 5).

This increase in biomass accumulation due to increasing stand rotation lengths is in agreement with the current body of literature relating to loblolly pine biomass dynamics (Albaugh et al., 2012; Coleman & Aubrey, 2018; Gharis et al., 2015; Gonzalez-Benecke et al., 2011; Jokela et al., 2010). Therefore, when managing solely with the goal of maximizing carbon accumulation within forest stands, increasing the rotation length to 50 years is ideal for increasing carbon storage. Additionally, this is only when considering the two rotation lengths of 28 and 50. Extending rotation lengths past 50 years was not conducted in this experiment for the following reasons:

1. LobDSS' maximum rotation length is 50 years. As this is a widely used forest growth and yield model amongst Loblolly forest managers, understanding the dynamics of this model is key to understanding what may be perceived by landowners in their use of this management regime.
2. Due to financial constraints, it is unlikely that forest managers will continue to manage their stand of loblolly pine past that of 50 years, as the costs will dwarf that of the increasing marginal benefits (Mei, 2023a). This assumption will be examined within

Chapter 3 of this study, which will examine the effects of revenue generated through carbon markets on revenue generation.

3. loblolly pine growth will begin to plateau shortly after maturity is reached at age 50, therefore additional accumulation of aboveground biomass will be marginal at best (Maynor et al., 2021).

2.5.2 Aboveground biomass under different site indices

Cumulative aboveground biomass over the course of a 50-year rotation period with the average SI range for an industrial loblolly pine plantation within the coastal plains of North Carolina (65, 70, 75, 80), (Carmean et al., 1989; Pienaar & Shiver, 1980) corroborates the findings found within the current body of literature in that the increasing SI values directly corresponds to the increase in aboveground biomass accumulation (Gonzalez-Benecke et al., 2011; Socha et al., 2017). Within both treatments of high and low thinning, the higher SI values resulted in higher aboveground biomass accumulations. These dynamics of higher SI valued models producing a greater amount of aboveground carbon remains true throughout the entire rotation period.

2.5.3 Aboveground biomass under different thinning regimes

As referenced within (Zhao et al., 2019), the differing levels of thinning used in forest management has a large determining impact on the aboveground biomass accumulation. Understanding these dynamics is critical from the perspective of forest carbon managers to maximize the storage level and capacity within forested areas. Thinning has a direct effect on aboveground biomass accumulation, which is critical to improving forest carbon management.

While thinning was present within the management regimes of all treatments at the age of 19, the degree to which thinning occurred was different among the treatments. Those treatments where 120 trees/acre were the thinning treatment demonstrated higher amounts of aboveground carbon accumulation throughout the long-term rotation when compared to those treatments where 90 trees/acre remained. This stands in agreement with the current body of literature, specifically (Baldwin et al., 2000). While stands with more pronounced thinning regimes demonstrated higher branch level biomass, total aboveground biomass was greater within stands with lower levels of thinning. The effects of differing thinning regimes when considering rotation lengths of the past 50-years is unclear, due to both the aforementioned factors of a lack of financial incentive to manage in this way, as well as a lack of literature regarding the effects of thinning on long-term (post 50-years) stands of loblolly pine.

Additionally, a greater amount of carbon accumulated within the Loblolly tree pre-thinning remains within the tree post-thinning within models where a lower level of thinning is present, as less carbon is being emitted from the tree at the point of the thinning. Therefore, if the goal of the forest management is to increase carbon storage within their stand, decreasing the level of thinning within this context leads to a greater amount of carbon stored within the stand long-term.

2.5.4 Ecological drivers of aboveground biomass accumulation

The accumulation of aboveground biomass within loblolly pine stands is driven by both the ecophysiological processes of the trees themselves, as well as macro-scale ecosystem dynamics. The differing roles that each of these factors can play within the growth of both stand and individual tree growth rates depends on a variety of factors (Harms & Lloyd, 1981; Pope & Graney, 1979). The effects of rotation lengths, SI, and thinning are examined within this case study context, all having varying degrees of impact on the accumulation of aboveground biomass. In summary, this study finds that the current body of literature regarding the knowledge that each factor has upon the aboveground carbon accumulation within the study forest stands to be accurate in its findings.

2.5.5 Management implications

Within the context of forest carbon management, this study looks to bridge the gap between the goals of management for the purpose of revenue-driven harvesting, and forest management with the purpose of increasing carbon storage within forested areas. This study, and the following chapter, contributes to the growing body of literature that demonstrates that these two management goals are not diametrically opposed, and instead, can be pursued together (Baker et al., 2010; Mei, 2023b, 2023a; Sartori et al., 2024).

In support of bridging these goals, this study confirms its hypothesis that over the course of a 50-year rotation period, continuous accumulation of aboveground biomass was witnessed in the modeled loblolly pine stands. While these results only stand for this case study, the implementation of deferred harvesting in support of increased carbon storage within loblolly pine stands was shown to be effective.

2.5.6 Study limitations

This study was conducted as a case study examining the effects of deferred harvesting on a loblolly pine plantation within a coastal plains site in North Carolina. Our growth and yield dataset from the flux tower provided empirical coboration of the LobDSS growth and yield estimates. The flux tower dataset utilized, while robust in comparison to other long-term loblolly pine datasets, reflects the conditions and management practices conducted at this site. Additional studies can help to determine the impact of deferred harvesting on sites with different site conditions and quality than the case study site. Additionally, while soil carbon was not considered during this study, literature notes the importance of soil carbon in forest carbon management efforts, which reiterates the importance of understanding these dynamics within a deferred harvesting context.

2.6 Conclusions

As noted in (H.-J. Wang et al., 2012), forest carbon management relies heavily on the tools that it uses, with effective forest growth and yield models and simulation methods serving as one of the most important of these tools. While LobDSS is one of the most widely used of these tools, its output lacks a measure of carbon storage within modeled stands aside form biomass. This is not taking into account potential carbon pools such as soil carbon, or emissions sources such as harvest emissions (Tahvonen & Rautiainen, 2017). Additionally, other forest growth and yield models such as PTAEDA, and SiMS also simulate these forest growth and yield rates, they likewise do not consider these unmodeled forest carbon impacts (Burkhart et al., 2008; Peay et al., 2022). While specific models are utilized to understand forest carbon dynamics with greater precision, incorporating greater ease of access to these higher-precision carbon models for forest managers may serve as a method of increasing the knowledge base regarding opportunities forest managers have to increase carbon storage within their forested areas.

CHAPTER 3- Cost-benefit analysis of the use of carbon payments in support of deferred harvesting within an industrial loblolly pine plantation

3.1 Introduction

Within the greater context of forest carbon management strategies, deferred harvesting serves as an effective method of increasing both landowner revenue and carbon storage (Carino & Biblis, 2002; Mei, 2023b). Deferred harvesting can accomplish both seemingly conflicting management goals through extending the rotation length of the managed stand, therefore increasing the biomass stored within the area while still allowing for harvesting, which stands in opposition to the old growth model of increasing carbon storage, which prevents harvesting. Within the context of climate smart forestry management strategies, old growth forests have been demonstrated to be debatable in their effectiveness as a climate mitigation tool both in their questionable additionality as well as the financial barrier for participation that exists for forest landowners who rely on the revenue (Buongiorno & Zhou, 2015; Gundersen et al., 2021; Hoover et al., 2012; Luyssaert et al., 2008). Considering these two constraints (additionality and the financial cost), alternative forest management methods to increase carbon storage have been developed, with deferred harvesting serving as a crucial potential strategy for landowners who rely on revenues from harvesting. Depending on economic, policy, and ecological contexts, deferred harvesting may be a potential strategy to thread this needle.

The use of carbon payments through carbon offset markets serves as an intriguing potential additional revenue source that is provided using deferred harvesting. Carbon offset programs that allow for large scale emitters to “offset” their emissions through paying individuals or organizations engaging in pro-environmental behaviors to continue these behaviors, thus “offsetting” the emissions created by the emitter (Lederer, 2012; Tahvonen &

Rautiainen, 2017). These programs are commonly facilitated through a third party broker, who links emitters and those engaging in pro-environmental behaviors, in addition to certifying that the behaviors occurring are offsetting emissions (Haya et al., 2023; McLennan et al., 2014; Tarnoczi, 2017). These programs can provide an additional revenue stream in addition to the benefits incurred through selling harvested material if additional carbon storage when compared to the baseline is occurring.

