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# Financial Feasibility of Increasing Carbon Sequestration in Mississippi Forests Sector

Prakash Nepal

# FINANCIAL FEASIBILITY OF INCREASING CARBON SEQUESTRATION IN MISSISSIPPI FOREST SECTOR

By

Prakash Nepal

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FINANCIAL FEASIBILITY OF INCREASING CARBON SEQUESTRATION IN

MISSISSIPPI FOREST SECTOR

By

Prakash Nepal

Approved:


___________________________________
Robert K. Grala
Assistant Professor, Department of Forestry
(Director of Dissertation)

___________________________________
Donald L. Grebner
Professor, Department of Forestry
(Co-Major Professor)

___________________________________
Ian A. Munn
Professor, Department of Forestry
(Committee Member)

___________________________________
Scott D. Roberts
Associate Professor, Department of Forestry
(Committee Member)

___________________________________
Rubin Shmulsky
Professor, Department of Forest Products
(Committee Member)

___________________________________
Andrew W. Ezell
Head and Graduate Coordinator
Department of Forestry

___________________________________
George M. Hopper
Dean of the College of Forest Resources

Name: Prakash Nepal

Date of Degree: April 29, 2011

Institution: Mississippi State University

Major Field: Forest Resources

Major Professor: Robert K. Grala and Donald L. Grebner

Title of Study: FINANCIAL FEASIBILITY OF INCREASING CARBON SEQUESTRATION IN MISSISSIPPI FOREST SECTOR

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Candidate for Degree of Doctor of Philosophy

The specific objectives of this project were: 1) Determine financial viability of enrolling forest landowners in Chicago Climate Exchange (CCX) forestry carbon offset protocols; 2) Determine financial trade-offs associated with managing loblolly pine (*Pinus taeda* L.) and Cherrybark oak (*Quercus pagoda* Raf.) stands for increased carbon sequestration and timber; 3) Examine financial feasibility of increasing carbon accumulation in wood products carbon by extending rotation length of loblolly pine stands; and 4) Explore potential impacts of carbon policies and programs on future carbon accumulation in Mississippi's forest sector.

Results indicated that forest landowners could benefit from participation in CCX carbon offset programs without implementing substantial changes in timber management regimes. The largest net revenue ($6,032/ha) from managing loblolly pine stands jointly for timber and carbon sequestration was obtained by enrolling in two CCX contracts. However, enrollment in three subsequent contracts accrued the largest joint revenue ($1,128/ha) in case of cherrybark oak. Managing stands only for increased $CO_2$ sequestration (50 years for loblolly pine and 80 years for cherrybark oak) decreased

revenues from timber by up to 31% for cherrybark oak and 12% for loblolly pine stand. Results showed a potential to increase carbon accumulated in wood products by 16 t/ha to 67 t/ha for rotation increases in loblolly pine stands from five to 65 years, respectively. However, carbon prices of \$50/t $CO_2$e and \$110/t $CO_2$e would be needed to provide sufficient incentives to forest landowners to extend rotation by five and 10 years, respectively. Finally, results indicated that implementation of carbon policies and programs can increase carbon accumulation in Mississippi by up to 264.24 Teragram (Tg) by 2051, depending on future harvest levels. In general, carbon policy scenarios representing a decreased harvest in short-run and increased-harvest in long-run, accumulated more carbon in forests but less carbon in wood products than a baseline scenario representing constant harvest at the 2006 level and increased harvest scenario representing future microeconomic conditions in the U.S.

The results of this study can be helpful to forest landowners considering enrollment in carbon offset programs and policy makers interested in management of forest resources for mitigating $CO_2$ emissions.

DEDICATION

I would like to dedicate this research to my parents, Mr. Hom Nath Nepal and Mrs. Kamala Nepal; my wife, Neeti Nepal; and to my daughter, Himangi Nepal; for their love, continuous support, and encouragement.

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# CHAPTER I

# GENERAL INTRODUCTION

## 1.1 **Introduction**

There has been an increasing effort to mitigate negative effects of global warming, a process that leads to a gradual increase in earth's temperature. It is believed to be caused by high concentration of greenhouse gases (GHGs) in the atmosphere with carbon dioxide ($CO_2$) being the greatest contributor (IPCC 2001). Efforts to reduce the negative impacts of global warming have focused on reduction of atmospheric concentration of $CO_2$. The process of removing $CO_2$ from the atmosphere by increasing the carbon content in carbon pools other than the atmosphere is referred as carbon sequestration (US EPA 2010). Trees have the ability to sequester atmospheric $CO_2$ during the process of photosynthesis. Because of this ability, forestry activities are widely recognized as one of the promising $CO_2$ mitigation strategies (EPA 2010). Examples of forestry activities reducing atmospheric $CO_2$ include protecting existing forests, expanding area of new forests, delaying harvest, increasing inventory of long-lived wood products, and replacing non-wood materials with wood products (Sedjo 2001). The forest sector can play an important role in reducing atmospheric $CO_2$ because it has the ability to sequester $CO_2$ at lower cost relative to other methods such as direct emission reduction (Richards 2004, Sedjo 2001, Newell and Stavins 2000, Plantinga et al. 1999). Although forestry alone cannot offset all $CO_2$ emissions, plantation and natural forests can be a part of emission mitigation strategies (Woodbury et al. 2007, Han et al. 2007, Birdsey and

Heath 1995). According to Birdsey and Heath (1995), forests in the United States sequestered a net total of 10.3 billion metric tons (t) of $CO_2$ per year during 1952-1992, which offset approximately 25% of U.S. anthropogenic emissions of $CO_2$ during that period.

The wood products industry also offers a considerable potential for achieving additional increases in carbon sequestration by locking carbon in wood products for long time periods and preventing it from being immediately released back into the atmosphere (Skog et al. 2004, Birdsey and Lewis 2003, Skog and Nicholson 2000, Skog and Nicholson 1998, Winjum et al. 1998, Row and Phelps 1996). According to Dewar (1990), more carbon could be sequestered in wood products by substituting long-lived wood products (e.g. lumber) for short-lived wood products (e.g. pulpwood). Based on the 1993 Resource Planning Act (RPA) assessment base projection, estimates by Skog et al. (2000) indicated that carbon accumulation in roundwood products would increase to 210 Tg/year by 2040. These amounts are substantial in relation to the U.S. forest sector total carbon sequestration potential indicating important role wood products carbon could play in $CO_2$ mitigation goals.

To increase the potential for mitigating $CO_2$ emissions, several voluntary and mandatory carbon programs such as the Chicago Climate Exchange (CCX), Regional Greenhouse Gas Initiative (RGGI) and Climate Action Reserve (CAR) have been established in the U.S. These programs provide monetary incentives to landowners for managing their forests for increased carbon sequestration. Various types of forest activities are eligible for carbon payments such as new plantations, existing forests managed for increased carbon, and long-life wood products. Most of current carbon programs provide payments for carbon sequestration and allow for managing forests for timber during the contract period. Therefore, timber and carbon can be viewed as joint outputs that forest owners should consider to increase revenues through forest management. Financial incentives available through carbon programs have been considered in management decisions by an increasing number of forest landowners. Demand for carbon offsets is expected to increase with the implementation of a mandatory GHG reduction program leading also to higher carbon prices.

Although the topic of forest carbon sequestration potential and its economic impacts have been widely discussed, limited information is available for Mississippi as related to the economics of carbon sequestration in standing trees and harvested wood products. In addition, most studies that explored economic aspects of forest carbon sequestration were based on hypothetical carbon payment scenarios. Studies on financial and management implications of enrolling in actual carbon markets are scarce.

Forestry constitutes one of the prominent economic activities in Mississippi. With 65% of the land in forest cover (Mississippi Forestry Association 2008), and annual production of more than 800 million cubic feet of timber (Howell and Johnson 2009), the Mississippi forest sector can effectively contribute to achieving U.S. carbon sequestration goals. However, little information is available on managing specific commercial tree species in Mississippi under existing carbon sequestration programs. To develop viable strategies for increasing carbon sequestration through forest sector, it is necessary to understand the carbon sequestration potential for commercial species and associated financial trade-offs resulting from carbon-oriented forest management in the context of existing carbon markets. Although existing carbon platforms offer forest landowners an opportunity to generate additional income, managing forests for increased $CO_2$ sequestration might be challenging because such management can potentially conflict with timber production. Whether carbon management based on enrollment in existing carbon protocols will affect stand thinning and harvest regimes, and landowner revenues is still unclear. Greater participation of forest landowners in carbon markets, and consequently higher rate of carbon sequestration, may be achieved by providing landowners with information on potential financial returns associated with enrollment in carbon sequestration programs. Chapters II and III explored these issues for two commercially important tree species in Mississippi, loblolly pine (*Pinus taeda L*) and cherrybark oak (*Quercus pagoda Raf.),* based on stand enrollment in Chicago Climate Exchange (CCX) forestry carbon offset protocols. Chapter II examined financial viability of managing loblolly pine stands enrolled in CCX forestry carbon offset protocols jointly for timber and carbon sequestration by identifying management regimes that generated the largest Net Present Value (NPV). Chapter III investigated trade-offs in terms of generated returns and quantities of sequestered $CO_2$ for two major commercially important species in Mississippi: loblolly pine and cherrybark oak.

Chapter IV examined financial feasibility of increasing carbon sequestration in harvested wood products. This was achieved by quantifying amounts of carbon accumulated in wood products harvested from a loblolly pine stand at various rotation ages and determining compensation needed to make these rotations financially feasible.

Because carbon accumulation in forests and harvested wood products largely depends on current and future harvest levels, another important research question related to forest sector $CO_2$ mitigation potential is to understand the impact of future harvests on carbon accumulation in forests and wood products. Chapter V explored how future carbon accumulation in forests and wood products is impacted by carbon policies resulting in different future harvest levels. Carbon accumulated in forests and harvested wood products was quantified for six different harvest scenarios including constant, increased and mixed level harvests for period 2006-2051. Chapter VI summarizes important findings of four studies included in this dissertation and offers recommendations for future research.

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CHAPTER II

# FINANCIAL IMPLICATIONS OF ENROLLING MISSISSIPPI FOREST LANDOWNERS INTO CARBON OFFSET PROGRAMS[1]

## 2.1 Abstract

This study examined the financial viability of managing loblolly pine (*Pinus taeda* L.) stands for increased carbon sequestration by Mississippi nonindustrial private forest (NIPF) landowners under three Chicago Climate Exchange (CCX) forestry carbon offset programs: afforestation, managed forests, and long-lived wood products. At carbon prices of $4.25 per metric ton of carbon dioxide equivalent (t $CO_2$e) and $10/t $CO_2$e, a forest management regime that provided the largest Net Present Value (NPV) from timber production also provided the largest NPV when the stand was jointly managed for timber and increased carbon sequestration, regardless of number of contracts. At a carbon price of $4.25/t $CO_2$e, a joint management for timber and increased carbon sequestration generated an additional NPV of up to $937/hectare (ha) when compared to the best management regime for timber only. Carbon prices of $10/t $CO_2$e and $20/t $CO_2$e increased NPV by $2,406/ha and $5,335/ha, respectively.

Key words**:** afforestation, carbon credits, Chicago Climate Exchange, loblolly pine, Net Present Value, stand density index.

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[1] This manuscript is forthcoming in the Southern Journal of Applied Forestry. Authors of this manuscript are Nepal P., R.K. Grala, and D.L. Grebner.

## 2.2 Introduction

Carbon offset programs developed to mitigate high concentrations of atmospheric carbon dioxide ($CO_2$) provide Mississippi forest landowners with an opportunity to generate additional income. The majority of forests in the Southern Region are owned by nonindustrial private forest (NIPF) landowners with diverse ownership goals (Best and Wayburn 2001). These landowners manage their forests for various benefits such as timber, wildlife habitat, scenic value, and other non-timber benefits (Best and Wayburn 2001). NIPF landowners provided the majority of timber harvested in the southern U.S. (Alig et al. 1990). According to Smith et al. (2004), 194.15 million cubic meters (m3) (68%) of the 2001 total timber removal in the U.S. southern region was completed on NIPF lands. This indicated that NIPF landowners could play a major role in mitigating U.S. $CO_2$ emissions by sequestering more carbon in standing trees and harvested wood products. However, it was unclear if NIPF landowners who manage their forests for timber production would be willing to manage these forests also for increased carbon sequestration because such management most likely will require longer rotations and might conflict with their timber management objectives.

The likelihood that forest landowners will engage in carbon sequestration programs depends on several factors including potential monetary returns. Fletcher et al. (2009) demonstrated that larger payments and lack of a withdrawal penalty had a positive impact on carbon supply. They also demonstrated that only 7% of surveyed landowners were willing to supply carbon at carbon prices of \$6 to \$18 per metric ton of carbon dioxide equivalent (t $CO_2$e). Greater participation of forest landowners in carbon markets can be increased by providing them with information on potential monetary returns associated with enrollment in such programs.

Currently, four primary platforms for trading carbon credits exist in the U.S.: Chicago Climate Exchange (CCX), Department of Energy (DOE) National Voluntary Reporting of Greenhouse Gases Program, California Climate Action Registry (CCAR), and Regional Greenhouse Gas Initiative (RGGI). All programs recognize afforestation and managed forests as offset projects except RGGI which recognizes afforestation only. CCX is the only exchange platform (Ruddell et al. 2006) and the largest marketplace for trading forest carbon offset credits in the U.S. Although the U.S. currently does not have a mandatory greenhouse gas (GHG) reduction program, the first such program might be in effect as early as 2012 if the American Clean Energy and Security Act of 2009 (also known as the Waxman-Markey bill) is passed by the U.S. Senate.

It is expected that carbon offset demand will increase with the implementation of a mandatory GHG reduction program leading also to higher carbon prices. For example, the European Climate Exchange (ECX), a mandatory GHG reduction program, started in 2005 with a total volume of 94 million t $CO_2$e that increased to 2,421 million t $CO_2$e by August 2009. Similarly, CCX started trading carbon credits in 2003 with an initial volume of 0.03 million t $CO_2$e that increased to 3.7 million t $CO_2$e by May 2009 (CCX 2009a). Currently, the ECX trades carbon credits at about \$20/t $CO_2$e compared to CCX price of \$0.10/t $CO_2$e.

Several studies that examined the impact of carbon payments on forest management at the stand level indicated that such payments would result in longer rotations. Huang and Kronrad (2006) who studied the impact of carbon revenues on rotation and profitability of loblolly pine (*Pinus taeda* L.) plantations in east Texas reported that the rotation age for stands jointly managed for timber and carbon may increase or decrease depending on the alternative rate of return (ARR). An ARR of 7.5%

or higher resulted in increased rotation, whereas with a lower ARR, the rotation length stayed the same for stands planted on low quality sites and shortened for higher quality sites. Stainback and Alavalapati (2002) conducted an economic analysis of carbon sequestration for slash pine (*Pinus elliottii*) stands in the southern U.S. and demonstrated that a carbon price of $20/t could increase Land Expectation Value (LEV) by as much as 56%. They concluded that carbon subsidies and taxes led to longer rotations and increased the sawtimber supply and decreased the pulpwood supply. Others who examined the feasibility of joint management for timber and carbon sequestration also suggested longer rotations but with substantial increases of landowner income. Pohjola and Valsta (2007) indicated the importance of thinning and delayed harvest for increased revenues at carbon prices of €10 and €20/t $CO_2$e when analyzing the impact of a carbon tax/subsidy program for Norway spruce (*Picea abies*) and Scott pine (*Pinus sylvestris*) in Finland. McCarney et al. (2008) who analyzed joint management for timber, carbon, and wildlife habitat in the Canadian boreal plains reported that multiple-use management would be the best approach for managing forests at low carbon prices, whereas higher carbon prices would lead to land-use specialization. Nepal et al. (2009) investigated the financial feasibility of sequestering carbon by loblolly pine stands in Mississippi and reported a 10-year increase in rotation age and up to a 52% increase in LEV at a carbon price of $4.50/t $CO_2$e.

These studies considered hypothetical carbon subsidies and tax incentives and did not account for specific carbon payment schemes offered by existing carbon programs. There is a need to examine financial implications of enrolling into current carbon programs to provide NIPF landowners with information on potential revenues associated with carbon sequestration and best management strategies to attain these revenues. This study examined financial viability of managing loblolly pine stands enrolled in CCX forestry carbon offset contracts held jointly for timber and carbon sequestration by identifying management regimes that generated the largest Net Present Value (NPV). This study used NPV because an inherent assumption in LEV approach is that the stand is managed with the same management regime in perpetuity. However, after the first rotation, if subsequent plantations were established on the same land parcel, carbon sequestered by these plantations would not qualify for credit because it would no longer satisfy additionality criterion. Consequently, the analysis was completed only for carbon contracts implemented during the first rotation using NPV.

## 2.3 **Methods**

### 2.3.1 Financial analysis

The study used NPV and Annual Equivalent Value (AEV) as indicators for determining viability of managing loblolly pine stands for increased carbon sequestration. NPV and AEV were determined for stands managed for timber only and stands jointly managed for timber and carbon sequestration and enrolled in up to three subsequent CCX contracts. The landowner always started with an afforestation contract, which was followed by two subsequent managed forest contracts and a long-lived wood products contract.

The analysis was conducted on pre-tax basis using a 5% real discount rate, which has often been used to evaluate forest investments. For example, Bullard et al. (2002) reported that the pre-tax minimum acceptable real rates of return required by Mississippi NIPF landowners ranged from 5.7 to 10.7% depending on the length of the investment and household income. In another study, Bullard and Straka (1998) indicated that U.S.

Forest Service and forestry corporations used discount rates of 4 and 8%, respectively. Data on prices and costs associated with timber production and enrolling into CCX carbon offset programs was collected from various sources (Table 2.1). The analysis used average stumpage prices for pulpwood and sawlogs and it was assumed costs associated with thinning and final harvests were incurred by loggers. It also was assumed that NIPF landowners received payments for sequestered carbon at the end of each contract year and that there was no catastrophic loss of carbon during the contract. Therefore, carbon previously placed in the forest carbon reserved pool (FCRP) was traded at the end of the contract period. Although the current CCX market period ends on December 31, 2010, and no decision was made on extending it beyond this date, the analysis was completed for different combinations of contracts with a total duration up to 45 years. The analysis utilized 3,780 scenarios reflecting two stand management objectives (i.e., timber management and joint management for timber and carbon sequestration), three planting densities, 10 thinning intensities and timing options, seven harvest ages (i.e.,20, 25, 30, 35, 40, 45, 50 years), three types of carbon contracts, and three carbon price levels. Based on the financial analysis, the harvest age that provided the largest NPV was considered as financially best. Reported harvest ages in the manuscript represents the financially best harvest ages.

### 2.3.2 Carbon accumulated in loblolly pine stands and harvested wood products

Forest Vegetation Simulator (FVS) was used to generate volume information needed to determine amounts of carbon sequestered by loblolly pine stands established with 1,077 trees per hectare (TPH), 1,494 TPH, and 1,818 TPH, respectively, in Mississippi on a medium quality site (Site Index of 32 meters at base age of 50 years).