Within the context of carbon offset programs within North Carolina, while there was consideration of the state joining the Regional Greenhouse Gas Initiative (RGGI) in 2023 (*North Carolina Legislature Defeats Hope of Joining RGGI | International Carbon Action Partnership*, 2023), currently forest landowners within the state must rely on Voluntary Carbon Markets (VCMs) without state policies that provide additional incentive in participating within these programs (Daniels, 2010; Thompson et al., 2009). While the current literature reviewing the different uses of VCM in support of increasing carbon storage levels and potential impacts on material markets are robust, there is a scarcity of case studies examining individual circumstances. These studies are needed both to increase landowner awareness regarding the potential financial and ecological benefits through participation within these markets, as well as contributing to the greater body of knowledge within this field. Therefore, this study examines the potential economic benefits of the practice of utilizing carbon payments to support deferred harvesting within the context of an industrial loblolly pine plantation within Washington County, NC.

3.2 Objectives and hypothesis

Building on the aboveground biomass accumulation models presented in the previous chapter, this study seeks to determine a range of benefits that landowners may be able to gain from participation in a variety of carbon markets. For each of the management scenarios, benefits gained from participation in a VCM were determined over a 50-year rotation period and compared to the management costs incurred by the landowner for this same period. To determine the potential landowner benefits over the deferral period, the breakeven carbon price was calculated to determine the minimum price carbon payments would have to be for the landowner to benefit from participating in a carbon offset program. To compare breakeven carbon prices and real-world carbon market prices, prices from four of the major carbon offset programs (RGGI), California Cap and Trade, EU Emissions Trading System (ETS), and Ontario Emissions Performance Standards (EPS) were utilized to gain a cohesive picture of potential benefits. Additionally, multiple discount rates were considered for potential benefits over time. This study asks the following questions:

1. Will the carbon breakeven price calculated for each treatment fall within the range of prices represented within real-world carbon markets?
2. How will deferring harvest from the age in which NPV is maximized impact landowner revenue?

In regards to the first question, if these prices are approximate (or lower) than real-world carbon prices, then participation within these carbon markets would lead to benefits approximate to, or greater than those calculated with the breakeven carbon price. I hypothesize that the breakeven carbon prices will be lower than those within real-world carbon prices. This second question will determine if the use of deferred harvesting is financially feasible for a forest manager within this context, as total revenue gained over the deferral period is less than the costs accrued during the same period, the manager will be losing money, and therefore unlikely to defer harvest. I hypothesize that the additional revenue generated from carbon payments in addition to the timber revenue sources will lead to a net positive amount of revenue over the deferral period across all treatments. Therefore, for all treatments the NPV will remain positive for the entirety of the deferral period.

3.3 Methods

3.3.1 Study site

The study site for this experiment is located at the Parker Tract loblolly pine plantation located on the North Carolina coastal plain, with the nearest municipality being Plymouth, Washington County, NC, USA (35°48'32"N 76°40'41"W, Figure 1). This site is an operationally-managed loblolly pine plantation, with plantation forestry being the dominant use of the site for several decades. The areas consists of a flat, loamy soil with poor drainage and an elevation of 8m above sea level (Middleton et al., 2017). This site is currently managed by Weyerhaeuser Co. in collaboration with NC State University, and the US Forest Service, who conduct research on forest growth measurements, water cycling, and carbon fluxes for >30 years.

This site has been managed by Weyerhaeuser Co. for the purpose of industrial loblolly pine plantation harvesting since the acquisition of the site. Therefore, our dataset reflects management practices commonly practiced by pine plantation forest managers. As this is a poorly drained coastal plain site, bedding, weed control, phosphorus fertilization, and hardwood control were implemented at planting. Elemental nitrogen fertilization of 150 lbs/acre occurred at age 15 with additional phosphorus treatments occurring at this same time. Additionally, thinning at age 19 occurred at this site, which is reflected in all experimental analyses.

3.3.2 Data collection

Biometric data used to create a baseline management scenario of the conditions at Parker Tract, NC was gathered over a 29-year rotation length. Data gathering methods were summarized in (Aguilos et al., 2020), with the same measurements of age (years), height, (m), and dbh (cm) used in this study. To construct this long-term dataset, chrono-sequencing was utilized to determine the growth dynamics throughout years 2-27 of the 29 year long rotation. Years 0-2 and 28 and 29 were not measured in the original study. Therefore, two plots from another study were used, with one being measured through ages 2-9 (CC1), and the other planted in 1990 being measured through its ages 15-27 (US-NC2) (Figure 1). Identical management and preparation strategies were undertaken at the same ages in CC1 as they had been applied to US-NC2 to replicate the growth dynamics present in US-NC2.

Tonnage prices of forest material products were determined using NC State Extension's Quarterly Price report (Q3), in which statewide prices are given forest timber products for each financial quarter. To determine accurate estimations of monetary value of timber products, the prices of Pine pulpwood, Pine chip-N-saw, and Pine sawtimber were used from the Q3 2024 report (*Quarterly Price Report*, 2024). To determine carbon pricing options, four different prices from four different carbon offset programs were considered: RGGI, California Cap and Trade, EU ETS, and Ontario EPS. Prices for these programs were found at the World Bank Group's Carbon pricing dashboard (*Carbon Pricing Dashboard*, 2024), and were accessed on January 15th, 2015, therefore prices reflected within the analysis will reflect prices present on the dashboard at that time.

3.3.3 Financial valuation equations

To determine the total revenue for forest landowners for each year of deferral, a cost-benefit analysis was completed to determine if the use of deferred harvesting was overall beneficial. The first step was to determine the aboveground biomass for each year, which was determine using the LobDSS aboveground biomass models in Chapter 2. LobDSS models also generated the total tonnage of forest products (pulpwood, chip-n-saw, and sawtimber) that would be harvestable each year. The tonnage of product total was multiplied by the Q3 North Carolina timber process for the product type, thus determining the total value of harvestable forest product at each year of deferral. For all financial valuation equations, dry weight aboveground biomass was used, in which all green weight aboveground biomass values were multiplied by 0.48 to determine dry weight (Clark & Taras, 1976). To determine the value of carbon payments from enrollment in an offset program in USD for every year after the beginning of the deferral period, the following equation was used:

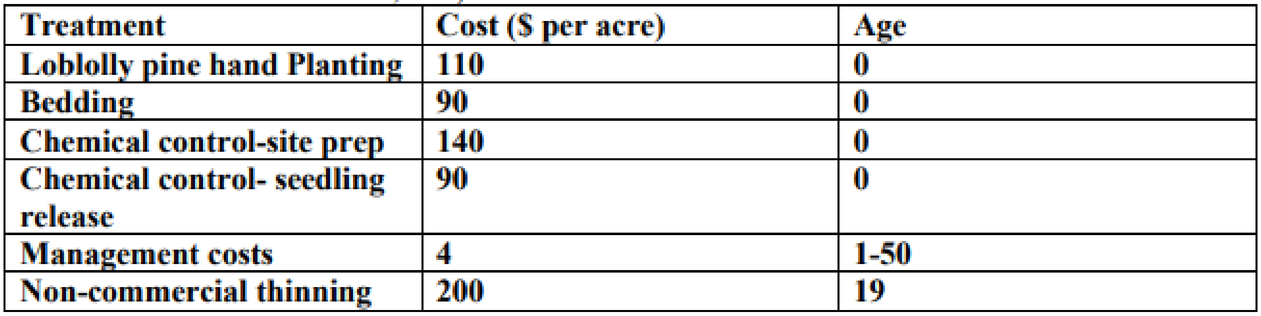
$$\boldsymbol{Cp = \left(\left(\left((AB_{29+d} - AB_{29}) * .446\right) * 0.485\right) * 3.667\right) * P}$$

where Cp is value of carbon payments ($/tCO2) for a specific year, AB_{29} is the aboveground biomass total (Mg/ha) for the last year before the deferral period (or the total aboveground biomass at year 29), d is the number of years after the deferral period, and P is the price of carbon ($/tCO2) based on the offset program being used. 0.446 is the unit conversion of Mg/ha to tons/acre, and 0.485 is used to determine the amount of carbon present in aboveground biomass (t/CO2), that being that carbon is 48.5% of total biomass within mature pine species (King et al., 2007). 3.667 is the conversion rate of carbon-to-carbon dioxide.

Costs per year were determined using the North Carolina prevailing rates for sub-practices fact sheet, with D-13 Fairfield being the region in which the study site is located, and a baseline management rate of $4 per year was assumed based on (*Is Reforestation a Profitable Investment?*, 2024; *PREVAILING RATES FOR SUB-PRACTICES : NCFS FOREST DEVELOPMENT PROGRAM*, n.d.) Management practice costs are shown with Table 2:

Table 2. Table displaying costs incurred by forest manager through management of industrial loblolly pine plantation in Washington County, NC for a rotation period of 50 years. Costs were determined through historical data regarding management decisions as well as recommendations made by Weyerhaeuser. Value of costs were determined using (*Is Reforestation a Profitable*

Investment?, 2024; *PREVAILING RATES FOR SUB-PRACTICES : NCFS FOREST DEVELOPMENT PROGRAM*, n.d.).



Treatment	Cost ($ per acre)	Age
Loblolly pine hand Planting	110	0
Bedding	90	0
Chemical control-site prep	140	0
Chemical control- seedling release	90	0
Management costs	4	1-50
Non-commercial thinning	200	19

As the site has been managed with the intention of selling harvested forest material, the high investment price was taken into account from the prevailing rates fact sheet, as this additionally more closely follows the high-investment forest management plan found within (*Is Reforestation a Profitable Investment?*, 2024).

To determine costs and benefits derived from the thinning occurring in year 19, the following equation was utilized:

$$TC = C_{19} - (PW_{19} - PW_{20}) - (CS_{19} - CS_{20})$$

Where TC is the Thinning Costs ($ USD), C_{19} is the costs associated with that year, those being the baseline management costs and the cost of thinning ($ USD), PW_{19} is the value of Pulpwood at year 19 ($ USD), PW_{20} is the value of Pulpwood at year 20 (post-thinning) ($ USD), CS_{19} is the value of Chip-n-saw at year 19, and CS_{20} is the value of Chip-n-saw at year 20 (post-thinning) ($ USD).

To determine the total revenue generated for each year, the total costs were subtracted from the total benefits for each year. To determine the Net Present Value (NPV) at the site at any given year, the standard NPV equation was utilized, that being:

$$NPV = R_a/(1+i)^a$$

Where NPV is the Net present Value for each given year (USD), a is the age of the stand (years), and i is the interest rate. This NPV calculation was utilized to determine the harvest age in which NPV is maximized. Using this maximum year of NPV, all subsequent years until age 50 the carbon breakeven price is calculated. The carbon breakeven price formula was:

$$CBP = (NPV_{MA} - NPV_{MA+d})/(AB_{MA+d} - AB_{MA})$$

Where CBP is Carbon Breakeven Price ($ USD), NPV_{MA} is the NPV ($ USD), at the year in which it is maximized, d is the deferral period after the year in which NPV is maximized, and AB_{MA} is the green weight aboveground biomass (Mg/ha) of the NPV maximized year. To determine the percentage change of NPV over time for each treatment, the following equation was used:

$$\Delta C = (AB_{MA+d}/AB_{MA})/-1$$

Where ΔC is percentage change in NPV value, NPV_{MA} is the NPV ($ USD), at the year in which it is maximized, d is the number of years after the optimal harvest age that the harvest is occurring.

A range of discount rates were considered to simulate multiple possible economic outcomes. Those discount rates used were: 3%, 4%, 5%, 5.5 or 5.6%, and 6%. Either 5.5 or 5.6% were used, as this was the lowest possible discount rate at which the age where NPV was maximized at age 29. As with the baseline scenario of harvest occurring at age 29, these rates were used to best simulate the possible landowner benefits within this baseline management scenario. To reflect economic conditions over the course of the 29-year observed data set, 5.5% was used for both thinning treatments of SI 65 and 70, and the 120-thinning treatment of SI 75 and 5.6% was used for the 90 thinning intensity treatment of SI 75 and both thinning treatments of SI 80.

To compute carbon breakeven price over multiple management and economic scenarios, breakeven price was calculated from the point at which NPV is maximized until the end of the maximum 50-year rotation period. Therefore, this age of NPV maximization differs over the course of the scenarios, with scenarios with a lower discount rate having a higher age where the NPV is maximized.

3.4 Results

3.4.1 Carbon breakeven price

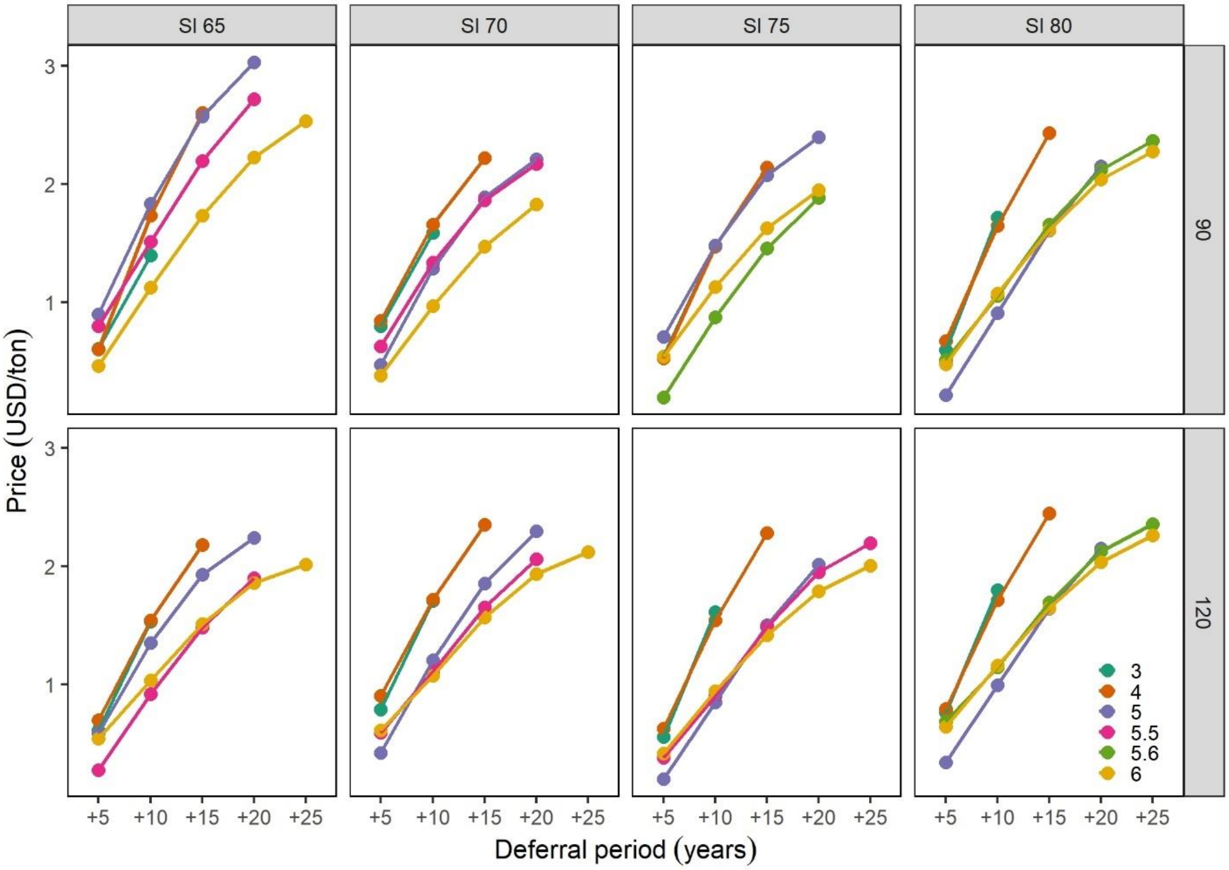


Figure 6. Carbon breakeven price (USD/ton) under multiple management scenarios (SI values of 65, 70, 75, 80 and thinning intensities of 90 and 120 trees/acre remaining post-thin) and discount rates for a 25-year deferral period. Base refers to year in which NPV is maximized, or “optimal harvest age”, in which carbon breakeven price is calculated in subsequent years until age 50. +5, +10, +15, +20, and +25 refer to 5-year deferral increments after optimal harvest age. Within each treatment either discount rates of 5.5% or 5.6% are used to place optimal harvest age at age 29, where harvesting occurred in observed data. Figure created using R Studio faceting.