These three planting densities represented low, medium, and high end of planting densities operationally common in Mississippi. Stands were treated with selected thinning regimes based on Reineke's Stand Density Index (SDI) (Reineke, 1933). Since the crown closure or on-set of competitive interaction occurs at around 15 to 25% of maximum SDI, and a lower limit of self-thinning is considered at 55-65% of maximum SDI, a situationally appropriate thinning limit varies between 65% (upper limit) and 15% (lower limit) (Jack and Long 1996, Long 1985). Three upper limits (65%, 55%, and 45% of maximum SDI) and three lower limits (15%, 25%, and 35% of maximum SDI) were selected to represent 10 different thinning regimes. A thinning regime with an upper limit of 45% of maximum SDI was selected to promote an individual tree growth for sawlog production. An upper limit of 65% of maximum SDI was selected to favor a stand growth for pulpwood production, whereas an upper limit of 55% of maximum SDI was selected to maintain individual tree growth and stand growth for both sawlog and pulpwood production. These upper and lower limits were selected based on theoretical growth-growing stock relationships described by Long et al. (2004), Jack and Long (1996), and Long (1985). A thinning regime that retained 25% or less of maximum SDI was considered as heavy intensity thinning. A medium intensity thinning regime retained 25 to 35% of maximum SDI (Long 1985). The upper thinning limit determined the age at which a stand was thinned, whereas the lower limit determined the proportion of trees to be removed. For example, for a loblolly pine stand with maximum SDI of 505 (USDA 2001), the upper limit of 55% indicated that thinning would occur when SDI reaches 278 and the lower limit of 35% implied that a certain proportion of trees would be removed resulting in a residual SDI of 177. Timing and intensity of thinnings designed to meet the specified upper and lower limits of SDI was presented in Table 2.2.

Carbon stored in aboveground live and belowground live biomass was estimated with the FVS carbon sub model (Reinhardt et al. 2007). The estimate of aboveground live carbon was determined using an algorithm for merchantable, crown, and unmerchantable biomass excluding bark, which was based on region specific volume equations combined with the specific gravity of wood. Estimates of belowground live carbon were based on allometric relationships developed by Jenkins et al. (2003).

Estimates for carbon stored in wood products were determined by using factors and equations published by CCX (CCX 2008). The volume of harvested wood was converted to carbon weight (tons) using the CCX conversion factor (CCX 2008). Next, the carbon weight was distributed to two wood products categories: pulpwood and sawlogs. Next, the weight of carbon remaining in wood products in use and in landfills 100 years from harvest was calculated using the CCX conversion factor (CCX 2008). Finally, carbon weight was converted to t $CO_2$e by multiplying by appropriate conversion factors (Table 2.3).

### 2.3.3 CCX requirements

The study considered enrollment in three CCX forestry carbon offset projects: afforestation, sustainably managed forests, and long-lived wood products. Under the afforestation protocol, afforestation projects initiated after December 31, 1989 and reforestation projects implemented on degraded forest lands and initiated after January 1, 1990 are eligible (CCX 2009d). This protocol does not allow thinning or harvesting of any form during the contract period which typically is 15 years. Carbon credits are issued for the carbon sequestered in live trees and soil organic carbon. A portion of earned credits (20%) is placed into the forest carbon reserve pool (FCRP) as an insurance against catastrophic carbon loss. If carbon loss does not occur, then the reserve is released back to the project owner at the end of contract period.

Under the managed forests protocol, forest landowners are issued carbon credits for the net amount of additional carbon sequestered in reference to the baseline year. This study assumed a baseline year at 15 years, following immediately the end of the first contract period. The second baseline was determined at age of 30 years, which corresponded to the end of the second contract period. While this protocol allows for active stand management including harvesting, it does not allow for clear-cut harvests. This protocol also requires that 20% of the sequestered carbon to be placed in FCRP to offset potential carbon losses.

In a case of long-lived wood products protocol, forest landowners earn credits for carbon stored in wood products that are still in use (or in a landfill) 100 years from the harvest date. This protocol does not require carbon credits to be placed in FCRP. All three protocols require an annual accounting report and annual audit verification report from a CCX-approved verifier. Currently, there are 12 CCX-approved verifiers for forestry carbon offset projects and their list can be found at the CCX Web site (CCX 2010).

Forest landowners incur various upfront costs when enrolling into CCX carbon contracts such as those for certifying forests for sustainability, forest management plan preparation, and forest inventory. In addition, NIPF landowners incur participation costs including an aggregator's fee, annual verification fee, and CCX fee. Certification costs were omitted because landowners can certify their forests free of charge from voluntary certification programs such as American Tree Farm System (ATFS) as long as they have a forest management plan. Upfront costs including the cost of forest management plan preparation and initial inventory was assumed to be $20/ha (Bilek et al. 2009). An aggregator fee was assumed to be 10% of the carbon payment (AgraGate Climate Credits Corporation 2008). The verification cost is verifier-specific and depends on crew size and time spent on verification. This study assumed a verification cost of $0.25/t $CO_2$e (Bilek et al. 2009). Finally, the analysis included a CCX registration fee of $0.20/t $CO_2$e (AgraGate Climate Credits Corporation 2008). Participation costs were assumed to occur annually.

## 2.4 **Results**

When managed for timber only, a loblolly pine stand generated the largest NPV of $5,126/ha when it was established with a medium planting density (1,494 TPH), moderately thinned at ages of 16 and 25 years, with each thinning removing 38% of the merchantable volume, and harvested at age of 35 years. At a low planting density (1,077 TPH), the largest NPV generated from timber management only was $4,701/ha with a harvest age of 35 years and three medium intensity thinnings at ages 16, 20 and 25 years, with an average merchantable volume removal at 27%. A high planting density (1,793 TPH), generated the largest NPV from management for timber only at $5,049/ha with a harvest age of 35 and two medium intensity thinnings at age 16 and 25 years removing 40% of merchantable volume. Overall, medium intensity thinning regimes fared better for timber management because they generated larger revenues than heavy, and no thinning scenarios.

When the stand was managed under CCX forestry carbon offset protocols and enrolled in one (0-15 years) or two carbon contracts (0-30 years), the best strategy for joint management of timber and carbon sequestration was also the best timber management for all evaluated planting densities. However, enrollment in three subsequent contracts required a rotation age 11 years longer when compared to the best timber only management strategy decreasing the NPVs from timber by $300/ha, $293/ha, and $261/ha for low, medium, and high planting densities, respectively.

With carbon payments accounted for, net revenues increased substantially for the stand jointly managed for timber and increased carbon sequestration. At a carbon price of $4.25/t $CO_2$e, enrollment in one, two, and three contracts generated NPVs of $5,912/ha, $6,032/ha, and $5,768/ha, respectively, all with a medium planting density (Table 2.4). These amounts were generated with a medium thinning intensity regime and rotation ages of 35, 35, and 46 years, respectively.

For low, medium, and high planting densities, enrollment in one contract increased NPVs by 14 to 17% when compared the best scenario for timber management only. Similarly, enrollment in two contracts increased NPVs by 18 to 19%. While enrollment in three contracts also increased NPVs, increases were smaller than increases generated by enrollment in one or two contracts (Table 2.4). Analysis based on AEV indicated similar results regarding the best management regimes (Table 2.5). Analysis of thinning regimes from a perspective of joint management for timber and carbon sequestration showed that, in general, the medium intensity thinnings resulted in largest net revenues.

Sensitivity analysis was conducted to examine the effect of various carbon prices on net revenues from joint management for timber and increased carbon sequestration (Table 2.4). At a higher carbon price of $10/t $CO_2$e, the largest NPVs generated by enrollment in one contract were $6,383/ha, $7,147/ha, and $7,245/ha for low, medium and high planting densities, respectively. Enrollment in two contracts increased NPVs to

$7,107/ha, $7,451/ha, and $7,453/ha, respectively. However, when the stand was enrolled in three contracts, NPVs increased to $6,678/ha, $/7,232/ha, and $7,284/ha for low, medium and high planting densities, respectively. When compared to best management strategy for timber only, these amounts corresponded to NPV increases of 36, 51, and 42% for one, two and three contracts, respectively, for a low planting density. Similarly, corresponding increases in NPV for medium planting density were 39, 45, and 41%, whereas for a high planting density, they were 43, 48, and 44%. A current ECX price of $20/t $CO_2$e, resulted in NPVs as high as of $8,175/ha, $10,036/ha, and $9,097/ha for one, two, and three contracts, respectively, when a low planting density was used. Similarly, for a medium planting density, increases in NPVs were $9,295/ha, $10,451/ha, and 9,776/ha, respectively. With a high planting density, NPV increases due to joint management for timber and carbon sequestration were $9,577/ha, $10,271/ha, and $9,934/ha, respectively. When compared to timber management only, these amounts corresponded to revenue increases of up to 113% for a low planting density, 104% for medium planting density, and 103% for high planting density.

## 2.5 Discussion and conclusions

Study results indicated that Mississippi's NIPF landowners in can increase their revenues by managing loblolly pine stands jointly for timber and increased carbon sequestration. Enrollment in CCX offset protocols for two contracts can increase landowner revenues by up to 19% ($937/ha) at a carbon price of $4.25/t $CO_2$e, up to 51% ($2,406) at a carbon price of $10/t $CO_2$e and up to 113% ($5,335) at a carbon price of $20/t $CO_2$e. These results were similar to Huang and Kronrad (2006) who reported a 39% increase in Soil Expectation Value (SEV) for loblolly pine stands in east Texas at a carbon price of \$10/t $CO_2e$ and a real discount rate of 5%. Results also were comparable to Pohjola and Valsta (2007) who reported a NPV increase of up to 78% for the Scots pine stands and 65% for the Norway spruce stands in Finland at a carbon price of €10/t $CO_2e$.

This study indicated that the largest net revenue from managing the stand jointly for timber and increased carbon sequestration was obtained by enrolling in two contracts. This approach did not require any change in the rotation age suggesting that timber management and increased carbon sequestration were not necessarily incompatible. The timber management regime that generated the largest NPV also generated the largest NPV when managing the stand jointly for timber and carbon sequestration for a majority of analyzed scenarios.

This result was different from Pohjola and Valsta (2007), Nepal et al. (2009), and van Kooten et al. (1995) who reported increased rotation length due to carbon payments. This occurred because in this study carbon payments terminated after 15 years when enrolled in one contract and 30 years if enrolled in two contracts. Consequently, carbon payments did not influence harvest age beyond the contract duration. If carbon payments were available for an extended period, then the rotation age would have increased due to continuous carbon payments. This study indicated a rotation age increase of 11 years when carbon payments were available for 45 years. Enrollment in three contracts however, reduced net revenues from management for timber only compared to the best management strategy for timber only. This increase in rotation age and decrease in timber revenue was due to the restriction on clear-cut harvests until the end of third consecutive contract which was 45 years.

Timing, frequency, and intensity of thinnings had important implications on the amount of accumulated carbon and generated net revenues. The no thinning scenario was a better option for increasing revenues from a joint management for timber and carbon sequestration if enrolled for more than one contract and if carbon price was \$20/t $CO_2$e. However, it was the least preferred option if enrolled in only one contract because it reduced the carbon amount accumulated in long-lived wood products. This occurred because revenue from carbon was the same for all thinning scenarios for the first contract as there was no thinning or harvesting during contract duration. Any carbon sequestration increase was attributable to carbon accumulated in long-lived wood products which increased with longer rotations. However, this increase in carbon revenue was offset by the discount factor.

With a base carbon price of \$4.25/t $CO_2$e, a medium planting density performed better in terms of generated revenues for all contracts. A low planting density always generated the smallest joint revenues. Although the low planting density resulted in larger average tree diameter, the average sawtimber and pulpwood prices used in the analysis did not account for potential increases in revenues due to price premiums for large diameter trees. Average prices were used in the analysis because price data for different log dimensions were not available. For the higher carbon price of \$10/t $CO_2$e, a high density planting performed better in terms of net revenues, regardless of number of contracts, because it favored total biomass production and larger carbon payments resulted in larger net revenues. For a carbon price of \$20/t $CO_2$e, a high planting density generated the largest joint revenues from enrollment in one, and three contracts. However, a medium planting density generated the largest joint revenues from enrollment in two contracts. This occurred because with this price, a no thinning regime offered carbon revenues greater than timber revenues. A high planting density with the no thinning regime, while increasing carbon revenue, it also slightly decreased timber revenues when compared to a medium density planting. Therefore, the joint revenue was smaller for a higher planting density than the medium planting density for two contracts.

There is error inherent in all growth and yield models. Results presented in the study were dependent on the accuracy of the FVS in projecting tree growth and yield. Although reliability of projection decreases with the projection length, the FVS does not provide an estimation error. It is possible that results have been somewhat overestimated. However, it would be difficult to indicate its exact magnitude. Nevertheless, relative values presented would be similar despite any potential estimation error and provide useful information to landowners on potential benefits to enrolling into carbon contracts.

This study presented an alternative approach for analyzing the financial impact of carbon sequestration on stand management by utilizing payment structures of an existing carbon program. The study determined the best strategies for managing loblolly pine stands jointly for timber and increased carbon sequestration, which will be helpful to forest landowners considering enrollment in carbon sequestration programs. Previous studies analyzed the impact of hypothetical carbon taxes and subsidies on rotation length and NPV, and only a few identified the best strategies for increasing revenues from a joint stand management for timber and increased carbon sequestration. This study considered only selected thinning scenarios and three carbon offset protocols. Additional research is needed to account for alternative thinning scenarios and monetary incentives available to NIPF landowners from other carbon programs. Further research is also needed to determine the impact of a price premium for large diameter trees on revenues generated from managing forests for carbon sequestration.

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Table 2.1 Summary of the costs and revenues associated with managing loblolly pine (*Pinus taeda* L.) stands in Mississippi for timber and carbon sequestration under Chicago Climate Exchange (CCX) forestry carbon offset protocols.

| Costs/Revenues | Amount | Source |
|---|---|---|
| Costs: | | |
| Seedling | \$0.05/seedling | Plum Creek (2010) |
| Planting | \$0.088/seedling | Barlow et al. (2009) |
| Chemical site preparation | \$145.00/ha | Barlow et al. (2009) |
| Aggregator's fee | 10% of total carbon revenue | AgraGate Climate Credits Corporation (2008) |
| Verification fee | \$0.25/t $CO_2$e | Bilek et al. (2009) |
| CCX fee | \$0.20/t $CO_2$e | AgraGate Climate Credits Corporation (2008) |
| Revenues: | | |
| Carbon credit price | \$4.25/t $CO_2$e | CCX (2009c) (average closing prices of first quarter, 2008) |
| Sawtimber stumpage price | \$37.19/t | Timber Mart-South (2008) |
| Pulpwood stumpage price | \$9.29/t | Timber Mart-South (2008) |

Table 2.2 Thinning regimes defined based on thinning intensity and timing and upper and lower limits of maximum Stand Density Index (SDI) for loblolly pine (*Pinus taeda* L.) stands in Mississippi managed for timber and carbon sequestration.

| Trees per hectare | Upper limit[1] (% of Max SDI | Lower limit[1] (% of Max SDI) | Number[2] of thinnings | Thinning timing[2] (years) | Thinning intensity[2] (% of merch. volume) |
|---|---|---|---|---|---|
| 1077 | 45 | 15 | 2 | 15,40 | 67,67 |
| | 45 | 25 | 2 | 15,25 | 47,46 |
| | 45 | 35 | 4 | 15,20,25,35 | 28,29,22,23 |
| | 55 | 15 | 1 | 20 | 74 |
| | 55 | 25 | 2 | 20,45 | 57,53 |
| | 55 | 35 | 2 | 20,30 | 41,34 |
| | 65 | 15 | 1 | 25 | 76 |
| | 65 | 25 | 1 | 25 | 62 |
| | 65 | 35 | 1 | 25 | 47 |
| 1494 | 45 | 15 | 2 | 15,35 | 73,65 |
| | 45 | 25 | 2 | 15,25 | 57,48 |
| | 45 | 35 | 4 | 15,20,25,35 | 41,30,23,27 |
| | 55 | 15 | 1 | 15 | 73 |
| | 55 | 25 | 2 | 15,30 | 57,54 |
| | 55 | 35 | 3 | 15,25,40 | 41,39,34 |
| | 65 | 15 | 1 | 20 | 78 |
| | 65 | 25 | 1 | 20 | 64 |
| | 65 | 35 | 2 | 20,45 | 50,43 |
| 1793 | 45 | 15 | 2 | 10,25 | 64,69 |
| | 45 | 25 | 3 | 10,15,25 | 42,42,44 |
| | 45 | 35 | 4 | 15,20,25,35 | 46,31,23,26 |
| | 55 | 15 | 2 | 15,45 | 76,70 |
| | 55 | 25 | 2 | 15,30 | 61,54 |
| | 55 | 35 | 3 | 15,25,40 | 46,39,35 |
| | 65 | 15 | 1 | 15 | 76 |
| | 65 | 25 | 2 | 15,45 | 61 |
| | 65 | 35 | 2 | 15,30 | 46,43 |

[1]Upper and lower limit of maximum SDI were selected based on theoretical growth-growing stock relationship. Source: Long et al. (2004), Jack and Long (1996), and Long (1985).
[2]The information on the number and timing of thinning was generated by using Forest Vegetation Simulator to satisfy given upper and lower limits of SDI. Thinnings at 15 years, as suggested by FVS, were actually assumed to occur at the beginning of year 16 since no harvest of any form is allowed during the Chicago Climate Exchange afforestation contract, which is typically for 15 years.

Table 2.3 Conversion factors used to convert harvested volume of loblolly pine (*Pinus taeda* L.) from the South-Central Region of the U.S. to metric tons of carbon dioxide equivalents (t $CO_2$e).

| Wood products category ($ft^3$) | Carbon ($lbs/ft^3$) | Carbon remaining in use and in landfills 100 years from harvest (U.S. tons) | $CO_2$e (U.S. tons) | $CO_2$e (Metric tons) |
|---|---|---|---|---|
| Pulpwood | 15.57 | 0.162 | 3.67 | 0.907 |
| Sawlogs | 15.57 | 0.334 | 3.67 | 0.907 |

Source: Chicago Climate Exchange (CCX) (2008).

Table 2.4 Net Present Value[1] (NPV) in 2008 dollars generated by a loblolly pine (*Pinus taeda* L.) stand grown at a site index of 32 meters (base age 50 years) in Mississippi managed for timber and for both timber and carbon sequestration under Chicago Climate Exchange (CCX) forestry carbon protocols.

| Trees per ha | Management for timber only | Management for timber and carbon | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Carbon price (\$4.25/t $CO_2$e) | | | Carbon price (\$10/t $CO_2$e) | | | Carbon price (\$20/t $CO_2$e) | | |
| | | 1st contract[2] | 1st & 2nd contracts[3] | 1st, 2nd & 3rd contracts[4] | 1st contract[2] | 1st & 2nd contracts[3] | 1st, 2nd & 3rd contracts[4] | 1st contract[2] | 1st & 2nd contracts[3] | 1st, 2nd & 3rd contracts[4] |
| | | ($/ha) | | | | | | | | |
| 1077 | 4,701 | 5,353 | 5,533 | 5,288 | 6,383 | 7,107 | 6,678 | 8,175 | 10,036 | 9,097 |
| 1494 | 5,126 | 5,912 | 6,032 | 5,768 | 7,147 | 7,451 | 7,232 | 9,295 | 10,451 | 9,776 |
| 1793 | 5,049 | 5,904 | 5,986 | 5,761 | 7,245 | 7,453 | 7,284 | 9,577 | 10,271 | 9,934 |

[1]The NPVs were calculated at a discount rate of 5%.
[2] One contract covering a total of 15 years.
[3] Two contracts covering a total of 30 years.
[4] Three contracts covering a total of 45 years.