Over a maximum 25-year deferral period, carbon breakeven price increases over time for each management scenario simulated, with increased deferral periods rendering increased carbon breakeven prices (Figure 6). Carbon prices begins to plateau within longer deferral periods (20, 25 years) and higher discount rates (5.5/5.6% and 6%). As deferral period is based on the difference between the year in which NPV is maximized and the end of the possible deferral period (50-years), deferral period is shortest within discount rates of 3%, and is longest within discount rates of 6%. Carbon price reaches its highest value in scenario SI 65, thinning intensity of 90 trees/acre, and discount rate of 5%, while the lowest carbon breakeven price is present within scenario SI 75, thinning intensity of 120 trees/acre, and discount rate of 6%.

3.4.2 Revenue per management scenario under differing carbon prices

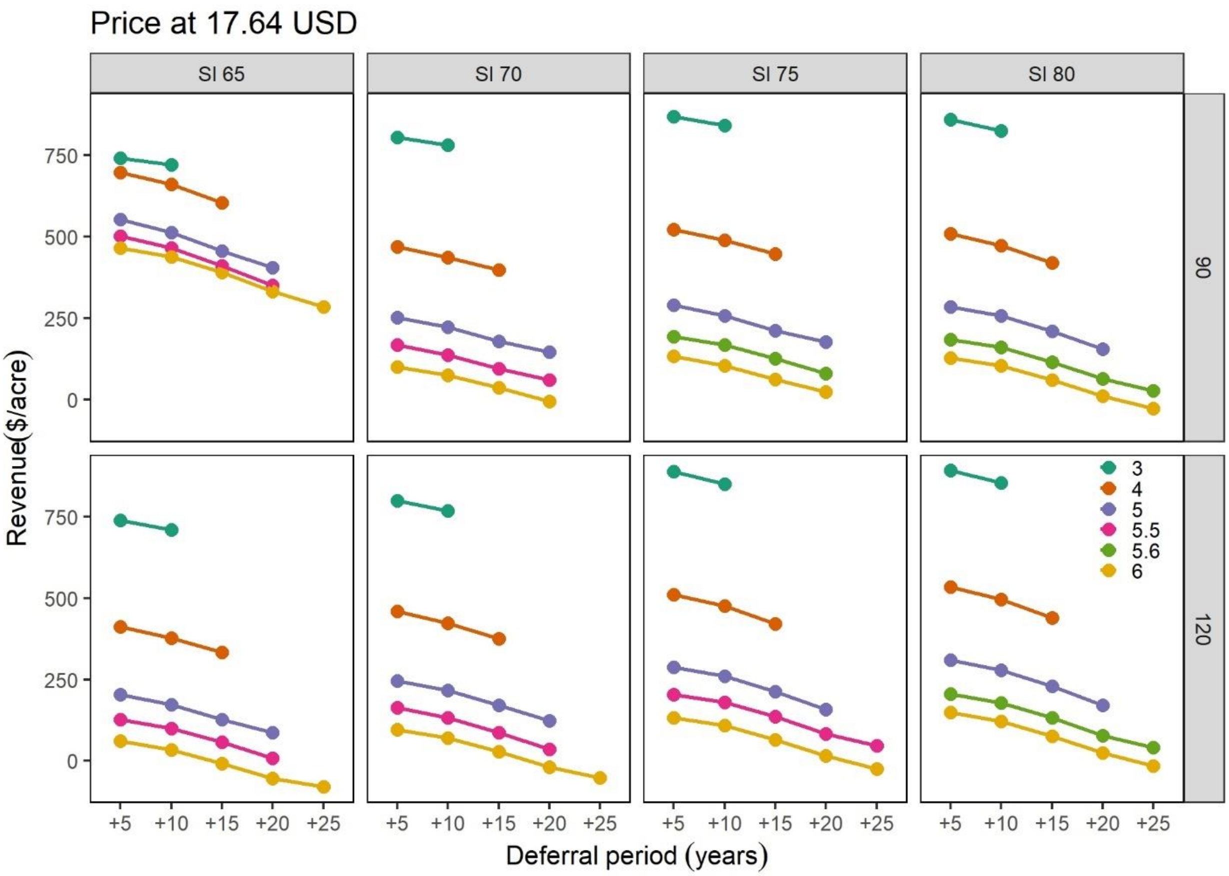


Figure 7. Revenue (USD/acre) per scenario over a 25-year deferral period under multiple management scenarios (SI values of 65, 70, 75, 75, 80 and thinning intensities of 90 and 120 trees/acre remaining post-thin) and discount rates with the static carbon price of 17.64 (USD) for an industrial loblolly pine plantation in Washington County, NC Within each treatment either discount rates of 5.5% or 5.6% are used to place optimal harvest age at age 29, where harvesting occurred in observed data. 17.64 (USD) refers to carbon price used within Regional Greenhouse Gas Initiative (RGGI). Figure created using R Studio faceting.

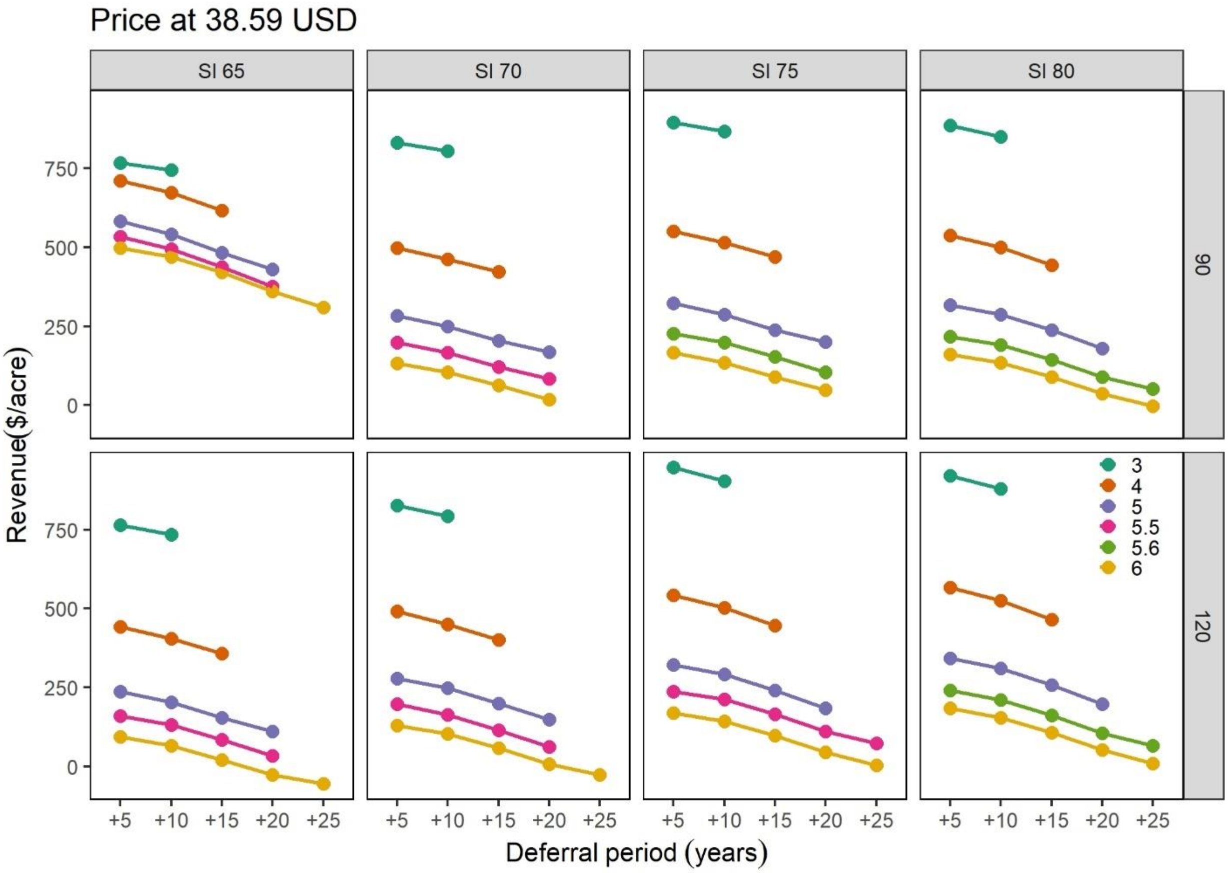


Figure 8. Revenue (USD/acre) per scenario over a 25-year deferral period under multiple management scenarios (SI values of 65, 70, 75, 75, 80 and thinning intensities of 90 and 120 trees/acre remaining post-thin) and discount rates with the static carbon price of 38.59 (USD) for an industrial loblolly pine plantation in Washington County, NC Within each treatment either discount rates of 5.5% or 5.6% are used to place optimal harvest age at age 29, where harvesting occurred in observed data. 38.59 (USD) refers to carbon price used within the California Cap and Trade market. Figure created using R Studio faceting.

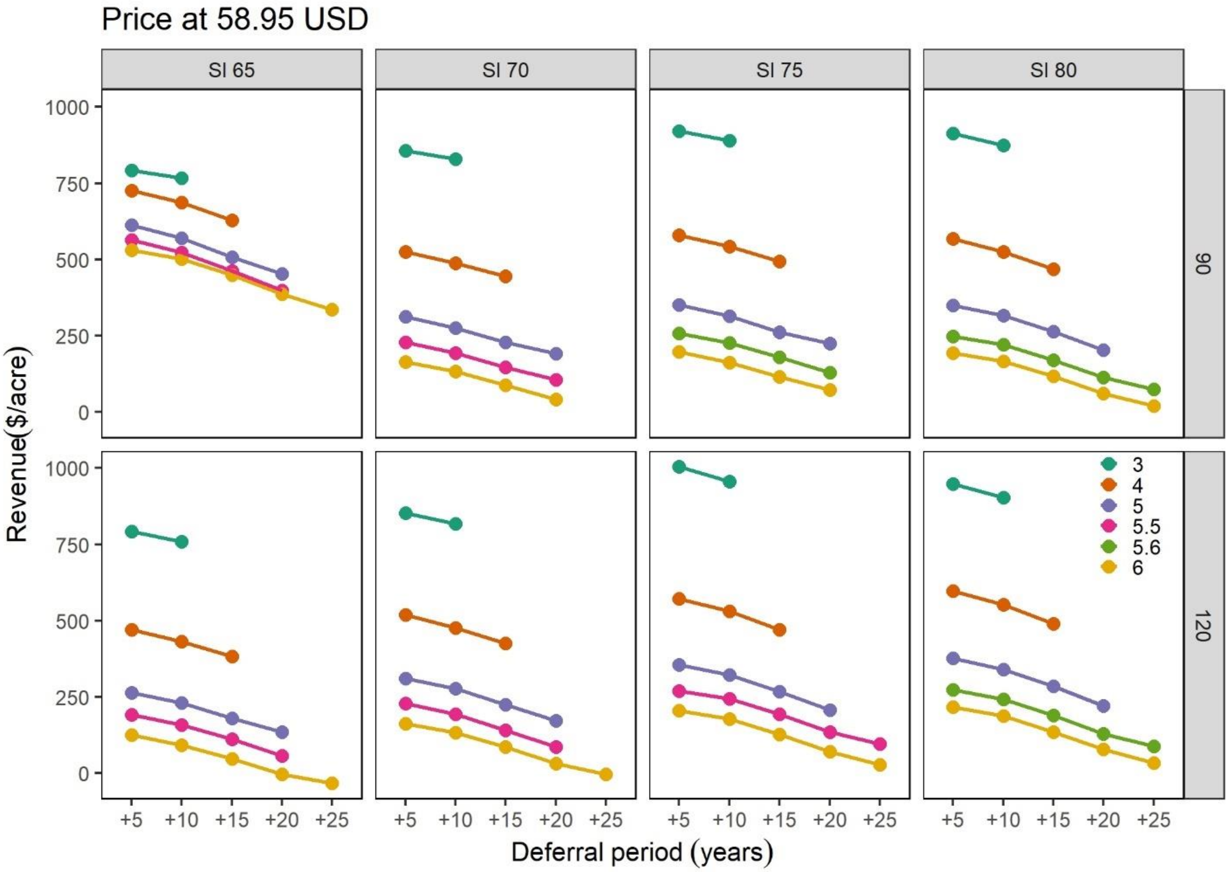


Figure 9. Revenue (USD/acre) per scenario over a 25-year deferral period under multiple management scenarios (SI values of 65, 70, 75, 75, 80 and thinning intensities of 90 and 120 trees/acre remaining post-thin) and discount rates with the static carbon price of 58.95 (USD) for an industrial loblolly pine plantation in Washington County, NC. Within each treatment either discount rates of 5.5% or 5.6% are used to place optimal harvest age at age 29, where harvesting occurred in observed data. 58.95 (USD) refers to carbon price used within the Ontario Emission Performance System. Figure created using R Studio faceting.