Table 2.5 Annual Equivalent Value[1] (AEV) in 2008 dollars generated by a loblolly pine (*Pinus taeda* L.) stand grown at a site index of 32 meters (base age 50 years) in Mississippi managed for timber and for both timber and carbon sequestration under Chicago Climate Exchange (CCX) forestry carbon protocols.

| Trees per ha | Management for timber only | Management for timber and carbon | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Carbon price ($4.25/t $CO_2$e) | | | Carbon price ($10/t $CO_2$e) | | | Carbon price ($20/t $CO_2$e) | | |
| | | 1st contract[2] | 1st & 2nd contracts[3] | 1st, 2nd & 3rd contracts[4] | 1st contract[2] | 1st & 2nd contracts[3] | 1st, 2nd & 3rd contracts[4] | 1st contract[2] | 1st & 2nd contracts[3] | 1st, 2nd & 3rd contracts[4] |
| | | ............ ($/ha) ............ | | | | | | | | |
| 1077 | 293 | 336 | 349 | 298 | 403 | 459 | 376 | 524 | 650 | 512 |
| 1494 | 322 | 373 | 381 | 325 | 454 | 473 | 407 | 598 | 680 | 550 |
| 1793 | 312 | 367 | 372 | 324 | 454 | 477 | 410 | 617 | 668 | 559 |

[1]The AEVs were calculated at a discount rate of 5%.
[2] One contract covering a total of 15 years.
[3] Two contracts covering a total of 30 years.
[4] Three contracts covering a total of 45 years
.

# CHAPTER III

# CARBON SEQUESTRATION POTENTIAL AND FINANCIAL TRADE-OFFS ASSOCIATED WITH LOBLOLLY PINE AND CHERRYBARK OAK MANAGEMENT IN MISSISSIPPI[2]

## 3.1 **Abstract**

Forests can be a part of diversified portfolio of mitigative strategies focused on decreasing atmospheric concentration of carbon dioxide ($CO_2$) because they can absorb $CO_2$ at relatively low cost and for long time periods. However, managing forests for increased carbon sequestration can potentially conflict with management for timber and result in financial trade-offs. The magnitude of these trade-offs is still unclear. This research examined the potential for increasing amounts of sequestered carbon through management of loblolly pine (*Pinus taeda* L.) and cherrybark oak (*Quercus pagoda* Raf.) stands in Mississippi and determined associated financial trade-offs. Physical quantities of carbon and revenues were determined for stands managed only for timber, only for carbon, and simultaneously for timber and carbon under selected thinning and harvest age scenarios.

Results indicated a potential for sequestering up to 1,188 metric tons of $CO_2$ per hectare (Mt $CO_2$/ha) by a 80-year old cherrybark oak stand and up to 963 t $CO_2$/ha by a 50-year loblolly pine stand and wood products harvested from these stands. Revenues from timber production and joint management for timber and carbon were maximized

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with harvest ages of 50 and 35 years for cherrybark oak and loblolly pine, respectively. At these harvest ages, the cherrybark oak stand sequestered 38% less $CO_2$, whereas the loblolly pine stand sequestered 30% less $CO_2$ when compared to harvest ages maximizing physical quantities of $CO_2$. Managing stands only for increased $CO_2$ sequestration decreased revenues from timber by up to 31% for cherrybark oak stand and up to 12% for loblolly pine stand. The results suggested that increasing $CO_2$ sequestration by dedicated management of loblolly pine and cherrybark oak stands can be a viable strategy in Mississippi. However, at the analyzed carbon price of \$3.77/Mt $CO_2$ e, landowners are more likely to enroll in shorter carbon contracts because it would not require them to change thinning and harvest regimes for timber production. At higher carbon prices, landowners are more likely to select longer carbon contracts because greater revenues from carbon payments will increase landowner overall return. These findings will be helpful to forest landowners considering participation in carbon sequestration programs and policy makers who can use this information in developing future carbon programs.

## 3.2 Introduction

Global warming, a process of gradual increase in earth's temperature, is one of the most frequently discussed environmental problems. It is believed to be caused by greenhouse gases (GHGs) with carbon dioxide ($CO_2$) being the greatest contributor (IPCC 2001). Increasing concentration of $CO_2$ in the atmosphere has been attributed mainly to burning fossil fuels such coal, oil, and natural gas (IPCC 2001). Efforts to decrease a negative impact of global warming have focused on reduction of atmospheric concentration of $CO_2$. Tree can absorb $CO_2$ during the process of photosynthesis and the forest sector can play an important role in reducing atmospheric $CO_2$ because it is relatively less costly compared to other methods (Richards 2004, Sedjo 2001, Newell and Stavins 2000, Plantinga et al. 1999). According to Birdsey and Heath (1995), all forests in the United States sequestered a net of 10.3 billion metric tons of $CO_2$ per year from 1952 to 1992, which offset approximately 25% of U.S. anthropogenic emissions of $CO_2$ during that period.

To increase potential for mitigating $CO_2$ emissions, several voluntary and mandatory carbon programs such as Chicago Climate Exchange (CCX), European Climate Exchange (ECX), Climate Action Reserve (CAR) have been established to provide monetary incentives to landowners for managing their forests for increased carbon sequestration. Various types of forest activities are eligible for carbon payments such as new plantations, existing forests managed for increased carbon, and long-life wood products.

With 65% of land in forests (Mississippi Forestry Association 2008), and annual production of 22.65 million cubic meters of timber (Howell and Johnson 2009), Mississippi forest sector can play an important role in achieving U.S. carbon sequestration goals. Existing carbon markets offer forest landowners an opportunity to generate additional income. However, managing forests for increased $CO_2$ sequestration might be challenging because such management can conflict with timber production and result in financial trade-offs. Although carbon sequestration potential and its economic impacts has been widely researched (Stainback and Alavalapati 2005, Huang and Kronrad 2001, van Kooten et al. 1995, Plantinga et al. 1999), information on the impact of managing under specific carbon sequestration programs is limited and it is unclear if it will affect thinning and harvest regimes, and generated revenues. Moreover, financial feasibility analyses of accumulating carbon in long-life wood products are still rare.

There is a strong need to better understand carbon sequestration potential in Mississippi forests and harvested wood products and associated financial trade-offs in order to develop appropriate carbon sequestration strategies. The objectives of this study were to examine the potential for increasing carbon sequestration through management of loblolly pine (*Pinus taeda* L.) and cherrybark oak (*Quercus pagoda* Raf.) stands in Mississippi and determine associated trade-offs in terms of generated financial returns versus sequestered quantities of $CO_2$. Loblolly pine and cherrybark oak are two major commercially important species in Mississippi. The analysis evaluated stands managed only for timber, only for $CO_2$ sequestration, and stands jointly managed for timber and $CO_2$ under selected thinning and harvest age regimes.

## 3.3 **Methods**

This study determined the quantities of $CO_2$ sequestered by loblolly pine and cherrybark oak stands managed for timber only, $CO_2$ sequestration only and jointly managed for timber and $CO_2$ sequestration. Impacts of possible ranges of harvest ages and thinning timing and intensity were evaluated in terms of their carbon sequestration potential for each management scenario. The carbon sequestration potential was defined as the maximum possible amount of $CO_2$ sequestered under each management scenario. Attainable financial returns under each management scenario were determined and compared with each other. The trade-offs in financial revenues and $CO_2$ sequestration were determined by comparing attainable revenues and physical quantity $CO_2$ sequestered under each management scenario.

### 3.3.1 Determining potential for sequestering $CO_2$ in standing trees and harvested wood products

Estimates of $CO_2$ sequestered in live aboveground and belowground biomass of loblolly pine and cherrybark oak stands were generated using a carbon submodel of the Forest Vegetation Simulator (FVS), a tree growth and yield model developed by USDA Forest Service (Reinhardt et al. 2007, Dixon 2003). The quantity of carbon stored in harvested wood products was estimated based on volume of wood in use 100 years from harvest. This was estimated based on volume of primary wood products (sawlog and pulpwood) available for subsequent processing. The quantity of carbon remaining in use and landfills after 100 years from harvest was determined for each wood product category based on CCX conversion factors (CCX 2009a).

The estimates of timber growth and volume was obtained for stands established on a medium quality site (Site Index of 105 and base age of 50 years) with 746 trees/ha (cherrybark oak) and 1,495 trees/ha (loblolly pine). Both stands were treated with light, medium, and high intensity thinning regimes based on Reineke's Stand Density Index (SDI). Each thinning regime was determined based on upper and lower growing stock limits. The upper limit determines the age at which the stand is thinned, whereas the lower limit determines how many trees are removed from the stand during thinning (Oregon Department of Forestry, 2004). A total of 15 different thinning regimes were considered including three upper limits (60%, 55% and 50% of maximum SDI) and five lower limits (25%, 30% 35%, 40% and 45% of maximum SDI). The timing and intensity of thinnings designed to meet the specified SDI criteria and analyzed harvest ages are presented in Table 3.1. These ages were considered to represent ranges of likely harvest ages that landowners may apply to manage their stands only for timber, only for $CO_2$ sequestration, or both for timber and $CO_2$ sequestration.

#### 3.3.1.1 Assumptions related to participation in carbon offset programs

The analysis was conducted for landowner participation in three CCX forest carbon offset projects (afforestation, managed forests, and long-life wood products). An afforestation protocol allows landowners for enrolling afforestation projects initiated after December 31, 1989 as well as reforestation projects conducted on degraded forestlands and initiated after January 1, 1990 (CCX 2009a). This protocol does not permit any form of harvesting during the contract period. Carbon credits are issued for the carbon sequestered in live trees and soil organic carbon. A portion (20%) of these credits is placed in the forest carbon reserve pool (FCRP) to offset loss of carbon due to catastrophic events such as hurricanes, tornados, forest fire, and pest infestation. The reserved carbon pool is released back to landowner at the end of contract period if there were no catastrophic loss of sequestered carbon. Under managed forest protocol, tree harvesting, except clear-cut, is permitted (CCX 2009a). Landowners are issued carbon credits for the net amount of additional carbon sequestered in reference to the predefined base line year. In this study, the base line years were established at 15, 30, 45, 60 and 75 years, and corresponded to the end of the first, second, third, fourth and fifth carbon offset contract, respectively. This protocol also requires that 20% of the sequestered carbon be placed in FCRP. The long-lived wood products protocol provides landowners with payments for carbon stored in long-life wood products that are still in use (or in landfills) 100 years from the harvest date (CCX 2009a).

## 3.4 **Results**

### 3.4.1 Potential for sequestering $CO_2$ in standing trees

The unthinned loblolly pine and cherrybark oak stands accumulated the greatest amount of $CO_2$ in standing trees. In case of a thinned stand, the rate of carbon sequestration depended on a thinning regime. In general, a light thinning promoted a greater accumulation of carbon both in standing trees and in harvested wood products. An unthinned cherrybark oak stand, sequestered the largest amount of $CO_2$ in standing trees at age of 80 years (1,030 metric tons of carbon dioxide equivalent per hectare (t $CO_2$e/ha)), whereas a thinned stand accumulated at this age 961 t $CO_2$e/ha. In contrast, an unthinned stand of loblolly pine sequestered the largest amounts of $CO_2$ at age 50 years that corresponded to 855 t $CO_2$e/ha. The corresponding amounts of carbon stored in a thinned stand was 771 t $CO_2$e/ha.

### 3.4.2 Potential for sequestering $CO_2$ in harvested wood products

The amount of $CO_2$ sequestered in harvested wood products varied depending on implemented thinning regimes and harvest ages. In general, $CO_2$ in harvested wood products tended to increase with harvest age and more frequent light thinnings. In the case of cherrybark oak stand, the maximum amount of wood products carbon (235 t $CO_2$e/ha) was sequestered when the stand was harvested at age of 80 years and was thinned three times at ages 35, 45, and 60 years. Similar pattern was observed for loblolly pine stand. The maximum amount of carbon dioxide (237 t $CO_2$e/ha) was sequestered with a harvest age of 50 years and six thinnings at ages 16, 20, 25, 30, 35 and 40 years.

A thinned cherrybark oak stand always sequestered more $CO_2$ in harvested wood products under all thinning scenarios (except those with harvest age of 60 years) when compared to an unthinned stand. When accounted for harvested wood products, the amount of total sequestered $CO_2$ ($CO_2$ in standing tree and in harvested wood products) increased to 1,188 t $CO_2$e/ha for a stand harvested at age of 80 years and thinned three times (at 35, 45 and 60 years) (Figure 3.1). In the case of loblolly pine, harvested wood products also increased the total amount of sequestered $CO_2$. A thinned stand accumulated more $CO_2$ with harvest ages longer than 40 years, whereas an unthinned stands accumulated more $CO_2$ with harvest ages shorter than 40 years when carbon in harvested wood products was included. Wood products increased amount of sequestered $CO_2$ to 963 t $CO_2$e/ha at harvest age of 50 years. This amount was accumulated with six consecutive thinnings at the ages of 16, 20, 25, 30, 35, and 40 years (Figure 3.2).

### 3.4.3 Financial returns generated from managing the stands only for timber

The largest net revenue generated from managing the cherrybark oak stand only for timber was US $534/ha when the stand was harvested at age of 50 years and thinned at ages 30, 35 and 45 years which removed approximately 23% of basal area in each thinning. The largest net revenue from an unthinned was also generated at age 50 years but was 10% less than revenue generated from a thinned stand ($484/ha). A loblolly pine stand generated substantially higher net revenue ($5,128/ha) when harvested at age of 35 years and treated with two thinnings at ages 16 and 25 years and an average removal of 46% of basal area in each thinning. This revenue was approximately 25% larger than the largest net revenue ($4,098/ha) from an unthinned stand generated at age 30 years.

### 3.4.4 Financial returns generated from managing the stands only for $CO_2$ sequestration

The stands managed only for $CO_2$ differed from stands managed only for timber and jointly managed for timber and $CO_2$ sequestration in terms of objectives and sources of revenue. The objective for stands managed only for $CO_2$ was to maximize the physical amount of $CO_2$ sequestered by standing trees and harvested wood products. The objective for stands managed only for timber or jointly managed for timber and $CO_2$ sequestration was maximization of net revenues. In addition, it was assumed that revenue from the stands managed for only $CO_2$ was generated only from carbon contracts and not from timber. Although it is unlikely that landowners will manage their stands only for $CO_2$, this scenario was included for comparison. The maximum amounts of sequestered $CO_2$ in standing trees and harvested wood products were determined for an unthinned and thinned stands for the range of possible harvest ages. Harvest was necessary to determine amount of carbon stored in wood products. The largest amount of $CO_2$ was stored at 80 years for cherrybark stands and 50 years for the loblolly pine stands. Net revenues generated from these stands were substantially smaller than net revenues generated from stands managed only for timber.

For cherrybark oak, the largest possible net revenues generated from managing the stands only for increased $CO_2$ sequestration was $182/ha. This revenue was generated by an unthinned stand enrolled in five contracts and harvested at age 80 years. Likewise, for loblolly pine, the largest possible net revenue generated by stands managed for increased $CO_2$ sequestration was $379/ha, which was generated by an unthinned stand enrolled in three carbon contracts and harvested at age 50 years.

### 3.4.5 Financial returns generated from managing the stands jointly for timber and $CO_2$ sequestration

The largest attainable net revenues from managing a cherrybark oak stand jointly for timber and $CO_2$ varied from $637/ha to $1,128/ha depending on thinning timing, intensity, and number of carbon offset contract. The largest net revenue of $1,128/ha was generated if the stand that was not thinned, harvested at age of 50 years, and enrolled in three contracts. When the stand was enrolled in one and two contracts, the largest net revenues were $693/ha and $997/ha, respectively. The corresponding net revenues from an unthinned stand were $637/ha and $954/ha, respectively, which were 8% and 5% less than the largest net revenue from thinned stands managed jointly for timber and $CO_2$ sequestration. The joint revenues for an unthinned stand for one and two contracts were smaller for two reasons. First, the timber revenue from unthinned stand was less than revenue from thinned stand. Second, since the stands were not thinned, the payments for carbon stored in harvested wood products were available only at the final harvest. When enrolled in three contracts, an unthinned stand generated the largest joint revenue of $1,128/ha at harvest age of 50 years compared to the best revenue of $1,083/ha from a thinned stand. The reason why an unthinned stand provided the highest joint revenue was because the rate of carbon accumulation culminated at age 45 years and, therefore, the contribution of payment for carbon in standing trees was greatest in a case of an unthinned stand. When the stands were enrolled in four carbon contracts the joint revenue from unthinned and thinned stands declined by 27% and 6%, respectively compared to the largest revenues generated from enrollment in three contracts. In contrast, enrollment in five contracts reduced the joint revenue for both unthinned and thinned stands by 35% and 12%, respectively (Figure 3.3).

The largest possible net revenue generated from managing loblolly pine stand for timber and $CO_2$ sequestration varied between $3,732/ha to $5,812/ha. A thinned stand always generated larger net revenue than unthinned stand regardless of the number of carbon contracts. The largest net revenue of $5,812/ha was generated when the stand was harvested at age of 46 years and enrolled in two contracts. The net revenues generated from a stand enrolled in one and two contracts were $5,760/ha and $5,812/ha, respectively when a stand was thinned twice (at ages 16 and 25 years) and harvested at age of 35 years. The corresponding net revenues from an unthinned stand were $4,712/ha and $4,874/ha, respectively, and were 22% and 19% smaller than net revenues from a thinned stand. Enrollments in three carbon contracts decreased the joint revenue to $5,564/ha for a thinned stand, and to $3,732/ha, for an unthinned stand (Figure 3.4).

### 3.4.6 Financial and carbon sequestration trade-offs

Figures 3.5 and 3.6 show financial trade-offs resulting from managing cherrybark oak and loblolly pine stands for increased $CO_2$ sequestration. These trade-offs represent difference in NPVs for harvest ages maximizing net timber revenue, net revenue from joint management for timber and $CO_2$ sequestration, and the physical quantity of sequestered $CO_2$. When adopting management for increased $CO_2$ sequestration, the net timber revenue from cherrybark oak stand decreased by $168/ha (31%) if enrolled in one, two, three, four and five contracts. In case of joint revenues, the reductions due to adopting management focused on increased $CO_2$ were $176/ha (25%), $188/ha (19%), $220/ha (20%) and $127/ha (12%) for enrollment in one, two, three and four contracts, respectively. There was no decrease in joint revenue when the stand was enrolled in five contracts. Similar results were observed for loblolly pine. For loblolly pine, adopting management focused only on increased $CO_2$ sequestration reduced net timber revenue by \$561/ha or 12% when enrolled in one, two, and three contracts. Similarly, the reductions in joint revenues due to management focused only on increased $CO_2$ were \$572/ha (11%), \$550/ha (10%), and \$273/ha (5%) when enrolled in one, two, and three contracts, respectively.