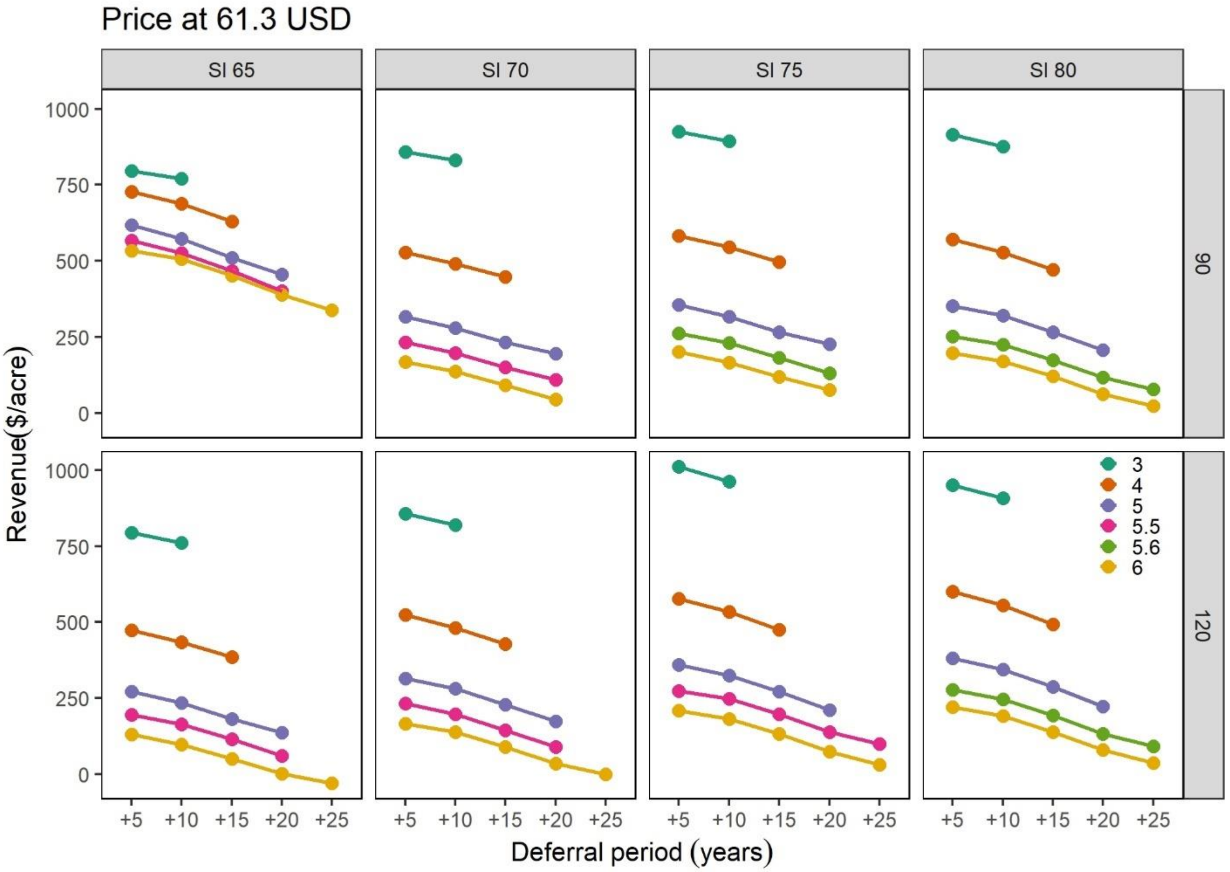


Figure 10. Revenue (USD/acre) per scenario over a 25-year deferral period under multiple management scenarios (SI values of 65, 70, 75, 75, 80 and thinning intensities of 90 and 120 trees/acre remaining post-thin) and discount rates with the static carbon price of 61.3 (USD) for an industrial loblolly pine plantation in Washington County, NC. Within each treatment either discount rates of 5.5% or 5.6% are used to place optimal harvest age at age 29, where harvesting occurred in observed data. 61.3 (USD) refers to carbon price used within the European Union Emissions Trading System. Figure created using R Studio faceting.

When calculating Revenue (USD) based on carbon prices gathered from international carbon markets, values calculated are higher generally than those calculated with breakeven carbon price (Figures 6-10). Over multiple management scenarios, revenue is dependent on carbon price, with a higher price resulting in a higher revenue when comparing similar scenarios. Revenue remains throughout the majority of management scenarios, with revenue becoming negative when the discount rate is higher, leading to a higher opportunity cost for the landowner.

3.4.3 Percent change in NPV per treatment

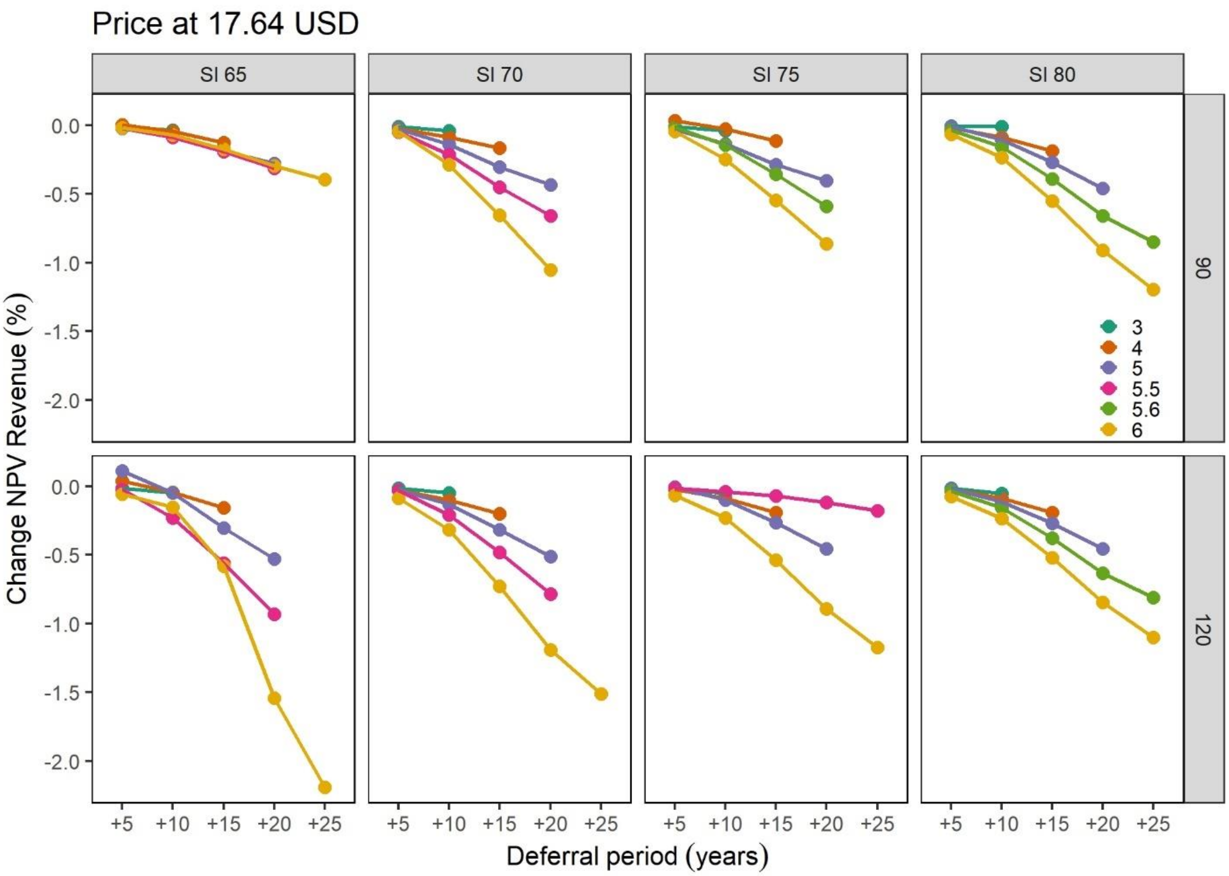


Figure. 11. Percent Change in NPV per management scenario (SI values of 65, 70, 75, 80 and thinning intensities of 90 and 120 trees/acre remaining post-thin) and discount rates. Base refers to year in which NPV is maximized, or “optimal harvest age”, in which carbon breakeven price is calculated in subsequent years until age 50. +5, +10, +15, +20, and +25 refer to 5-year deferral increments after optimal harvest age. Within each treatment either discount rates of 5.5% or 5.6% are used to place optimal harvest age at age 29, where harvesting occurred in observed data. Figure created using R Studio faceting.

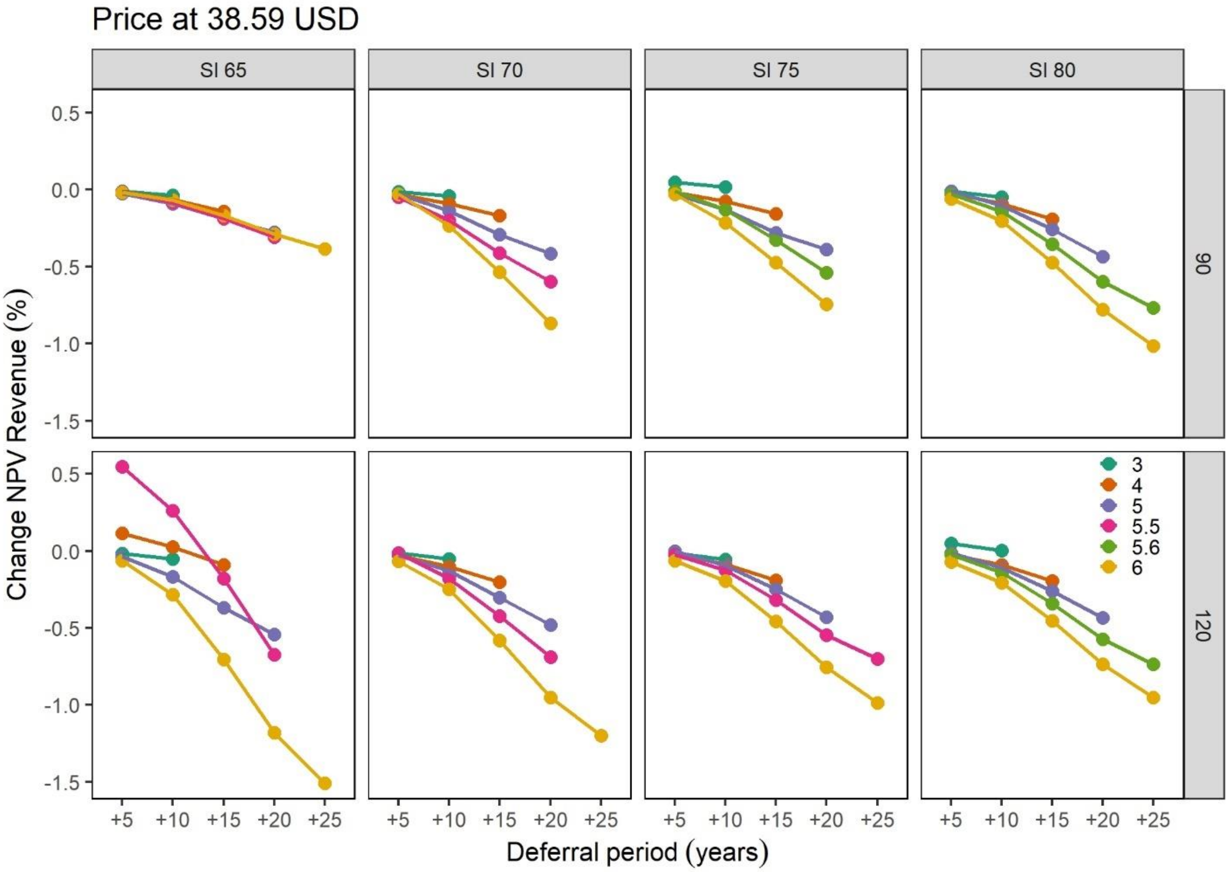


Figure. 12. Percent Change in NPV per management scenario (SI values of 65, 70, 75, 80 and thinning intensities of 90 and 120 trees/acre remaining post-thin) and discount rates. Base refers to year in which NPV is maximized, or "optimal harvest age", in which carbon breakeven price is calculated in subsequent years until age 50. +5, +10, +15, +20, and +25 refer to 5-year deferral increments after optimal harvest age. Within each treatment either discount rates of 5.5% or 5.6% are used to place optimal harvest age at age 29, where harvesting occurred in observed data. Figure created using R Studio faceting.

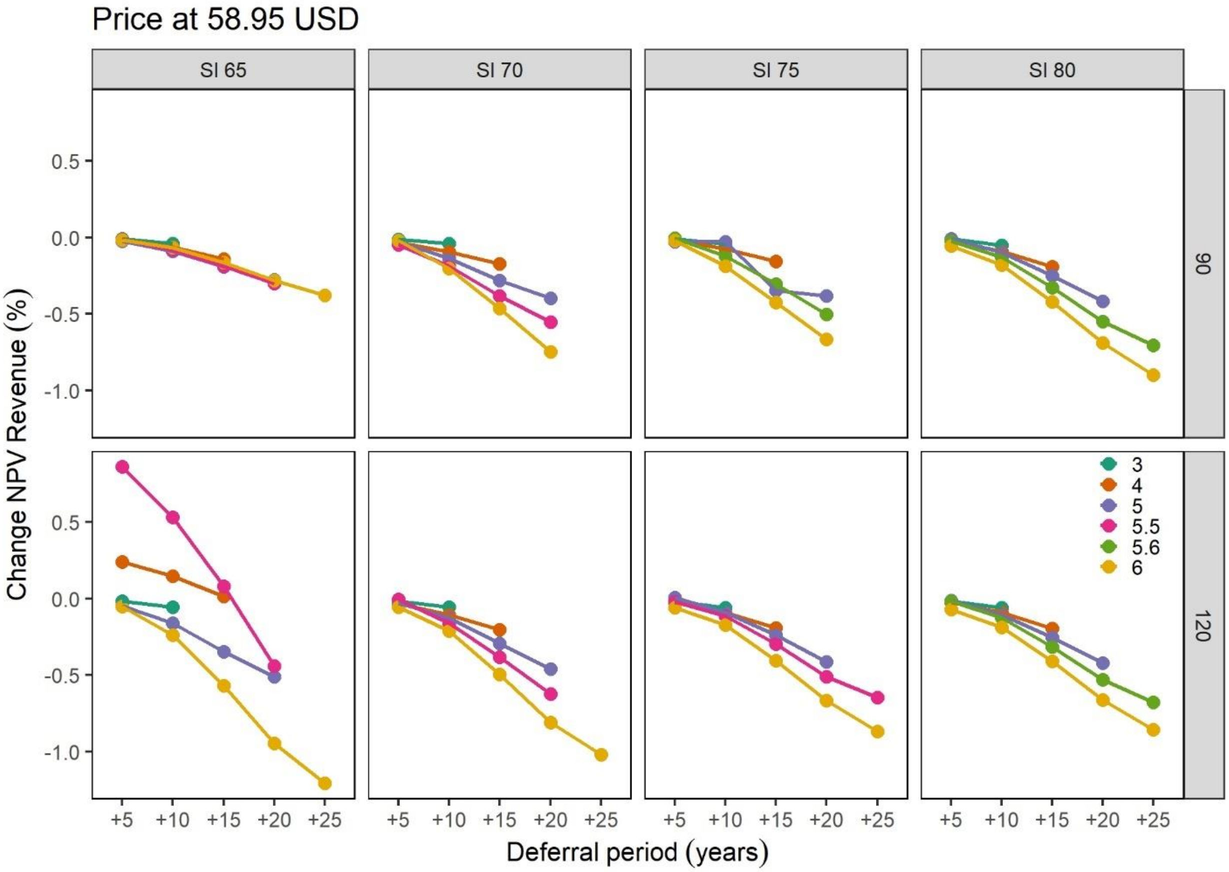


Figure. 13. Percent Change in NPV per management scenario (SI values of 65, 70, 75, 80 and thinning intensities of 90 and 120 trees/acre remaining post-thin) and discount rates. Base refers to year in which NPV is maximized, or “optimal harvest age”, in which carbon breakeven price is calculated in subsequent years until age 50. +5, +10, +15, +20, and +25 refer to 5-year deferral increments after optimal harvest age. Within each treatment either discount rates of 5.5% or 5.6% are used to place optimal harvest age at age 29, where harvesting occurred in observed data. Figure created using R Studio faceting.