Considering trade-offs in physical amounts of accumulated $CO_2$, it was found that managing the stand for timber and joint revenue sequestered substantially less $CO_2$ than managing the stands for increased $CO_2$ sequestration when the stands were thinned. The harvest age maximizing timber revenue by a thinned stand was 50 years for cherrybark oak and 35 years for loblolly pine. At these harvest ages the stands sequestered 38% less carbon (598 t $CO_2$e/ha versus 961 $CO_2$e/ha for cherrybark oak and 474 t $CO_2$e/ha versus 771 t $CO_2$e/ha for loblolly pine) when compared to harvest age  maximizing physical quantities of sequestered $CO_2$ (50 years for loblolly pine and 80 yrs for cherrybark oak). However, for an unthinned stand, the difference in sequestered $CO_2$ between the stand managed for increased $CO_2$ and stand managed for timber and joint revenue was smaller (89 t $CO_2$e/ha or 9% for cherrybark oak stand and 82 t $CO_2$e/ha or 10% for loblolly pine stand).

## 3.5 Discussion and conclusions

This study have provided information on carbon sequestration potential of two major commercial species in Mississippi and associated financial and $CO_2$ sequestration trade-offs when enrolled in CCX carbon trading program. The results indicated a potential for increasing the amount of sequestered $CO_2$ through management of cherrybark oak and loblolly pine stands in Mississippi. The analysis revealed that landowners could generate an additional revenue of up to \$549/ha and \$684/ha from a cherrybark oak and loblolly pine stands, respectively by enrolling in carbon contracts. The results indicated that estimates of revenues generated from loblolly pine stand are consistent with previous studies (Rousseau 2008, Huang and Kronrad 2006, Huang and Kronrad 2001). Revenue estimates from cherrybark oak managed for timber were similar to Grebner et al. (2004) who reported a land expectation value for southern oak between \$49/ha to \$748/ha depending on weather condition and site preparation. The results of this study differed largely from Huang et al. (2004) who found that revenue of more than \$7,400/ha can be generated from a cherrybark oak plantation managed for timber grown in Lower Mississippi Alluvial Valley. In our study, a cherrybark oak plantation grown in similar conditions generated revenue of \$534/ha. The large discrepancy in the results can be attributed to costs associated with stand establishment and management and timber prices. For example, this study used a hardwood sawtimber price of \$31.16/ton, whereas Huang et al. (2004) assumed a price of \$475/thousand board feet (MBF) (equivalent to \$59/ton). The discrepancy also might be due to potentially different number of trees planted and assumptions related to seedling survival rate. In this study trees were planted at density of 3.65 m X 3.65 m (12 ft X12 ft) and a survival rate was assumed at 90%. However, Huang et al. (2004) did not provide information on planting density and survival rate.

The optimal harvest age for cherrybark oak managed only for timber was 50 years. Carbon payments did not have impact on harvest age if the stand were enrolled up to three contracts. However, it increased to 65 years and 80 years if enrolled for four and five contracts, respectively. For loblolly pine managed for timber, the optimal age was 35 years. Enrollment of this stand in one or two carbon contracts did not change the optimal harvest age. However, when enrolled in three contracts the optimal harvest age increased to 46 years. This finding is to some extent consistent with previous studies that indicated an increased rotation length due to carbon payments (Pohjola and Valsta 2007, Nepal et al. 2009, Huang and Kronrad 2006, van Kooten et al. 1995). Our results indicate that managing the forest stand for increased $CO_2$ sequestration did not always result in increased optimal harvest age and consequently can be integrated with management for timber. This result is related to carbon payment schedule in CCX contracts. For example, when the stand is enrolled in one contract, carbon payments terminate at the end of the contract (15 years) and do not have impact on the rotation age beyond 15 years. Similarly, if the stand is enrolled in two contracts, payments terminate after 30 years and this has no influence on timber production-oriented harvest age beyond that period.

The amount of $CO_2$ sequestered in standing trees and wood products increased with increase in harvest age for both species. The largest amounts of $CO_2$ were sequestered at harvest ages of 50 years for loblolly pine and 80 years for cherrybark oak. This result suggested that harvest age would need to be increased if stands were to be managed only for increased $CO_2$ sequestration. Such a management approach would decrease revenues generated from timber production and joint management for timber and $CO_2$ sequestration. The reduction in revenues depended on tree species and number of contracts. For cherrybark oak, managing the stand only for $CO_2$ sequestration decreased the timber revenue by up to $168/ha and joint revenue by up to $220/ha. For loblolly pine, the reduction in timber revenue and joint revenue was up to $561/ha and $564/ha, respectively. These differences in revenues resulting from managing the stands for increased $CO_2$ sequestration and the stands managed only for timber represents trade-offs of managing the stands for increased $CO_2$ sequestration and could be viewed as the minimum price required for encouraging forest landowners to adopt carbon oriented forest management strategies (McCarney et al. 2006). For example, landowners who consider managing their stands only for timber production might be encouraged to manage the stand for increased $CO_2$ if they will get a subsidy of \$168/ha (cherrybark oak) and \$561/ha (loblolly pine), which is equivalent to the amount they forgo by lengthening the harvest age to increase $CO_2$ sequestration.

Analysis of trade-offs in physical quantity of sequestered $CO_2$ revealed that the harvest age maximizing revenues from managing the stand only for timber and for both timber and $CO_2$ sequestration reduced $CO_2$ sequestration by 38% for both species when stands were thinned. This reduction is large in magnitude because it needs at least another 15 years for loblolly pine afforestation to offset the loss in sequestered $CO_2$ compared to best harvest age for stands managed for only timber. Similarly, it needs another 30 years for cherrybark oak plantation. The difference in revenue and sequestered $CO_2$ between stand managed for increased $CO_2$, timber or joint revenue tended to decrease with increase in number of carbon contracts. This indicated that longer term carbon payment would offset any decrease in loss of revenue due to adopting management for increased $CO_2$ sequestration.

The impact of managing the stands for increased carbon sequestration on timber and joint revenue were higher for cherrybark oak than loblolly pine stands. Reduction in revenue from management for increased $CO_2$ sequestration was relatively small in case of loblolly pine (12%) but substantially higher for cherrybark oak (31%).

This study has determined maximum possible revenues and quantities of $CO_2$ that could be generated and sequestered from loblolly pine and cherrybark oak stands in Mississippi under existing CCX carbon trading mechanism. Moreover, the study has identified trade-offs in generated revenues, rotation ages, and physical amounts of sequestered $CO_2$ at stand level for cherrybark oak and loblolly pine stands in Mississippi when the stands were managed for increased $CO_2$ sequestration, timber, and jointly for timber and $CO_2$ sequestration. The analysis revealed that landowners could benefit from participation in carbon trading and increase revenue without substantial changes in timber management.

We conclude that increasing $CO_2$ sequestration from loblolly pine and cherrybark oak management can be a viable strategy in Mississippi. However, at the analyzed carbon price (\$3.77/t $CO_2$e), landowners are likely to enroll in shorter carbon contracts which do not require them to change thinning and harvest regimes for timber production. This is because the loss of timber revenue due to delayed harvest can not be offset by an increase in carbon revenue at this price. With higher carbon prices, landowners are more likely to enroll in longer carbon contracts because revenue from carbon payments will increase overall return. If carbon payments are low as current carbon price in CCX of \$0.10/t $CO_2$ e, forest landowners will be willing to adjust their harvest regime for increased $CO_2$ only with additional compensations. The amount of this compensation would need to be equivalent to the loss of overall revenue due to delayed harvest age.

The findings of this research will help forest landowners make more informed decisions related to participation in carbon trading programs. Further research is needed to improve understanding of financial implications to forest landowners participating in other carbon programs such as Climate Action Reserve (CAR) and Regional Green House Gas Initiatives (RGGI). Also, investigating impacts of participation in carbon contracts on management for non-timber benefits such as wildlife habitat and recreation is needed to fully understand impact of carbon payment on forest management decisions.

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Table 3.1 The age, intensity, and number of thinnings for loblolly pine and cherrybark oak stands in Mississippi based on specified upper and lower limit of maximum Stand Density Index (SDI).

| Upper Limit (% of Max SDI) | Lower Limit (% of Max SDI) | Loblolly pine | | | Cherrybark oak | | |
|---|---|---|---|---|---|---|---|
| | | No. of thinnings | Thinning age (yrs) | Thinning intensity (% of basal area) | No. of thinnings | Thinning age (yrs) | Thinning intensity (% of basal area) |
| 60 | 25 | 2 | 16, 35 | 57 | 2 | 35, 75 | 56 |
| 60 | 30 | 2 | 16, 30 | 48 | 2 | 35, 65 | 48 |
| 60 | 35 | 2 | 16, 25 | 40 | 2 | 35, 60 | 41 |
| 60 | 40 | 3 | 16, 25, 45 | 33 | 2 | 35, 55 | 33 |
| 60 | 45 | 3 | 16, 20, 30 | 24 | 3 | 35, 50,70 | 25 |
| 55 | 25 | 2 | 16, 30 | 55 | 2 | 35, 65 | 55 |
| 55 | 30 | 2 | 16, 25 | 46 | 2 | 35, 55 | 46 |
| 55 | 30 | 3 | 16, 25, 40 | 38 | 3 | 35, 50,75 | 38 |
| 55 | 30 | 4 | 16, 20, 30, 45 | 29 | 4 | 35, 45, 60, 80 | 28 |
| 55 | 30 | 4 | 16, 20, 25, 35 | 22 | 5 | 35, 45, 55, 65, 80 | 21 |
| 50 | 25 | 2 | 16, 30 | 56 | 2 | 30, 50 | 50 |
| 50 | 30 | 3 | 16, 25, 45 | 44 | 3 | 30, 45, 70 | 42 |
| 50 | 35 | 3 | 16, 20, 30 | 35 | 4 | 30, 40, 55, 75 | 32 |
| 50 | 40 | 4 | 16, 20, 25, 35 | 27 | 5 | 30, 35, 45, 55, 70 | 23 |
| 50 | 45 | 6 | 16, 20, 25, 30, 35, 40 | 17 | 8 | 35, 40, 45, 50, 55, 60, 65, 75 | 14 |

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Table 3.2 Summary of the costs and revenues associated with timber production and enrollment in CCX forestry carbon offset programs for a loblolly pine stand in Mississippi.

| Costs/Revenues | Amount | Source |
|---|---|---|
| Costs: | | |
| Establishment (seedling, plantation and chemical site prep) | \$420 /ha (softwood)<br>\$474/ha (hardwood) | Andrew W. Ezell, Department of Forestry, Mississippi State University, pers. comm. Sept. 12, 2008 |
| Aggregator's fee | 10% of total carbon revenue | AgraGate Climate Credits Corporation (2008) |
| CCX fee | \$0.20/credit | AgraGate Climate Credits Corporation (2008) |
| Revenues: | | |
| Carbon credit price | \$3.76/t $CO_2$e | CCX (2009b) (average closing prices 2008) |
| Sawtimber stumpage price | \$33.54/ton (softwood)<br>\$ 31.16/ton (hardwood) | Forest2Market Mississippi Timber Reports (2008) |
| Pulpwood stumpage price | \$10.06/ton (softwood)<br>\$6.06/ton (hardwood) | Forest2Market Mississippi Timber Reports (2008) |

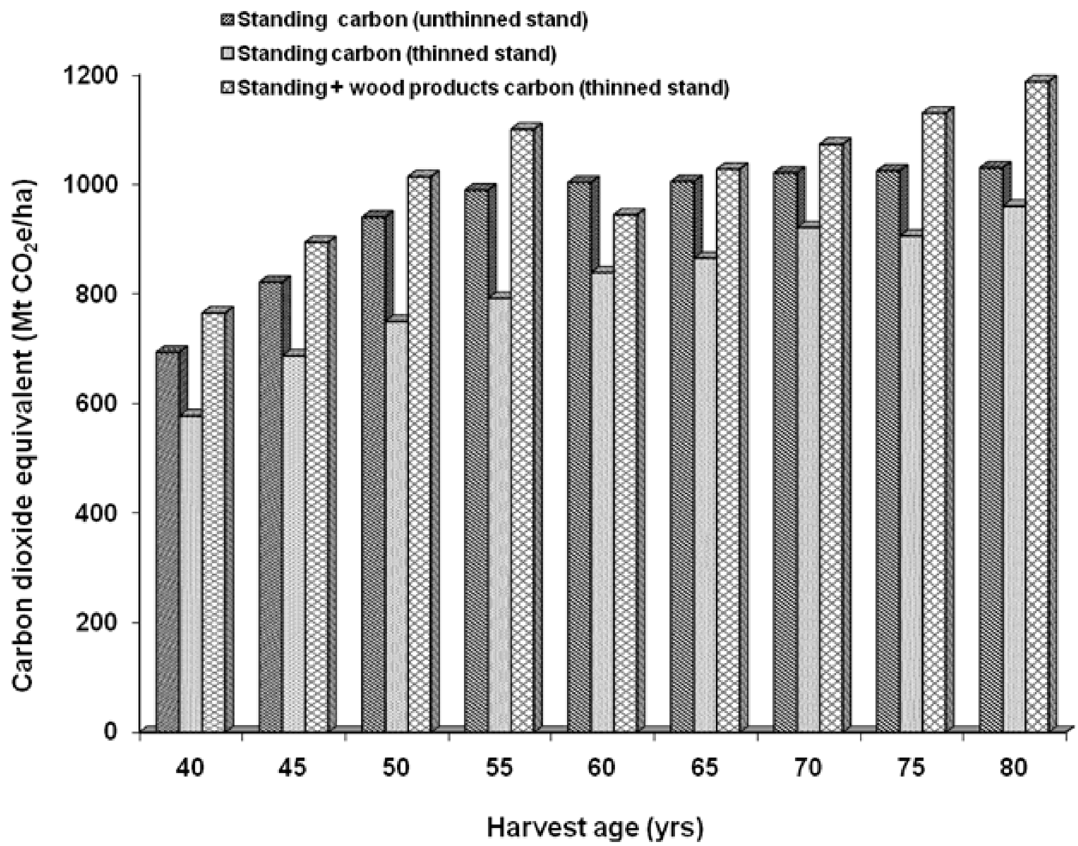


Figure 3.1 Amounts of $CO_2$e sequestered at different harvest ages by unthinned and thinned cherrybark oak stand and harvested wood products in Mississippi.

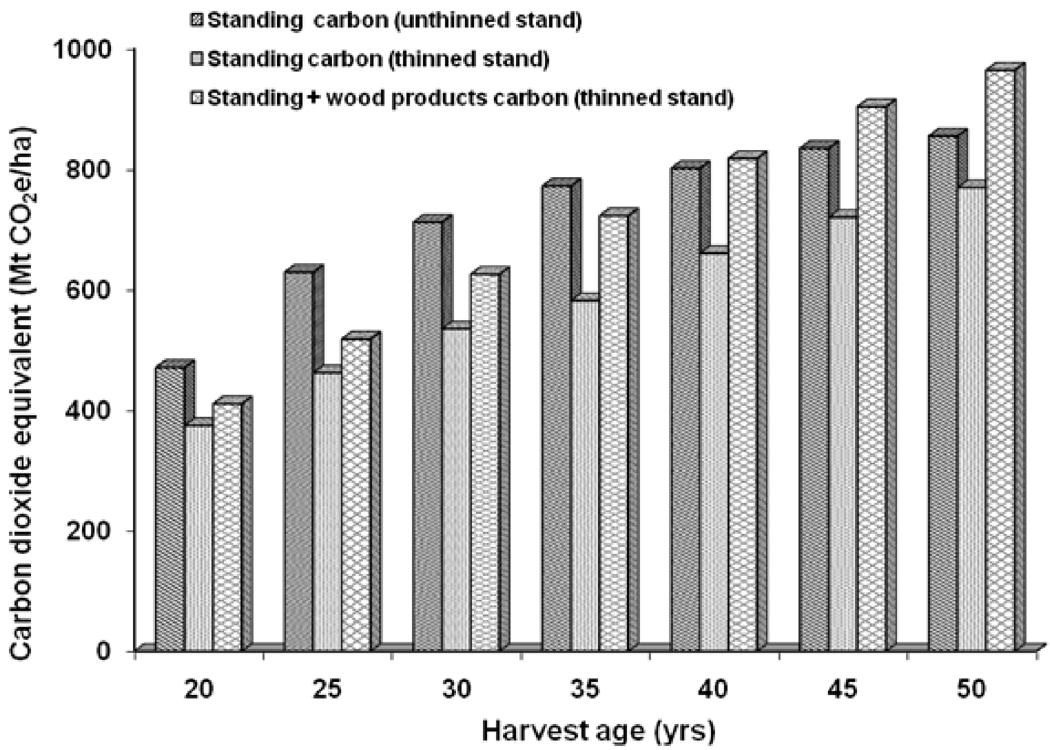


Figure 3.2 Amounts of $CO_2$e sequestered at different harvest ages by unthinned and thinned loblolly pine stand and harvested wood products in Mississippi.

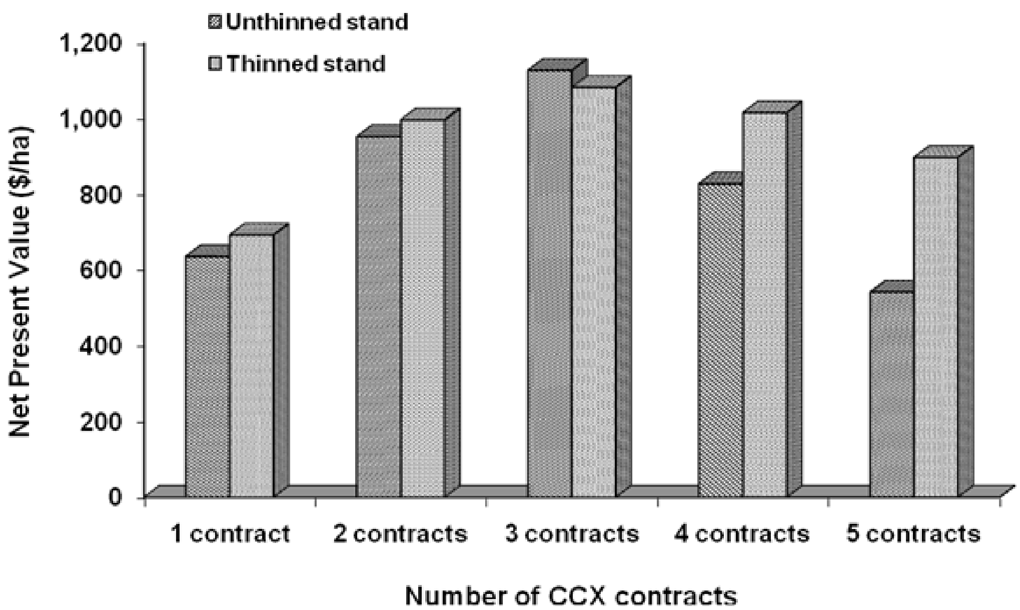


Figure 3.3 The maximum attainable net revenues generated by a cherrybark oak stand in Mississippi managed for joint production of timber and $CO_2$ sequestration.

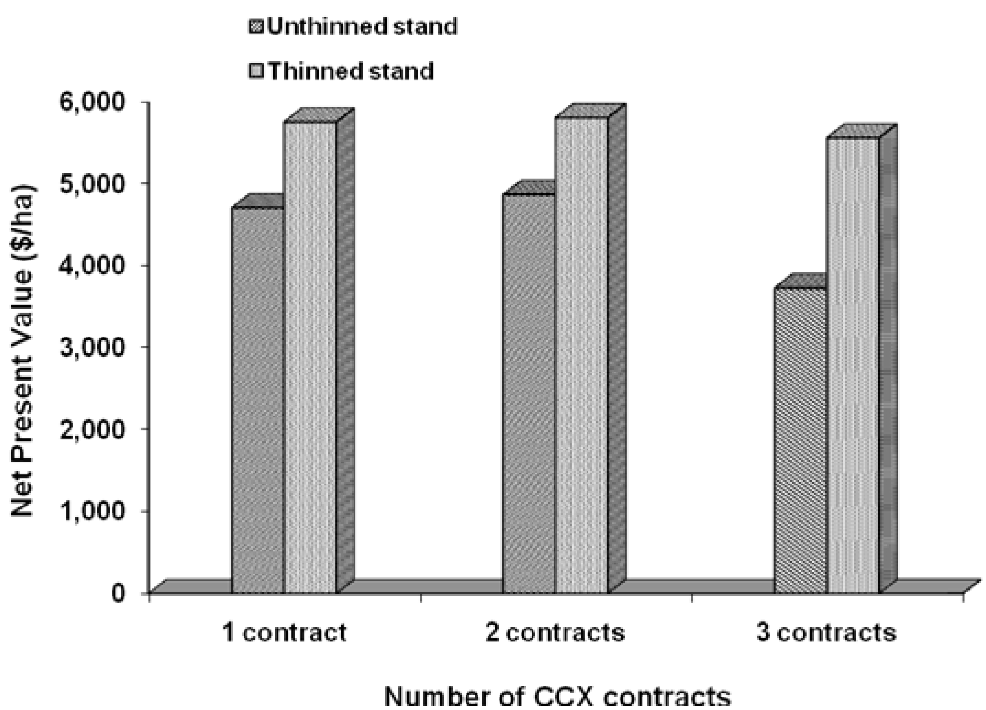


Figure 3.4 Maximum attainable net revenues generated by a loblolly pine stand in Mississippi from joint production of timber and $CO_2$ sequestration.

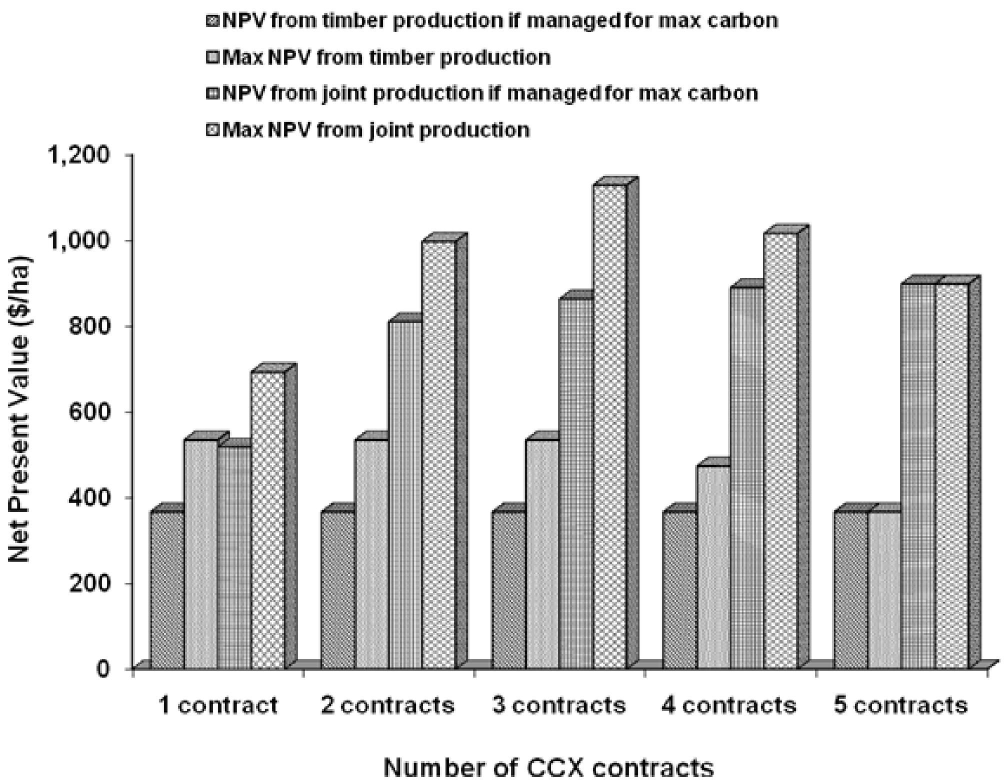


Figure 3.5 Net revenues generated by cherrybark oak stand in Mississippi managed only for timber and jointly for timber and $CO_2$ sequestration at harvest age maximizing sequestration of $CO_2$.

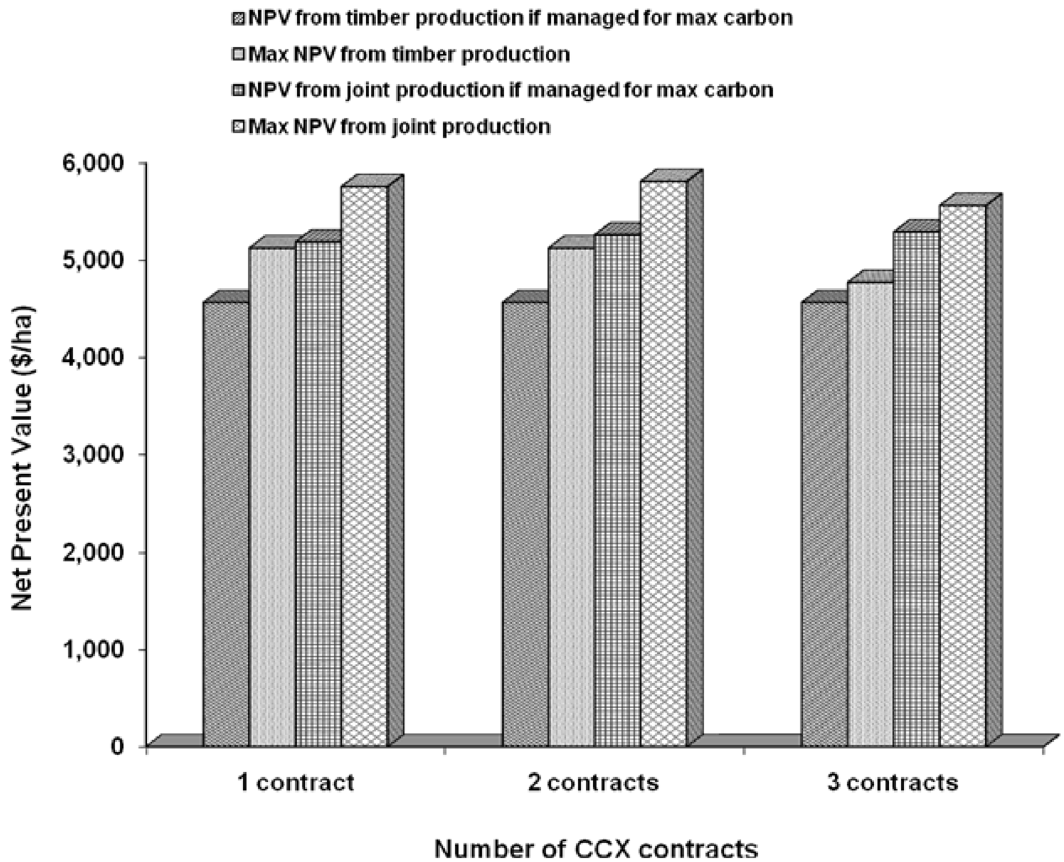


Figure 3.6 Net revenues generated by loblolly pine stands in Mississippi managed only for timber and jointly for timber and $CO_2$ sequestration at harvest age maximizing sequestration of $CO_2$.

# CHAPTER IV

# FINANCIAL FEASIBILITY OF INCREASING CARBON SEQUESTRATION IN HARVESTED WOOD PRODUCTS IN MISSISSIPPI[3]

## 4.1 Abstract

Longer forest rotation ages can potentially increase accumulation of carbon in harvested wood products due to a larger proportion of sawlogs that can be used for manufacturing durable wood products such as lumber and plywood. This study quantified amounts of carbon accumulated in wood products harvested from loblolly pine (*Pinus taeda* L.) stands grown in Mississippi by extending rotation ages traditionally used to manage these stands for timber. The financial viability of this approach was examined based on carbon payments received by landowner for sequestering carbon in standing trees and harvested wood products. Results indicated a potential to increase carbon accumulated in wood products by 16 metric tons (t) per hectare (ha) to 67 t/ha for rotation increases from five to 65 years, respectively. Carbon prices of \$50 per metric ton of carbon dioxide equivalent ($tCO_2e$) and \$110/$tCO_2e$ would provide sufficient incentive to forest landowners to extend rotations by five and 10 years, respectively. With 2.8 million ha of loblolly pine stands in Mississippi, this translates to a possible increase in wood products carbon of 44 million t and 81 million t for harvest ages increased by five and 10 years, respectively. Higher carbon prices lengthened rotation ages modestly due to low present values of carbon accumulated with long rotations.

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Key words: carbon, compensation, financial feasibility, net present value, rotation age, wood products.

## 4.2 Introduction

Forests have been widely recognized for their important role in cost effective mitigation of atmospheric carbon dioxide ($CO_2$) (Brown et al., 2004; Richards and Stokes, 2004; Sohngen and Brown, 2008; US EPA, 2010). Several forestry activities can help reduce $CO_2$ emissions. For example, expanding forested areas, protecting existing forests, implementing management regimes focused on carbon sequestration, and increasing inventory of long-lived wood products reduce atmospheric $CO_2$ by sequestering additional carbon (Sampson and Sedjo, 1997; Sedjo, 2001; Daigneault et al., 2010).

Although extensive research has been devoted to determining the amounts of $CO_2$ that can be sequestered by forests (Birdsey et al., 1993; Hoover et al., 2000; Murray et al., 2000; Seely, 2002; Smith et al., 2004) enhancing carbon sequestration through long-lived wood products has received relatively little attention. Studies related to carbon sequestration in wood products have focused on developing methodologies to estimate carbon stored in these products and their carbon sequestration potential (Skog and Nicholson, 1998; Winjum et al., 1998; Skog et al., 2004; Miner, 2006; Smith et al., 2006; Woodbury et al., 2007). These studies emphasized the role of wood products in mitigating atmospheric $CO_2$ by showing that a substantial increase in carbon storage was possible over long time periods and that wood products substantially contributed to annual carbon sequestration in the U.S. (Skog and Nicholson, 1998; Birdsey and Lewis, 2003; Woodbury et al., 2007). A recent estimate provided by Woodbury et al. (2007)

indicated that the U.S. forest sector sequestered 162 million metric tons (t) of carbon per year during 1990-2005, of which carbon sequestered in wood products and landfills accounted for 27%. In another study, Birdsey and Lewis (2003) reported estimates of carbon accumulated in forest biomass, forest floor, soil, wood product and landfill components of the U.S. forest sector during the period 1987-1997. They found that wood products and landfills accumulated 3,520 million t of carbon which accounted for 6% of the total carbon sequestered in the U.S. forest sector in 1997. Their estimates also revealed that the average carbon sequestration by the forest sector during that period was 190 million t/year for the whole U.S. Of this amount, carbon accumulated in wood products and landfills accounted for 60 million t/year (32%), which was the second largest carbon sink after forest biomass component (100 million t/year or 53%). These results suggested that although the wood products and landfill components represent relatively small percentage of total carbon stock, their share in annual carbon accumulation was substantial.

When a forest stand is harvested, no carbon is left in the standing tree carbon pool. However, carbon is stored in wood products, which decay slowly depending on the longevity of manufactured end-use products affected by wood processing, recovery, recycling, and landfill technology. According to Allen et al. (2005), the majority of pine plantations in the southern U.S. have been growing at substantially lower rate (11 to 13 t/ha/year) relative to pine plantations in other temperate and sub tropical countries. Studies have shown that this growth rate could potentially be increased to more than 22 t/ha/year with investments in intensive management (Stanturf et al., 2003). The majority of industrial landowners in Mississippi manage their pine plantations intensively with relatively short rotations. More than 19 million ha of planted pine stands in the southern

U.S. are intensively managed (Siry, 2008) with rotation age varying between 20 to 35 years (Bailey, 1986; Hotvedt and Straka, 1987; Schultz, 1997; Siry, 2008; Rayonier, 2009). Investments in intensive pine plantation management in the future will encourage short rotations producing a larger proportion of pulpwood products with shorter life spans and, therefore, sequestering less carbon than the long-lived wood products such as lumber. Extending rotation cycles offers an opportunity to increase accumulation of carbon in wood products due to a larger proportion of sawlogs available for manufacture of durable wood products such as lumber and plywood. Several studies that examined the financial feasibility of forest carbon sequestration and its impact on optimal rotation ages suggested that carbon payments improved financial viability of managing forests with longer rotations (van Kooten et al., 1995; Stainback and Alavalapati, 2002; Sohngen and Mendelsohn, 2003; Brown et al., 2004; Huang and Kronrad, 2006; Nepal et al., 2009). Carbon credit markets offer monetary incentives to landowners for sequestering carbon through forestry activities and, therefore, extending rotation lengths beyond the rotation age of stands traditionally managed for timber can be a viable approach to sequester additional amounts of carbon in harvested wood products.

While several studies have indicated that rotation length would increase if carbon payments were available to forest landowners, only a few studies have examined the financial feasibility of increasing carbon sequestration in harvested wood products. Sohngen and Brown (2008) quantified the total amount of carbon sequestered both in forests and harvested wood products in the southern and western U.S. by increasing rotation ages and determining a bare land value (BLV). They reported that it would be feasible to sequester from 15 to 209 million t of carbon dioxide equivalent ($CO_2e$) in the Southern U.S. at carbon prices of \$7/t$CO_2e$ and \$55/ t$CO_2e$, respectively. Their study however, did not account for the additionality criterion adopted by the majority of the carbon trading protocols requiring that carbon offset project sequesters carbon in addition to what would have been sequestered in the absence of the new project. However, the inherent assumption of BLV approach is that the stand is managed in the same manner in perpetuity. Consequently, only carbon accumulated during the first rotation would qualify for credit. Further, they did not provide separate estimates for carbon accumulated in standing trees and harvested wood products. In another study, Brown et al. (2004) estimated supply and cost of carbon sequestration resulting from changing forest management in California. Considered management activities included lengthening rotation ages, increasing riparian buffer zones, changing harvest methods from clear cuts to group selection cuts, and reducing forest fuel to decrease a likelihood of catastrophic wildfires. Their results suggested that lengthening the rotation by five years could accumulate up to four million $tCO_2e$ at a cost of less than \$13.60/$tCO_2e$. However, although they considered carbon accumulated in wood products, they did not examine carbon supply potential of specific tree species.

The southern U.S. is considered world's timber basket, supplying 25% of the world's timber for industrial products (USDA, 2001). As such, the southern region can play an important role in mitigating atmospheric $CO_2$. Of 3,520 million t of carbon stored in harvested wood products in the U.S. in 1997, almost half was sequestered in the wood products harvested from the southern U.S. (Birdsey and Lewis, 2003). With about 8 million ha of timberland and annual removal of about 30 million cubic meters ($m^3$) of timber (USDA, 2010), Mississippi has the potential to increase carbon sequestration both in standing trees and harvested wood products. In this study, we quantified the amounts of carbon that can potentially be accumulated in wood products harvested from loblolly pine (*Pinus taeda* L.) stands in Mississippi at various rotation ages and examined financial feasibility by incorporating carbon payments based on seven different carbon price levels.

## 4.3 **Methods**

### 4.3.1 Estimation of carbon sequestered in standing tree biomass

The quantity of carbon accumulated by a loblolly pine stand was derived based on region-specific volume equations and specific gravity relationships using Forest Vegetation Simulator (FVS) carbon sub model (Crookston and Dixon, 2005; Reinhardt et al., 2007). Carbon estimates were derived for both aboveground and belowground live biomass for a stand established in central Mississippi through afforestation with 1,494 seedlings per hectare (ha) on a medium quality site with site index of 27.43 meter (m) at base age 50 years. The analysis included sixteen different harvest scenarios with rotations of 25 years through 100 years at five-year increments. This study did not analyze the effect of thinnings on accumulated carbon and generated revenues. Although thinning prescriptions are readily available in literature for loblolly pine stands managed for timber with short rotations (20 to 35 years), the realistic thinning prescriptions are generally not available for rotations longer than 40 years. The harvest age generating the largest Net Present Value (NPV) from timber production was considered as a baseline rotation age, to which the increases in carbon accumulated in forests and harvested wood products resulting from extended rotation ages were compared.

### 4.3.2 Estimation of carbon sequestered in harvested wood products

This study used a carbon accounting method developed by Smith et al. (2006) to estimate quantity of carbon accumulated in harvested wood products. The method is based on a production approach which accounts for carbon accumulated in all wood products, including exports but excluding imports. Carbon estimates were determined based on the volume of pulpwood and sawlogs further processed to different primary wood product categories (e.g. paper and lumber) and a half-life of these products in 16 different categories of end-uses (e.g. newspaper, residential construction, and furniture) (Skog and Nicholson, 1998; Skog et al., 2004; Smith et al., 2006). Softwood sawlogs were allocated to lumber (32.40%), plywood (13.00%), non-structural panels (NSP) (1.90%), other industrial products (2.30%), paper (13.30%), and fuel and other emissions (37.10%) (Smith et al., 2006). Softwood pulpwood was allocated to oriented-strand boards (OSB) (13.50%), NSP (0.06%), paper (43.00%), and fuel and other emissions (43.00%) (Smith et al., 2006). These factors were developed based on regional softwood roundwood supply estimates for the United States in 2002 (Adams et al., 2006). Therefore, the estimates of carbon stored in primary wood products in this study were based on actual quantity of these products supplied in U.S. south-central region in 2002. Primary wood products were allocated to end-uses using conversion factors developed by Smith et al. (2006). These conversion factors were based on 1998 estimates of primary wood product usage in sixteen different end-uses in the United States, as reported by McKeever (2002). Therefore, the estimate of carbon stored in end-use products in this study was based on actual end-usage of primary products in south-central region in 1998.

The analysis accounted for carbon stored in wood products still remaining in use and carbon accumulated in wood products discarded to landfills (Figure 1) based on conversion factors developed by Smith et al. (2006) and Birdsey (1996).

### 4.3.3 Financial analysis

Financial feasibility of increasing carbon accumulation in harvested wood products was determined by calculating net present values (NPVs) for rotations focused on increased carbon sequestration (Equation 1) and comparing them with a baseline rotation age that generated the largest NPV from timber production.

$$NPV = \sum_{0}^{n} \frac{R_n}{(1+r)^n} - \sum_{0}^{n} \frac{C_n}{(1+r)^n} \qquad (4.1)$$

Where:

$R_n$ represents revenues from timber production and participation in carbon offset programs; $C_n$ stands for costs associated with stand establishment and management, and participation in carbon contract (Table 4.1); and $r$ is a real discount rate.