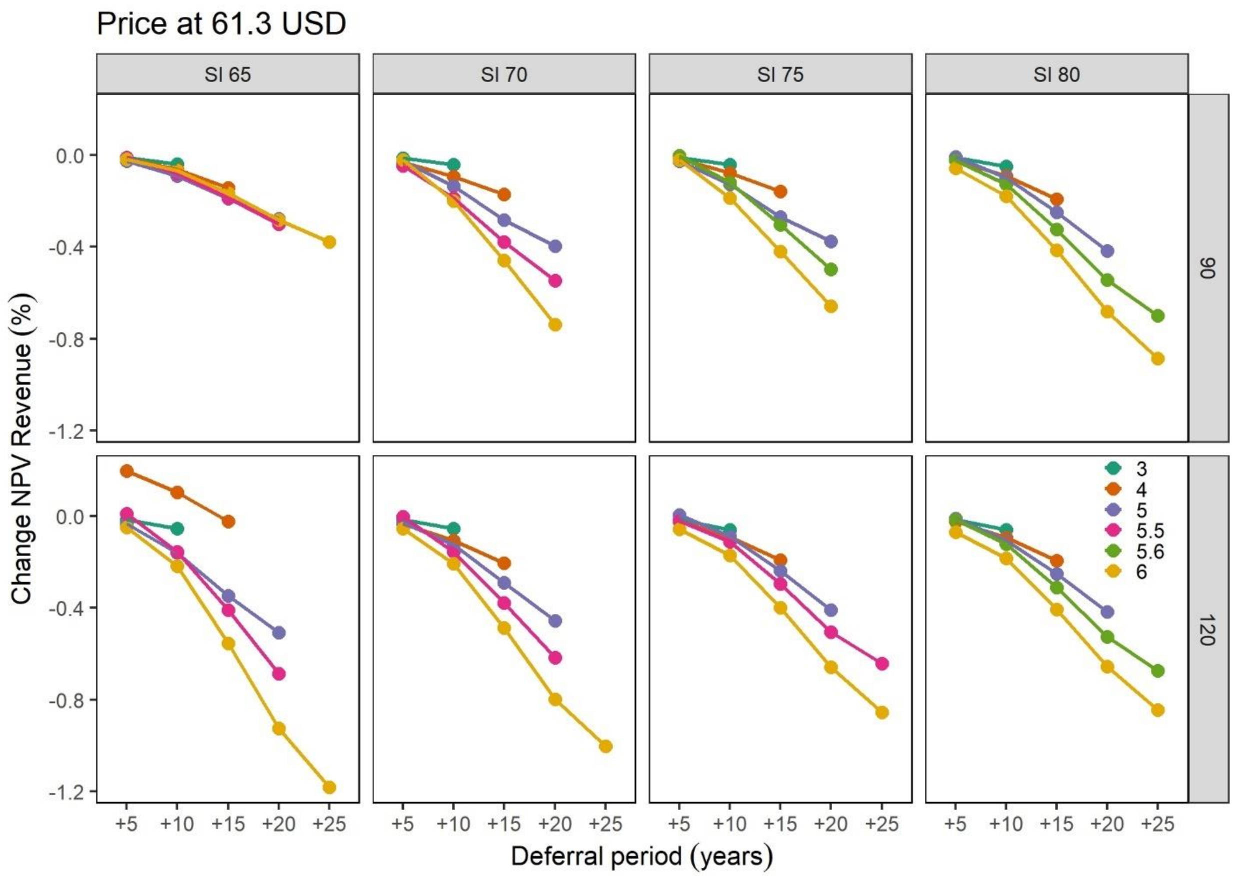


Figure. 14. Percent Change in NPV per management scenario (SI values of 65, 70, 75, 80 and thinning intensities of 90 and 120 trees/acre remaining post-thin) and discount rates. Base refers to year in which NPV is maximized, or "optimal harvest age", in which carbon breakeven price is calculated in subsequent years until age 50. +5, +10, +15, +20, and +25 refer to 5-year deferral increments after optimal harvest age. Within each treatment either discount rates of 5.5% or 5.6% are used to place optimal harvest age at age 29, where harvesting occurred in observed data. Figure created using R Studio faceting.

Over a maximum 25-year deferral period, NPV remains largely consistent in its rate of change across the deferral period (Figures 11-14). A decrease in percent change occurs over the course of the deferral period, with the decrease most prominent within higher discount rates of 5.5/5.6 and 6%.

3.5 Discussion

3.5.1 Carbon price

The price calculated for carbon breakeven prices for all treatments range between $0-$2 USD, with the largest breakeven prices coming at the end of the deferral period, or age 50 (Figure 5). The impacts incurred by both the discount rate and costs associated with continued management are increasing over the course of the deferral period. However, all calculated breakeven prices are considerably lower than those of real-world carbon markets. Therefore, this supports Hypothesis 1. As seen in Figures 6-10, participation in any of the real-world carbon markets would lead to considerably larger revenues for the landowner than revenues based on payment derived from carbon breakeven prices.

However, while each treatment does lead to higher revenues gained by the landowner through engaging in any carbon payment program, there are two potential limiting factors impacting carbon breakeven price that are not considered by this study. The first is potential fluctuations in both timber and carbon prices over the course of the deferral period. These fluctuations can lead to uncertainty on the part of the landowner within these scenarios, as sudden market-wide shifts within either timber or carbon markets can result in sharp shifts in the relative benefits incurred by the landowner. If a management decision is made with the belief that the landowner will receive payments from a carbon payment based on price x and the payments are x-1 when the deferral period begins, then the landowner will experience far fewer benefits than originally planned. This not only decreases the benefits incurred by the landowner but also decreases their likelihood of participating in and recommending forest carbon programs in the future.

The second of these limiting factors is the limited data with which certain calculations, namely unit conversions, can be made. Long-term loblolly pine carbon concentration amounts are poorly understood, as this study uses (King et al., 2007) for unit conversions of biomass amounts into carbon. King et al. 2007's data regarding Red Pine serves as the only research concerning long-term Pine carbon concentration dynamics. Similarly, while aboveground biomass is continuously increasing throughout modeled aboveground biomass, this may not be reflective of long-term biomass accumulations. LobDSS, while effective in determining harvestable amounts in short and mid-term rotations, is less accurate when considering long-term rotation lengths(Amateis et al., 2001; Peay et al., 2022; H.-J. Wang et al., 2012). Therefore, more research is needed to quantify long-term loblolly pine biomass accumulation in order to more effectively manage for increased carbon storage within these contexts.

3.5.2 Landowner benefits from carbon market participation

Within differing management scenarios, carbon prices, and discount rates, NPV remains positive throughout most deferred harvesting dates (Figures 7-10). Therefore, over the course of the majority of deferral periods, the NPV is within the positive range, confirming the second hypothesis. For all deferral periods within discount rates 3%, 4%, or 5%, the NPV values remain positive from the beginning of the deferral period until the end of the 50-year rotation period, however, within some scenarios under discount rates of 5.5/5.6% and 6%, NPV values decrease into the negative range, demonstrating the outsized impact that discount rate can have on the profitability of deferral programs (Emmerling et al., 2019; Li & Pizer, 2021; Price, 2018).

Additionally, NPV rates over the deferral period remain consistent, with a few exceptions (Figures 11-14). Due to the compounding value of discount rates, the greater the period of deferring harvest leads to gradually decreasing NPV values; there is a slightly negative trend in the NPV rates of change over the course of the deferral period. Therefore, while there may be a sudden increase in the NPV and total revenue generated for the forest manager for a brief period after the beginning of the deferral period, these gains will erode over the course of the total deferral period, if all else is constant.

This provides additional insight for landowners into the macroeconomic parameters that most influence the relative successes/benefits that can come from participation within a carbon market. Of these parameters, the most impactful is the discount rate. For landowners to have the greatest chance of benefitting from participating within a carbon offset market (when compared to their typical baseline of non-participation and harvesting during the optimal harvest age), landowners should base their decision largely on the discount rate, as rates of 3, 4, and 5% all are beneficial to increasing benefits, whereas 5.5/5.6 and 6% discount rates are less beneficial and are more likely to lead to negative NPV values during deferral. Additionally, policymakers looking to encourage participation within carbon offset markets can benefit from policy decisions which lower the discount rate, thus creating a more advantageous set of economic circumstances for carbon offset markets to flourish. As the current main discount rate used by the majority of the financial institutions through the U.S at the time of this study is 4.5%, current economic conditions are within the range in which participation would hypothetically be beneficial to the landowner (*Current Discount Rates*, n.d.).

While this study can simulate approximate costs and benefits associated with deferred harvesting and participation within a carbon offset market, not all costs and benefits are considered, specifically those costs associated with participation within a market. This study assumes that money spent is used without potential waste or mismanagement, and as carbon offset markets have a small regulatory framework within the United States, this may not be true in all cases that seek to participate with these markets (Babonneau et al., 2018; Charnley et al., 2010; Layton & Siikamäki, 2009; Lederer, 2012; Moser et al., 2022; Ristea & Maness, 2009; Ruseva, 2023; Smith & Heath, 2022). At the time of this study, North Carolina does not have a statewide carbon offset market, therefore there is little regulatory oversight determining if additionality in carbon storage is indeed being achieved, which in turn calls the “legitimacy” of monetary values associated with storage into question. Effective carbon accounting frameworks have been established, however there exists few guardrails for these markets outside of states that have official carbon programs other than the market itself. Ideally, this allows the market to quickly respond to updated carbon pricing to best reflect current needs, however this runs the risk of price fluctuation stoking distrust in the market, as well as carbon storage occurring within these projects at higher or lower levels than are accounted for.

3.6 Conclusions

For an industrial loblolly pine plantation in Washington County, NC, participation a carbon offset market with a carbon price higher than that of the breakeven prices calculated would lead to positive revenue values incurred for the landowner within most management scenarios. This study highlights the critical need for additional literature serving as case studies examining the effects and potential benefits carbon offset markets can have within the Southeastern American forestry sector. Greater insight into market-driven climate change solutions precipitates greater action within both forest managers and policymakers. Understanding the potential benefits that can come from climate-smart forestry practices and the costs that come alongside ignoring these practices is a critical step in increasing terrestrial carbon storage.

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