It was assumed that forest landowners obtained payments under Chicago Climate Exchange (CCX) afforestation and long-lived wood products carbon offset protocols (CCX 2008). Payments for carbon stored in standing trees accrued to landowners on annual basis, whereas one-time payment for carbon stored in harvested wood products was made at the time of harvest. It was assumed that 20% of carbon sequestered in standing trees would be placed in reserve pool as an insurance against carbon loss due to catastrophic events such as wildfire, insect, and disease outbreaks. The payment for this carbon occurred at the end of the contract period assuming that there was no catastrophic loss of carbon. The loss of carbon due to harvest was incorporated as negative credits. A financial analysis was conducted using a 5% real discount rate and 2008 costs (Table 4.1). A sensitivity analysis was conducted to examine the impact of carbon price on financial viability of increasing carbon accumulation in wood products using six carbon price levels: \$3.76/t$CO_2$e (2008 CCX average carbon price), \$10/t$CO_2$e, \$20/t$CO_2$e, \$30/t$CO_2$e, \$50/t$CO_2$e, \$100/t$CO_2$e, and \$100/t$CO_2$e. These prices were selected to represent a range of possible carbon prices reported in literature (Sohngen and Brown 2008, Sedjo et al. 1995).

## 4.4 **Results**

### 4.4.1 Carbon storage in standing trees versus wood products

Table 4.2 presents amounts of $CO_2$e sequestered in standing trees and harvested wood products for rotation ages from 25 to 100 years. With the increase in age, amounts of $CO_2$e sequestered in standing trees and wood products also increased. At a baseline rotation age of 35 years (rotation age generating the largest NPV from managing the stand only for timber production), a loblolly pine stand sequestered 660 t$CO_2$e/ha. When harvested, 539 t$CO_2$e/ha were transferred to the wood products, whereas remaining 121 t$CO_2$e/ha was emitted to the atmosphere. After 100 years from harvest, 161 t$CO_2$e/ha was still stored in wood products. Increasing the rotation age by 10 to 60 years increased $CO_2$e sequestration in standing trees by 55 t$CO_2$e/ha (18%) to 166 t$CO_2$e/ha (25%).

### 4.4.2 Carbon accumulation in harvested wood products

Estimates showed that 100 years from harvest about 33% of initial carbon sequestered in harvested sawlogs and 16% in pulpwood was still stored in wood products. About 21% of sawlog carbon was stored in lumber, 8% in plywood, 2% in paper, 1% in other industrial products, and 1% in NSP (Figure 2a). The remaining 67% of carbon was emitted to the atmosphere. Similarly, 9% of pulpwood carbon was stored in OSBs, 7% in paper, and less than 0.5% in NSP (Figure 2b). The remaining 83% of carbon was emitted to the atmosphere.

The total amount of $CO_2e$ sequestered in wood products 100 years from harvest at a baseline rotation age of 35 years was 160.85 $tCO_2e$/ha. Of this amount, the majority of $CO_2e$ (89%) was sequestered by the sawlogs component, whereas the pulpwood component sequestered only 11%. Longer rotations promoted sequestration of $CO_2e$ in wood products. As rotation age increased, the proportion of carbon accumulated in the sawlogs component also increased, whereas carbon accumulated in pulpwood component decreased (Table 3). For example, extending the rotation by 10 and 20 years increased amount of $CO_2e$ sequestered in sawlogs to 181.37 $tCO_2e$/ha (96%) and 199.90 $tCO_2e$/ha (98%), respectively. In contrast, the same increases in rotation length decreased amount of $CO_2e$ sequestered in pulpwood to 8.08 $tCO_2e$/ha (4%) and 4.94 $tCO_2e$/ha (2%), respectively. Sequestration of $CO_2e$ in sawlogs and pulpwood components remained relatively stable for rotation increases beyond 20 years.

Allocation of total sawlog carbon to primary wood product categories based on 2002 market supply estimates showed that at a baseline rotation age of 35 years, 88 $tCO_2e$/ha was accumulated in lumber, 36 $tCO_2e$/ha in plywood, 9 $tCO_2e$/ha in paper, 5 $tCO_2e$/ha in NSP, and 5 $tCO_2e$/ha in other industrial products. Similarly, allocation of total pulpwood carbon to primary product categories revealed that 40 $tCO_2e$/ha was stored in OSB, 28 $tCO_2e$/ha in paper, and 2 $tCO_2e$/ha in NSP (Table 3). Accumulation of carbon in the sawlog component increased for rotations up to 50 years, whereas in the pulpwood component, accumulation decreased. For rotations longer than 50 years, the share of both sawlog and pulpwood carbon remained relatively constant with lumber contributing about 60%, plywood 24%, paper 7%, NSP 3%, other industrial products 3%, and OSB 1% of total carbon accumulated in wood products.

### 4.4.3 Financial analysis

A loblolly pine stand managed for timber with a 35-year rotation generated the largest NPV of $3,364/ha (Table 4), and therefore, was used as a baseline for comparison with other harvest scenarios. Managing the stand for increased carbon sequestration increased revenues substantially. For example, if carbon was traded at $3.76/t$CO_2$e, NPV from managing the stands jointly for timber and carbon would increase to $3,680/ha, whereas at $30.00/t$CO_2$e NPV would increase to $7,309/ha, when payments for carbon stored in standing trees and wood products were accounted for. These revenue increases did not require changes in stand management and were achieved with a 35-year rotation. Carbon prices higher than $50.00/t$CO_2$e increased revenues further but also resulted in longer rotations required to achieve these revenue increases. For example, carbon prices of $50/t$CO_2$e and $100/t$CO_2$e generated NPVs of $10,132/ha and $17,406/ha, respectively, increasing rotation from 35 to 40 years. At these prices, an additional increase in $CO_2$e accumulated in standing trees and wood products carbon was 29 t$CO_2$e/ha, and 16 t$CO_2$e/ha, respectively. Similarly, a carbon price of $110/t$CO_2$e would increase revenues to $18,876/ha, lengthening the rotation by 10 years from 35 to 45 years and increasing net accumulation of carbon in standing trees and wood products by 55 t$CO_2$e/ha and 20 t$CO_2$e/ha, respectively. These results showed that it was financially feasible to increase carbon accumulation in standing trees and harvested wood products only at carbon prices above $50/t$CO_2$e. Below this price, no additional gain in carbon could be achieved because the financially optimal rotation age would remain same.

## 4.5 Discussion and conclusions

The analysis indicated that carbon stock both in standing trees and wood products can potentially be increased if a loblolly pine stand established through afforestation is managed with longer rotations. However, the actual increase in accumulated carbon will depend on the demand for wood products, which this study has not accounted for. When compared to a baseline rotation age of 35 years, a 100-year rotation could potentially increase quantity of carbon accumulated in standing trees by 25% and wood products by 42%. This result suggested that a longer rotation age promoted accumulation of carbon with a greater rate in wood products. This result is consistent with Woodbury et al. (2007) and Birdsey and Lewis (2003) who reported a higher rate of carbon sequestration in wood product carbon pool despite its small share in total carbon stock. However, carbon in standing trees was accumulating at increasing rate until age 35 years and at decreasing rate thereafter. Since a large proportion of carbon payment was for carbon sequestered in standing trees, a decreasing carbon sequestration rate meant a higher opportunity cost of managing the stand with long rotations. This is because carbon payments were based on annual carbon sequestration rate for standing trees and one-time payment for carbon accumulated in wood products. Revenue for carbon in harvested woods products accounted for very small share in total net revenue when discounted to present value.

Results suggested that increasing carbon sequestration in both standing trees and harvested wood products by extending rotation can be financially feasible but only at carbon prices higher than \$50/t$CO_2$e. If the stand was managed only for timber, it would be harvested at age 35 years. Landowners managing the stand for increased carbon sequestration would still harvest the stand at age 35 years if carbon prices were lower than \$50/t$CO_2$e. Carbon prices of \$50/t$CO_2$e to \$110/t$CO_2$e, would provide sufficient financial incentive for the landowner to increase rotation to 40 years and increase carbon sequestration in standing trees by up to 29 t$CO_2$e/ha and up to 16 t$CO_2$e/ha in wood products still in use and in landfills 100 years after harvest. Similar findings were obtained by Brown et al. (2004) who indicated that extending rotation ages would be a financially viable strategy for increasing carbon sequestration in California forests. According to them, increasing rotation age by five years was the most viable strategy for supplying low-cost carbon. This result can be explained by the fact that annual payments for carbon accumulated in standing trees tended to lengthen the rotation. However, longer rotations lowered the present value of a one-time credit for carbon sequestered in wood products 100 years from harvest. In addition, the rate of carbon sequestration in standing trees slowed down over time resulting in smaller present value for longer rotations. Moreover, larger negative credits applied for carbon loss due to harvest also contributed to smaller present value. The amount of carbon placed in the reserved pool was released back at the end of contract generating a one-time payment. Although a larger amount of carbon was accumulated in the reserve pool with longer rotations, the present value of payments from this portion of the carbon pool was smaller, resulting in shorter financial rotations. The combined effect was a relatively small increase in rotation length despite higher carbon prices.

The results suggested the importance of delaying harvest age to increase the amount of carbon accumulated in wood products by harvesting a larger proportion of sawlogs. Mississippi has about 2.8 million ha of loblolly pine forests. Assuming similar increases in carbon due to a five-year increase in rotation as estimated in this study for a loblolly pine stand established through afforestation, these forests can potentially increase carbon accumulation by 81 million t of $CO_2e$ in standing trees and 44 million t of $CO_2e$ in wood products. Primary wood product categories such as lumber, plywood and OSB, stored larger amounts of carbon than paper, NSP, and other products. Development of wood processing technology that increases the amount of these products would promote a greater accumulation of carbon in wood products. Strategies can, therefore, be aimed at improving technology used in forest operations and wood processing allowing for the reuse of by-products from thinning, harvesting and processing, and converting them into wood products with longer life cycles such as OSB.

Carbon payments can make it financially feasible to increase rotation age by five to 10 years and potentially increase carbon sequestered in standing trees by 4% to 8% and in wood products by 10% to 18%, relative to traditional rotation age of 35 years applied to stands managed for timber. The minimum carbon prices needed to achieve a five-year and 10-year increases in rotations were \$50/t$CO_2$e and \$110/t$CO_2$e, respectively. The factors attributable to requirement of such high carbon price were high transaction costs associated with participation in carbon sequestration program, large negative credit for standing trees carbon at harvest, small positive credit for carbon stored in wood products after harvest, and a discount factor. The current carbon price trends in the U.S. carbon market show that such high carbon prices are unlikely. However, increase in demand for carbon offsets is expected to increase carbon prices if mandatory carbon trading programs are introduced. For example, the projected carbon price in the proposed mandatory greenhouse program in the U.S. (The American Clean Energy and Security Act of 2009) ranged from \$16/t$CO_2$e in 2015 to \$36/$CO_2$e in 2030, based on 2005 dollar value (US Environmental Protection Agency, 2009). Although the bill was approved by U.S. House of Representatives in 2009, the U.S. Senate is not likely to pass this bill in near future. This situation has important implications for the development of carbon market in the U.S. as it will result in a decreased demand for carbon offsets and possibly lower carbon prices. Furthermore, current housing market in the U.S. indicates a low demand for the solid wood products, which can lead to a reduced timber harvests in the short-run and consequently reduced total carbon accumulation in wood products and relatively greater accumulation in standing trees. In the long-run, even if the stands are not managed specifically for carbon sequestration, the demand for solid wood products should increase due to increasing population and growing economy leading to larger accumulation of wood products carbon.

These results should be interpreted carefully as longer rotations are associated with potential financial and biological risks. The study assumed a constant timber price and did not take into account timber price premiums for large diameter sawlogs harvested with longer rotations (within a diameter range operationally acceptable by mills). Although costs and prices are likely to change in the future, the results and conclusion derived from the study still provide valuable information on financial viability of increasing carbon accumulation in wood products. Older loblolly pine stands are vulnerable to southern pine beetle (*Dendroctonus frontalis)* infestations. This risk can be greatly reduced by careful management aimed at maintaining healthy stands through thinnings and periodic sanitation operations such as removing dead, dying, and diseased trees (Nebeker et al., 1985). Older loblolly pine stands can be susceptible to wind damage, if neighboring stands are managed with shorter rotations. Hurricane Katrina severely damaged many stands whose height was above the average height of trees across the Mississippi Gulf coast landscape. This study has not taken such risk into account. Moreover, timber growth and yield estimates derived in this study are associated with uncertainty because of the potential modeling error for long projection periods.

The estimates obtained in this study pertain to an unthinned loblolly pine stand established through afforestation on a medium quality site (site index of 27.43 meter (m), base age 50 years) in central Mississippi with a planting density of 1,495 seedlings per ha. Thinning regimes, planting densities and site indices have important effect on rotation ages. In general, higher quality sites are associated with early thinnings, lower planting densities and shorter rotation ages than lower quality sites (Nebeker et al., 1985). Future research is needed to examine effects of these factors as related to managing loblolly pine stands for increased carbon sequestration. This study provided estimates of carbon that can potentially be sequestered in wood products. However, future accumulation of carbon in wood products will depend on demand for these products, which is determined by situation in the economy. It is therefore important to examine the future timber harvests under various demand and supply assumptions related to carbon and timber prices and available forest resources to better understand the dynamics of carbon accumulation in wood products. Furthermore, leakage associated with carbon sequestration projects can potentially diminish the impact of $CO_2$ mitigating strategies because these projects might increase clearing of forestlands not enrolled in carbon contracts to meet demand for timber. This study did not analyze this issue and further research is needed to examine its impact on derived estimates of sequestered carbon.

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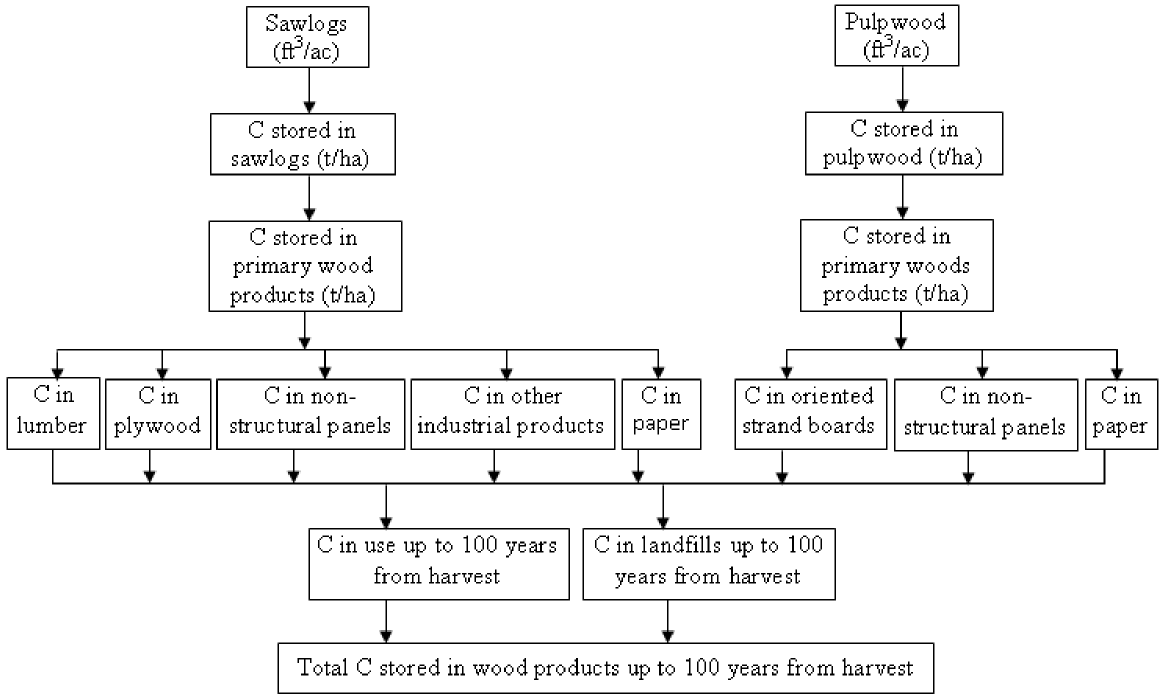


Figure 4.1 Flow chart showing steps in estimating carbon (C) accumulated in wood products harvested from loblolly pine stand located in Mississippi (derived from Smith et al. 2006). $ft^3$/ac stands for cubic feet/acre and t/ha stands for metric ton/hectare.

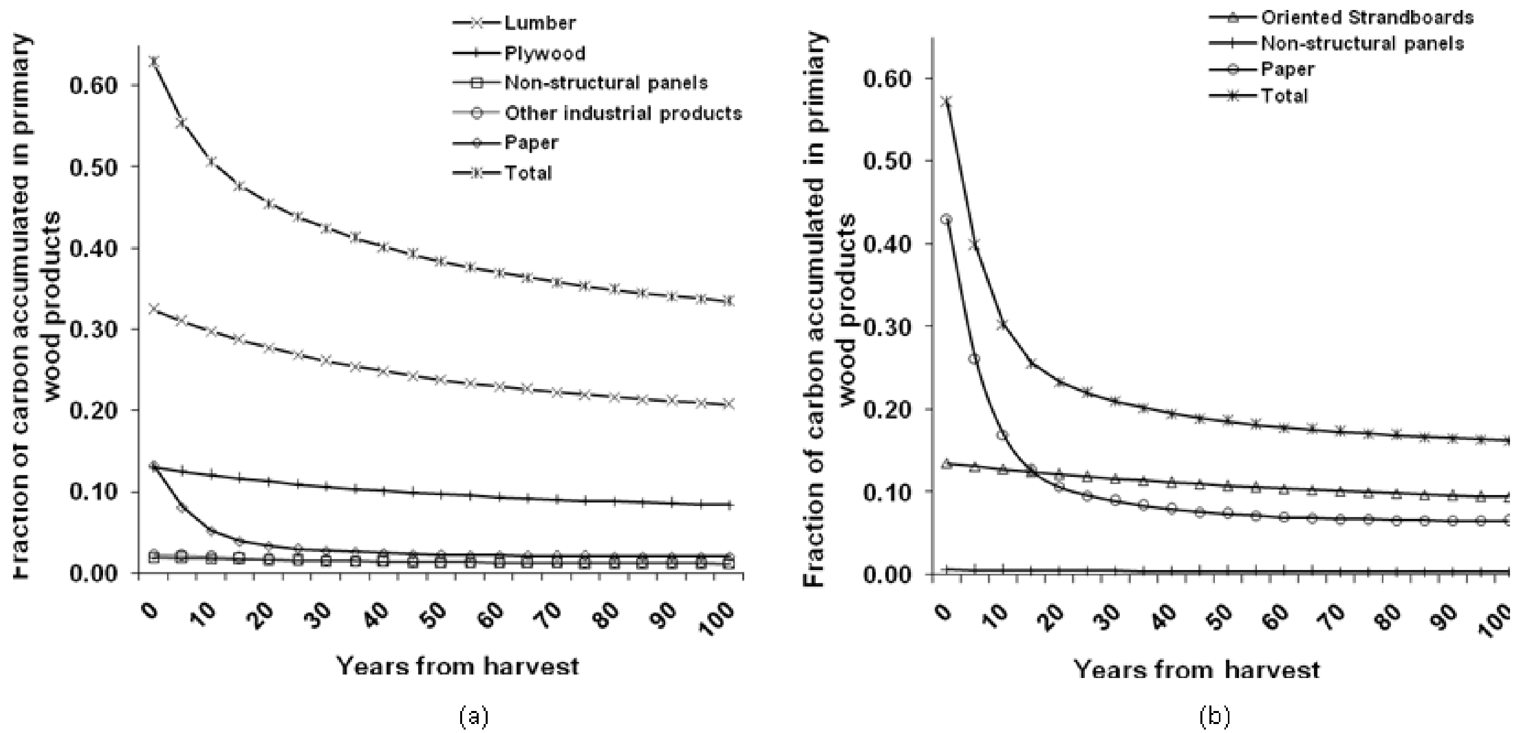


Figure 4.2 Fraction of carbon accumulated in primary wood manufactured from the sawlogs (a) and pulpwood (b) harvested from loblolly pine stand in Mississippi (based on conversion factors developed by Smith et al. 2006).

Table 4.1 Summary of the costs and revenues associated with managing loblolly pine (*Pinus taeda* L.) stands in Mississippi for timber and carbon sequestration (Source: Nepal et al., forthcoming).

| Costs/Revenues | Amount | Frequency | Source |
|---|---|---|---|
| Costs: | | | |
| Seedling | \$0.05/seedling | Once | Plum Creek (2010) |
| Planting | \$0.088/seedling | Once | Barlow et al. (2009) |
| Chemical site preparation | \$145/ha | Once | Barlow et al. (2009) |
| Aggregator's fee | 10% of total carbon revenue | Annually | AgraGate Climate Credits Corp.(2008) |
| Verification fee | \$0.25/t$CO_2$e | Annually | Bilek et al. (2009) |
| Transaction fee | \$0.20/t$CO_2$e | Annually | AgraGate Climate Credits Corp.(2008) |
| Revenues: | | | |
| Carbon price | \$3.76/t$CO_2$e, \$10/t$CO_2$e, \$20/t$CO_2$e, \$30/t$CO_2$e, \$50/t$CO_2$e, \$100/t$CO_2$e, \$110/t$CO_2$e, | Annually | (CCX 2009, Sohngen and Brown 2008, Sedjo et al. (1995) |
| Sawtimber stumpage price | \$37.19/t | Once | Forest2Market (2008) |
| Pulpwood stumpage price | \$9.29/t | Once | Forest2Market (2008) |

Table 4.2 Amount (t/ha) of carbon dioxide equivalents ($CO_2e$) accumulated by standing trees and wood products harvested from loblolly pine stand (Site Index 27.43 meter (m), base age 50 years) in Mississippi.

| Harvest age | $CO_2e$ in standing trees | Net increase relative to a baseline rotation of 35 yrs | Percent increase relative to a baseline rotation of 35 yrs | $CO_2e$ accumulated in harvested wood products | | Net increase relative to a baseline rotation of 35 yrs | Percent increase relative to a baseline rotation of 35 yrs |
|---|---|---|---|---|---|---|---|
| | | | | At the time of harvest | 100 yrs from harvest | | |
| 25 | 486 | - | - | 384 | 92 | - | - |
| 30 | 594 | - | - | 479 | 132 | - | - |
| 35 | 659 | - | - | 539 | 161 | - | - |
| 40 | 689 | 29 | 4 | 568 | 177 | 16 | 10 |
| 45 | 715 | 55 | 8 | 592 | 189 | 29 | 18 |
| 50 | 736 | 77 | 12 | 613 | 199 | 38 | 24 |
| 55 | 753 | 94 | 14 | 629 | 205 | 44 | 27 |
| 60 | 770 | 110 | 17 | 644 | 210 | 49 | 31 |
| 65 | 783 | 123 | 19 | 655 | 215 | 54 | 33 |
| 70 | 792 | 132 | 20 | 663 | 217 | 56 | 35 |
| 75 | 801 | 142 | 22 | 672 | 220 | 59 | 37 |
| 80 | 809 | 149 | 23 | 678 | 222 | 61 | 38 |
| 85 | 816 | 157 | 24 | 684 | 224 | 64 | 40 |
| 90 | 821 | 162 | 25 | 688 | 226 | 65 | 41 |
| 95 | 825 | 166 | 25 | 691 | 227 | 66 | 42 |
| 100 | 829 | 169 | 26 | 694 | 228 | 67 | 43 |

Table 4.3 Amount (t/ha) of carbon dioxide equivalents ($CO_2e$) accumulated 100 years from harvest in primary wood products manufactured from sawlogs and pulpwood harvested from loblolly pine stand (Site Index 27.43 meter (m), base age 50 years) in Mississippi at various rotation ages.

| | Wood Product $CO_2e$ | | | Periodic increment relative to a baseline rotation of 35 yrs | Sawlog products | | | | | Pulpwood products | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Age | Sawlog | Pulpwood | Total | | Lumber | Plywood | NSP | Other | Paper | OSB | NSP | Paper |
| 25 | 58.01 | 34.18 | 92.19 | - | 35.94 | 14.55 | 1.95 | 2.08 | 3.49 | 19.77 | 0.75 | 13.66 |
| 30 | 105.71 | 26.39 | 132.10 | - | 65.49 | 26.52 | 3.56 | 3.79 | 6.35 | 15.27 | 0.58 | 10.55 |
| 35 | 142.67 | 18.18 | 160.85 | - | 88.38 | 35.79 | 4.79 | 5.11 | 8.57 | 10.52 | 0.4 | 7.26 |
| 40 | 164.92 | 12.03 | 176.95 | 3.22 | 102.18 | 41.37 | 5.56 | 5.9 | 9.9 | 6.97 | 0.27 | 4.82 |
| 45 | 181.37 | 8.08 | 189.45 | 2.50 | 112.36 | 45.50 | 6.10 | 6.50 | 10.89 | 4.67 | 0.17 | 3.24 |
| 50 | 192.86 | 5.83 | 198.66 | 1.84 | 119.47 | 48.39 | 6.50 | 6.92 | 11.58 | 3.36 | 0.12 | 2.32 |
| 55 | 199.90 | 4.94 | 204.84 | 1.24 | 123.85 | 50.17 | 6.72 | 7.16 | 12.00 | 2.87 | 0.10 | 1.98 |
| 60 | 205.78 | 4.52 | 210.30 | 1.09 | 127.48 | 51.62 | 6.92 | 7.39 | 12.37 | 2.62 | 0.10 | 1.80 |
| 65 | 210.27 | 4.25 | 214.52 | 0.84 | 130.27 | 52.76 | 7.09 | 7.53 | 12.65 | 2.47 | 0.10 | 1.70 |
| 70 | 213.19 | 4.12 | 217.31 | 0.56 | 132.07 | 53.50 | 7.16 | 7.63 | 12.82 | 2.40 | 0.10 | 1.65 |
| 75 | 216.13 | 4.08 | 220.18 | 0.57 | 133.87 | 54.22 | 7.26 | 7.76 | 12.99 | 2.35 | 0.10 | 1.63 |
| 80 | 218.30 | 4.00 | 222.30 | 0.42 | 135.23 | 54.76 | 7.34 | 7.83 | 13.12 | 2.32 | 0.10 | 1.61 |
| 85 | 220.50 | 3.98 | 224.47 | 0.43 | 136.59 | 55.33 | 7.41 | 7.9 | 13.24 | 2.3 | 0.10 | 1.58 |
| 90 | 221.95 | 3.93 | 225.88 | 0.28 | 137.50 | 55.67 | 7.46 | 7.95 | 13.34 | 2.27 | 0.07 | 1.58 |
| 95 | 223.02 | 3.90 | 226.92 | 0.21 | 138.15 | 55.95 | 7.51 | 8.00 | 13.41 | 0.91 | 0.03 | 0.63 |
| 100 | 224.03 | 3.88 | 227.91 | 0.20 | 138.79 | 56.22 | 7.53 | 8.03 | 13.46 | 0.91 | 0.03 | 0.63 |

Table 4.4 Net Present Values (NPVs) generated from managing loblolly pine stand (site index 27.43 meter (m), base age 50 years) in Mississippi jointly for timber and carbon sequestration at various rotation ages and carbon prices.

| | Carbon prices ($/t$CO_2$e) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Age | 0.00 | 3.76 | 10.00 | 20.00 | 30.00 | 50.00 | 100.00 | 110.00 |
| | Net Present Value ($/ha) | | | | | | | |
| 25 | 2,361 | 2,492 | 3,046 | 3,930 | 4,814 | 6,585 | 11,011 | 11,898 |
| 30 | 3,226 | 3,465 | 4,211 | 5,407 | 6,605 | 8,996 | 14,978 | 16,174 |
| 35 | 3,364 | 3,680 | 4,545 | 5,928 | 7,309 | 10,075 | 16,991 | 18,374 |
| 40 | 3,041 | 3,404 | 4,310 | 5,765 | 7,222 | 10,132 | 17,406 | 18,863 |
| 45 | 2,618 | 3,011 | 3,942 | 5,436 | 6,928 | 9,915 | 17,384 | 18,876 |
| 50 | 2,171 | 2,581 | 3,520 | 5,024 | 6,528 | 9,537 | 17,060 | 18,565 |
| 55 | 1,736 | 2,154 | 3,085 | 4,579 | 6,071 | 9,057 | 16,522 | 18,016 |
| 60 | 1,361 | 1,783 | 2,702 | 4,174 | 5,649 | 8,596 | 15,964 | 17,438 |
| 65 | 1,037 | 1,457 | 2,359 | 3,801 | 5,244 | 8,131 | 15,346 | 16,791 |
| 70 | 761 | 1,173 | 2,048 | 3,451 | 4,854 | 7,659 | 14,672 | 16,075 |
| 75 | 534 | 939 | 1,788 | 3,152 | 4,515 | 7,240 | 14,052 | 15,413 |
| 80 | 346 | 741 | 1,564 | 2,882 | 4,199 | 6,837 | 13,427 | 14,743 |
| 85 | 195 | 580 | 1,376 | 2,650 | 3,927 | 6,479 | 12,856 | 14,131 |
| 90 | 72 | 445 | 1,213 | 2,443 | 3,673 | 6,133 | 12,286 | 13,516 |
| 95 | -27 | 331 | 1,072 | 2,258 | 3,443 | 5,814 | 11,742 | 12,928 |
| 100 | -109 | 240 | 951 | 2,095 | 3,238 | 5,523 | 11,239 | 12,382 |

CHAPTER V

# POTENTIAL IMPACT OF CARBON DIOXIDE MITIGATING POLICY ON CARBON ACCUMULATION IN MISSISSIPPI'S FORESTS SECTOR[4]

## 5.1 Abstract

This study examined future carbon accumulation by Mississippi forest sector under six potential harvests scenarios during 2006-2051. Results indicated a potential to increase carbon accumulation by 63.12 Teragram (Tg), to 264.24 Tg by 2051, depending on future harvest levels. The largest increase resulted from a scenario that reduced harvests by 2.5 % per year in the short-run (1-35 years) and then increased it by 1%/year in the long-run (36-45 years), representing a potential harvest scenario resulting from future carbon policies in the U.S. In contrast, the lowest increase resulted from a scenario that increased harvest at 1.25% per year during 2010-2050 and represented future harvest levels projected by USDA Forest Service 2005 RPA assessment based on overall future microeconomic condition in the U.S. Results also indicated a trade-off between carbon accumulation in forests and wood products, because carbon policy resulted in increased carbon accumulation in forests but reduced accumulation in wood products. The study results can be used by policymakers in considering potential carbon policies and programs to mitigate $CO_2$ emissions at state level in the U.S.

Keywords**:** forests carbon, wood products carbon, carbon policy, pulpwood, sawtimber, market equilibrium, price, demand.

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## 5.2 Introduction

Forest sector's role in mitigating atmospheric concentration of carbon dioxide ($CO_2$) is widely recognized (Woodbury et al. 2007, Smith and Heath 2004, Birdsey and Heath 1995, Plantinga and Birdsey 1993) because of its capability to sequester $CO_2$ in standing trees and wood products. The ability of the forest sector to sequester $CO_2$ is further enhanced due to its better cost-effectiveness relative to alternative mitigation strategies (Sohngen and Brown 2008, Richards 2004, Adams et al. 1999, Hoen and Solberg 1994). The forest sector's mitigation potential can be further improved by implementing policies and programs promoting $CO_2$ sequestration. For example, carbon offset programs existing in the U.S. (e.g. Chicago Climate Exchange, Regional Greenhouse Gas Initiative, California Action Reserve, and over-the-counter carbon market) and the proposed future programs (e.g. The American Clean Energy and Security Act of 2009) can help enhance forest sector's carbon sequestration potential by providing monetary incentives. These programs offer forest landowners an opportunity to generate additional income and, therefore, can motivate them to increase carbon sequestration on their land. By limiting harvests during participation in the programs, they can influence future timber supply and forest product markets. Several studies indicated that payments for carbon sequestered by forests will lead to longer forest rotations (Nepal et al. 2009, Sohngen et al. 2008, Sohngen and Mendelsohn 2003, Stainback and Alavalapati 2002, van Kooten et al. 1995) and reduced timber supply in the short-run. Depending on the extent of rotation increase, which in turn, is affected by carbon prices and costs associated with participation in carbon contracts, there will be a reduction in the timber supply for the period of extended rotation. However, there also will be an increased supply of timber in long-run when the stands managed with extended rotations are harvested (Sohngen et al. 2008, Sohngen and Mendelsohn 2003). Timber market will respond to such reduced supply with an increased timber price in short-run, whereas the increased supply in long-run will result in a timber price decrease (Sohngen et al. 2008) assuming that other factors related to timber supply remain constant. Understanding the impact of such changes on future carbon accumulation is important in developing appropriate carbon policies and programs in future.

Several studies examined impact of carbon policies on future carbon accumulation and timber supply at the global level (e.g. Sohngen et al. 2008, Sohngen and Mendelsohn 2007, Sohngen and Mendelsohn 2003, Sedjo and Sohngen 2000). In general, these studies indicated that carbon sequestration programs could achieve substantial carbon sequestration levels, but also potentially decrease timber supply in short-run and increase in long-run. Sohngen et al. (2008) and Sohngen and Mendelsohn (2007) analyzed the effect of carbon policy on carbon accumulation and timber supply at the global level using the Dynamic Timber Supply Model. They showed that carbon policy would induce owners of hardwood forests in the southern U.S. to withhold their forests from harvest in the short-run, which would results in an increased timber prices. However, they also showed that additional land supply, higher rotation ages, and improved management increased timber supply in long-run causing timber prices to fall. In another study, Sohngen and Mendelsohn (2003) estimated that global carbon sequestration would reach 102 billion metric tons (t) in 2100 as a result of implementing least cost strategy (minimize the present value of the total costs of greenhouse gas damage and its abatement) to control greenhouse gases. According to their estimate, implementation of such strategy would also increase global timber supply by up to 785 million cubic meter ($m^3$) by 2100 resulting in a lower global timber price in long-run.

Similarly, using the same modeling framework, Sedjo and Sohngen (2000) examined the impact of large-scale global forest carbon sequestration efforts on industrial forestry. They projected that 50 million hectares (ha) of global plantations managed for increased carbon sequestration would increase carbon sequestration by 15 to 20 Petagrams (Pg, one Pg = 1,000,000,000 t). However, they also showed that reduction in timber prices due to such expansion of carbon plantations would decrease area of industrial plantations only by 0.2 to 7.8 million ha over the period of 100 years, indicating a modest impact on industrial forestry.

Although these studies provide insight into the potential impacts of carbon policy on global-level carbon accumulation and timber supply, local effects of such policy are not well understood. The attempts to examine the impact of carbon policy on carbon accumulation and timber supply at the local level has largely been limited to harvest schedule modeling thorough linear program models (Bourque et al. 2007, McCarney et al. 2006). These studies came to a general conclusion that timber harvest would decrease when carbon constraints were imposed on objective function (maximize net present value of timber harvest), consequently reducing available timber supply. Bourque et al. (2007) investigated trade-off between maximizing timber extraction and maximizing total carbon storage from a large scale commercial forests and wood products in south central New Brunswick, Canada over a 80-year planning horizon. They reported that maximizing carbon accumulation reduced timber harvests to 19,000 $m^3$/year compared to the 110,000 $m^3$/year removed in timber maximization scenario. Similarly, McCarney et al. (2006) analyzed implication of a carbon market on timber and non-timber values in Alberta, Canada. They concluded that firms entering carbon sequestration contracts would decrease timber supply. They reported that increasing carbon sequestration by 240 million t will reduce timber supply by up to 6 million $m^3$ in a 125-year planning horizon.

In recent years, carbon accumulation in wood products has been gaining importance because annual addition of wood products carbon in the U.S. has been substantial (Woodbury et al. 2007, Birdsey and Lewis 2003, Skog et al. 2000). For example, during 1990-2005, the U.S. forest sector sequestered 162 Teragrams (Tg, one Tg = 1,000,000 t) of carbon per year, of which 27% was sequestered by wood products although their share in the total carbon stock was only 3%. This larger annual sequestration rate in wood products was due to cumulative addition of harvested wood in subsequent years. Similarly, study by Birdsey and Lewis (2003) showed that annual carbon sequestration by wood products during 1987-1997 accounted for 32% of the total annual carbon sequestration in the U.S. forest sector. Similar estimates were reported by Skog et al. (2000) who estimated that amount of carbon accumulated in wood products in U.S. doubled (to 150 Tg/year) in 1995 when compared to 1940. The accumulation of carbon in wood products depends on the amount of harvested volume, which in turn is largely determined by market forces (e.g. stumpage price, timber demand and supply). This is particularly true for private ownership whose harvest decisions are mostly market driven. Therefore, to examine future $CO_2$ mitigation potential of the U.S. private forestry, it is necessary to understand how much carbon can be accumulated in wood products in the future as a result of carbon policies affecting future harvest levels.

Timber production is one of the major economic activities in Mississippi. With more than 8 million ha of timberland and 30 million $m^3$ of annual timber harvest (USDA 2010), Mississippi has a great potential to increase carbon sequestration both in standing trees and harvested wood products and play an important role in U.S. $CO_2$ mitigation goal. However, an important question that needs to be addressed in relation to Mississippi's $CO_2$ mitigation potential is how future carbon accumulation in forests and wood products will be impacted by changes in future harvests due to 1) changes in overall microeconomic conditions, and 2) implementation of carbon policies and programs. This study attempted to answer this question by employing partial equilibrium modeling framework to examine impacts of six harvest scenarios on carbon accumulation in forests and wood products for four major forest products: softwood pulpwood, softwood sawtimber, hardwood pulpwood, and hardwood sawtimber in Mississippi during 2006-2051.

## 5.3 **Methods and materials**

### 5.3.1 The model

The sub-regional timber supply model (SRTS) (Abt et al. 2009) was used to examine the impact of six harvest scenarios on carbon accumulation in forests and harvested wood products during a 45-year period (2006-2051). Year 2006 was selected as a starting point for the analysis because it was the most recent year, for which forest inventory data was available for the state of Mississippi. The SRTS is a partial equilibrium model that combines economic and forest inventory information to determine impact of changes in timber demand and supply on forest resources and timber markets (Abt et al. 2009). The earlier version of this model was used to model timber supply issue in the U.S. South and Northeast (e.g., Bingham et al. 2003, Sendak et al. 2003, Prestemon and Abt 2002, Abt et al. 2000, Pacheco et al. 1997, Abt et al. 1993). The model has also been used in modeling impact of climate change on timber supply in the U.S. South (Abt et al. 2001). It has also been utilized in analyzing impact of non-market forest values on timber supply decisions by non- industrial private forest landowners (Pattanayak 2005). SRTS consists of three different program modules (market, inventory, and goal module) and an additional component for a land use modeling.

In the market module, demand for forest products is modeled as a function of stumpage price and a demand shifter, whereas supply of forest products is modeled as a function of product stumpage price and forest inventory. The demand-shifter is not specified and is implicitly estimated in determining market equilibrium (Abt et al. 2000). At the aggregate regional level, the equilibrium harvest in year *t* is determined by interaction of the following supply and demand functions (Abt et al. 2000):

$$Q^S{}_t = Q^S(P_t, I_t, v_t) \quad ..(5.1)$$

and

$$Q^D{}_t = Q^D(P_t, Z_t) \quad ..(5.2)$$

Where:

$Q^S{}_t$ and $Q^D{}_t$ represent current forest product supply (timber harvest) and demand, respectively. $P_t$ is product stumpage price, $I_t$ indicates initial forest inventory, $v_t$ stands for a supply shifter, and $Z_t$ is a demand shifter. The model assumes an increasing marginal cost of output implying an upward sloping timber harvest supply function ( $\partial Q^S{}_t / \partial P_t > 0$ ). Timber supply is positively related with the level of available merchantable inventory ( $\partial Q^S{}_t / \partial I_t > 0$ ). The model uses a constant elasticity functional form which means that specified elasticity is constant across all price-quantity combinations (Abt et al. 2009).

The inventory module estimates inventory changes over time by adding net timber growth and subtracting timber harvest estimated in the market module (Abt et al. 2009, Abt et al. 2000). The inventory is estimated as:

$$I_t = I_{t-1} + G - H \tag{5.3}$$

Where:

$I_t$ represents inventory at time $t$, $I_{t-1}$ represents inventory in the previous year, whereas $G$ and $H$ represent timber growth and harvest, respectively.

The market equilibrium for product prices and harvest levels is determined by subregion, product, and ownership categories based on specified demand-price, supply-price and supply-inventory elasticities, and inventory shifts estimated by the model (Abt et al. 2009, Abt et al. 2000).

The goal program module allocates product harvest estimated in the market module across five forest management types (plantation, natural pine, mixed pine, upland hardwood, and lowland hardwood) and five-year age classes based on specified product definition. A product definition includes a range of diameter classes that qualify for a particular product class and indicates what percentage of that class would degrade to pulpwood (Abt et al. 2009). In this study, four products were defined: softwood pulpwood, softwood sawtimber, hardwood pulpwood, and hardwood sawtimber. For both species, a log with a diameter between 12.5 to 17.25 centimeters (cm) qualified as pulpwood, whereas a diameter class between 22.5 and 27.25 cm qualified log as sawtimber (Abt et al. 2009). It was assumed that 20% of the softwood sawtimber and 40% of hardwood sawtimber class would degrade to a pulpwood category based on percentage degradation as defined in Abt et al. (2009). Figure 5.1 illustrates the model flow.

### 5.3.2 Model set up

#### 5.3.2.1 Forest inventory data

The major inputs utilized by the model are forest inventory, timber growth and removals, and acreage data arranged by Forest Inventory and Analysis (FIA) survey units, ownership, management types, species groups, and five-year age classes. This study utilized datasets specific to Mississippi provided by the FIA program of the United States Department of Agriculture (USDA) Forest Service (USDA Forest Service 2010). Due to the fact that harvest decisions on public lands are not necessarily market driven (Abt et al. 2009, Abt et al. 2000), this study analyzed only private owner data and excluded public ownership from the analysis. Within the private ownership, two sub categories were distinguished: corporate and non-corporate private ownership. The corporate ownership included forest industry, Timber Investment and Management Organizations (TIMOs) and Real Estate Investment Trusts (REITs). The non-corporate ownership category included private ownership other than forest industry, TIMOs and REITs, such as non-industrial private owners. The FIA estimates of the timber growth per acre (ac) are based on few plots that are highly variable for small regions (Abt et al. 2009, Abt et al. 2000). To minimize these variations, the model used regression to estimate growth equations based on species group, physiographic region, management type, and ownership category (Abt et al. 2009, Abt et al. 2000).

#### 5.3.2.2 Model parameters

In addition to inventory data, the model utilized 20 elasticity estimates representing responsiveness of demand and supply to changes in price and inventory: four demand-price elasticities specific to products categories, eight supply-price elasticities by product and ownership categories (two ownership and four products categories), and eight supply-inventory elasticities by product and ownership categories. Several studies examined price elasticity of timber supply from private forestlands and indicated that it was inelastic (Adams and Haynes 1996, Newman 1987, Daniels and Hyde 1986). Adams and Haynes (1996) estimated softwood supply-price elasticity at 0.321 and 0.290 and a hardwood supply-price elasticity at 0.407 and 0.480 for the south central U.S. industrial and non-industrial private owners, respectively. Newman (1987) examined price elasticity of supply for softwood pulpwood and solid wood products in the southern U.S. and determined that it was inelastic. Estimated price elasticities were 0.23 and 0.55, respectively. Similar results were obtained by Daniels and Hyde (1986) who estimated price elasticity of timber supply in the state of North Carolina at 0.267. Previous studies indicated that demand for wood products was also inelastic. For example, Newman (1987) determined that price elasticity of demand for pulpwood and solid wood products in the southern U.S. softwood stumpage market was -0.43 and -0.57, respectively. In terms of supply-inventory elasticities, studies generally suggested that it was unitary elastic (e.g., Adams and Haynes 1996, Newman 1987, Daniels and Hyde 1986). This study assumed supply-price and demand-price elasticities for all four products and ownership categories to be 0.5. Similarly, the supply-inventory elasticity was assumed to be 1.0 for all wood products and ownership categories. Although demand-price elasticity and supply-inventory elasticity can vary by products and owner categories, these elasticity specifications are consistent with previous studies. Similar elasticities were assumed by Abt et al. (2009) when projecting timber supply for multiple wood products in the southern U.S.

#### 5.3.2.3 Timber harvest scenarios

Six harvest scenarios were developed to examine the potential future impact on quantity of carbon accumulated in forests and harvested wood products in Mississippi (Table 5.1). The scenarios included a constant harvest, an increased harvest, and four combinations of decreased harvest during a short-run (1-35 year) and increased harvest during a long-run (36-45 years). The constant harvest scenario served as a baseline and assumed that future timber harvests will be constant at the 2006 level. The increased timber harvest scenario was developed based on harvest projection for the 2010-2050 reported in the 2005 Regional Planning Act (RPA) Assessment of the USDA Forest Service (Haynes et al. 2007). The RPA projection was defined based on expected labor force and productivity growth, gross domestic product, prices, inflation, interest rates, and other assumptions related to timber demand and supply (Haynes et al. 2007). According to this projection, softwood and hardwood harvests in the southern U.S. during 2010-2050 will increase, on average, by 1.25% and 0.44% per year, respectively. The harvest increase trend was predicted to be initially greater (1.6% per year) and smaller towards the end of projection (0.8% per year). The increased harvest scenario developed in this study assumed similar harvest changes.

The four mixed harvest level scenarios were developed to represent carbon policies that will result in differing levels of timber harvest reduction in short-term (1-35 years) and an increased timber harvest in long-term (36-45 years). A similar scenario was developed by Sohngen et al. (2008) when analyzing impact of carbon policy on global timber supply issues. They assumed increased product prices at 1% per year for a period up to 35 years and decreased prices up to 3% at around 45 years. Although a global market does not necessarily represents a local market, this study used similar assumptions, in terms of timber harvests reductions and increases. Given inelastic response of timber supply with respect to prices, the study assumed that reduction in harvests would take similar trajectory as increase in price presented in Sohngen et al. (2008). Authors are not aware of any study that quantified magnitude of harvest reductions and increases resulting from future carbon policies. Therefore, the levels of harvest reductions and increases were selected to conduct a sensitivity analysis. The four scenarios representing potential harvest impacts of carbon policy included: a) a decreased harvest at 1% per year for 1-35 years and an increased harvest at 1% per year for 36-45 years (harvest-1+1 scenario), b) a decreased harvest at 1% per year for 1-35 years and an increased harvest at 2.5% per year for 36-45 years (harvest-1+2.5 scenario), c) a decreased harvest at 2.5% per year for 1-35 years and an increased harvest at 1% for 36-45 years (harvest-2.5+1 scenario), and d) a decreased harvest at 2.5% for 1-35 years and an increased harvest at 2.5% per year for 35-45 years (harvest-2.5+2.5 scenario).

### 5.3.3 Carbon estimates

Forest carbon estimates were obtained for five forest management types in Mississippi using SRTS, which utilized combinations of ecosystem level equations developed by USDA Forest Service and other published sources (Foley 2009, US EPA 2008, Smith et al. 2006, Smith and Heath 2002). Quantity of carbon sequestered in five pools (live trees, standing deadwood, understory, down deadwood, and forest floor) were estimated separately using sets of equations presented in Foley (2009). However, only the total amount of accumulated carbon (sum of five carbon pools) is presented in this study.

Estimates of carbon accumulated in harvested wood products were derived using factors developed by Smith et al. (2006). Carbon accumulated in four products (softwood pulpwood, softwood sawtimber, hardwood pulpwood, and hardwood sawtimber) was estimated up to 100 years from the time of harvest based on proportion of these products allocated to different primary wood products (e.g., paper and lumber) and end-uses (e.g., newspaper, residential construction) (Smith et al. 2006). The study assumed that this carbon was permanently sequestered. Such assumption is consistent with major carbon offset programs in the U.S. (e.g. Chicago Climate Exchange and Climate Action Reserve) and several other studies (e.g. Minor 2006, Herzog et al. 2003, CGC 2010).

## 5.4 **Results**

### 5.4.1 Carbon accumulation in forests

In 2006, about 506.30 Tg of carbon were sequestered in Mississippi forests (Table 5.2). Of this amount, upland hardwood forests sequestered 152.78 Tg of carbon, followed by lowland hardwoods (116.72 Tg), plantations (116.65 Tg), and natural pine stands (75.46 Tg). Mixed pine stands sequestered the least amount of carbon (44.69 Tg). Carbon policy expressed by varying levels of future timber harvests had a substantial impact on the total amount of accumulated carbon. In 2051, the amount of carbon accumulated in Mississippi forests ranged from 657.92 Tg to 772.14 Tg depending on the harvest scenario. Although each forest type accumulated more carbon, their relative ranking in terms of sequestered carbon stayed the same.

The largest increase in carbon accumulation was achieved by a carbon policy resulting in a mixed-level -2.5+1 harvest scenario that sequestered 772.22 Tg of carbon representing a 53% increase in 2051. The increased harvest scenario sequestered the smallest amount of carbon (571.10 Tg), which represented an increase of 13% only.

When translated into annual rate of forest carbon sequestration during 2006-2051, these amounts corresponded to 5.91 and 1.44 Tg/year, respectively.

The amount of carbon accumulated in forests was largely determined by the initial forest inventory and harvest levels (Figures 5.2-5.3 and Table 5.4). Larger amounts of forest carbon were sequestered in scenarios representing a combination of a decreased harvest during first 35 years and an increased harvest during next 10 years (harvest -1+1, harvest -1+2.5, harvest -2.5+1, and harvest -2.5+2.5). These scenarios retained larger inventory of standing tress because of smaller timber removals except for softwood pulpwood. The constant and increased harvest scenarios sequestered smaller amount of carbon because of a larger removal of trees.

### 5.4.2 Carbon accumulation in harvested wood products

Table 5.3 presents carbon accumulated in wood products 100 years from harvest for the six harvests scenarios analyzed in the study. In 2006, wood products accounted for 1.68 Tg of sequestered carbon. The majority of carbon was accumulated in long-life wood products such as softwood and hardwood sawtimber that accumulated 46.00% and 24.50% of carbon, respectively. Wood products with a shorter life, softwood and hardwood pulpwood accumulated only 14.50% and 15.00% of carbon, respectively.

A similar trend in percentage contribution to carbon sequestration was observed at the end of projection in 2051 for all harvest scenarios. The amount of carbon stored in softwood pulpwood ranged from 8.54 Tg accumulated in the mixed level -2.5+1 harvest scenario to 13.94 Tg in the increased harvest scenario. The quantity of carbon stored in hardwood pulpwood was slightly higher and ranged from 8.87 Tg to 14.45 Tg for the two scenarios. In contrasts, accumulation of carbon in softwood sawtimber ranged from 27.16

Tg in the mixed level -2.5+1 harvest scenario to 44.24 Tg in increased harvest scenario, whereas carbon accumulation of carbon in hardwood sawtimber ranged from 14.46 Tg to 23.56 Tg for these two harvest scenarios, respectively. While the increased harvest scenario promoted a greater accumulation of carbon in hardwood pulpwood than softwood pulpwood, the trend was opposite for sawtimber.

## 5.5 Discussion and conclusions

Results indicated a potential to increase total carbon accumulation in Mississippi by 63.12 Tg (10%) to 264.24 Tg (32%) by 2051, depending on future harvest levels. The lowest increase, as expected, resulted from an increased harvest scenario, whereas the largest increase resulted from the scenario that reduced harvests by 2.5%/year for 35 years and then increased it by 1%/year for the next 10 years (mixed level-2.5+1 harvest scenario). The greatest accumulation of carbon was observed for plantations, mixed pine and upland hardwoods for all of the analyzed harvest scenarios. However, quantity of carbon accumulated decreased in natural pine and lowland hardwood management types in increased harvest scenario. Additionally, lowland hardwoods sequestered less carbon in other three scenarios reflecting a constant harvest, and a combination of a harvest reduced by 1% for 35 years, and harvest increased by 1% or 2.5% each for the next 10 years (harvest-1+1 and harvest-1+2.5 scenarios). The increases in carbon accumulation in plantations were mainly attributable to an increased plantation area resulting from higher stumpage prices. Scenarios that decreased plantation area at the end of projection also showed an increased forest carbon accumulation but of smaller magnitude. This was due to the movement of lower age class trees to an upper age class towards the end of projection period. Carbon increase in other forest management types was mainly due to increasing inventory and decreasing removals over the projection period. The decrease in carbon sequestered by lowland hardwoods was due to larger removals from this management type.

Estimates of accumulated forest carbon obtained in this study are consistent with estimates provided by other authors. For example, Birdsey and Lewis (2003) estimated the total amount of carbon sequestered by Mississippi forestry sector in 1997 at 1,247 Tg. However, a direct comparison is difficult because their estimates included total amount of carbon accumulated in forest ecosystem, soils, and wood products, with separate estimates for each component at the regional level but without separate estimates at the state level. A preliminary examination of their results for the U.S. South and the whole U.S. showed that about 44 to 50% of the total carbon was sequestered in the soils. Assuming similar proportion of soil carbon, the total amount of carbon accumulated in Mississippi forests would fall within the range of 623 to 698 Tg. In another study, Han et al. (2007) estimated that forest biomass in Mississippi stored 450 Tg of carbon based on total timberland biomass in 1997. Our estimate that 506.30 Tg carbon was stored in Mississippi forests in 2006 is a close estimate.

The estimates of carbon accumulated in wood products are also consistent with other studies; however, a direct comparison is not possible. Results of this study indicated that carbon accumulated in wood products represented a small percentage (0.33% in 2006 and 7 to 14% in 2051) of total carbon sequestered by the forest sector, depending on the harvest scenario. However, their contribution to the annual carbon sequestration during 2006-2051 was substantially higher (21 to 50%) for all harvest scenarios except the increased harvest scenario. Similar conclusion was presented by Woodbury et al. (2007). They estimated carbon sequestration from the U.S. forest sector during the period 1990-

2005 and reported that carbon in wood products was sequestered at an annual rate of 27% despite its small share (6%) in total carbon. Similar estimates were presented by Birdsey and Lewis (2003) who reported that carbon in wood products was sequestered at a rate of 42% annually during 1987-1997 despite small share (10-12%) in total carbon accumulated by the southern U.S. forest sector. The largest percentage of wood products carbon was accumulated in sawtimber (67%), whereas a pulpwood share was about 33%. This result suggested an opportunity to increase carbon accumulation in wood products by growing and harvesting a larger proportion of sawtimber instead of pulpwood through extended rotations.

Comparison of annual carbon sequestration rate in forests and wood products during 2006-2051 showed a higher annual sequestration rate in forests in all scenarios except for the increased harvest scenario. This was due to the larger annual timber removals in increased harvest scenario relative to other scenarios. Results also indicated a trade-off between forest and wood product carbon. The increased harvest scenario reduced carbon accumulation in forests but increased its accumulation in wood products.

Results of this study can be used by policy makers in considering potential carbon policies and programs to mitigate $CO_2$ emissions. This study investigated potential changes in carbon accumulation in forests and wood products in Mississippi. An increase in future harvest levels, as projected by 2005 RPA assessment due to changes in overall U.S. economy will increase carbon accumulation in wood products. However, this increase will occur at the expense of a lower carbon accumulation in forests, leading to a lower accumulation of total carbon in Mississippi when compared to mixed level harvest scenarios representing future carbon policies. A short-run reduction and a long-run increase in product removals, as induced by future carbon policies, would result in a lower carbon accumulation in wood products but a larger carbon accumulation in forests, leading to a larger accumulation of total carbon in Mississippi. Results thus indicated trade-offs between forests and wood products carbon accumulation.

There are some limitations related to future harvest assumptions, use of FIA data, SRTS model, and elasticity assumptions. Therefore, this study results should be interpreted carefully. First, this study assumed that projected harvest levels will hold in future. However, future harvest levels are associated with uncertainty because they are determined by future market outlook, government policies and programs, and other factors affecting timber supply such as natural growing conditions, technology improvements and catastrophic events such as wildfires, insects, and hurricanes. Second, FIA data is associated with sampling error (USDA 2010, Bob et al. 2009) indicating that estimates derived in this study are also associated with error. Third, the SRTS is a model based on simple economic framework and designed to examine short-run (5 to 25 years) sensitivity of market assumptions on timber supply and available forest resources. Long - term projections, as conducted in this study, are therefore associated with uncertainty. Fourth, although the estimates for demand-price, supply-price, and supply-inventory elasticities used in this study are consistent with literature, they are still uncertain. This also adds uncertainty to the carbon estimates derived in this study. However, despite these limitations, carbon estimates derived in this study still provide useful benchmarks for policy makers and other stakeholders interested in carbon sequestration programs.

This study did not account for the impact of carbon policy alternatives on stumpage prices and associated demand. When harvest is exogenous variable as assumed in this study, the SRTS can only adjust the price needed to achieve the desired harvest given the inventory trend. In this case, harvest does not react to changes in prices.

Therefore, the impact of carbon policy alternatives on stumpage prices and implied demand could not be estimated in this study. Future research should investigate economic impact of $CO_2$ mitigating policies on the forest sector. Although the harvest scenarios used in this study provide a valuable insight on potential impact of future carbon policies on carbon accumulation in Mississippi, the impact of such policies can be further explored. Future research should accommodate more scenarios to capture wide range of possible outcomes resulting from future carbon policies and programs not only at state level but also at the regional and national levels.

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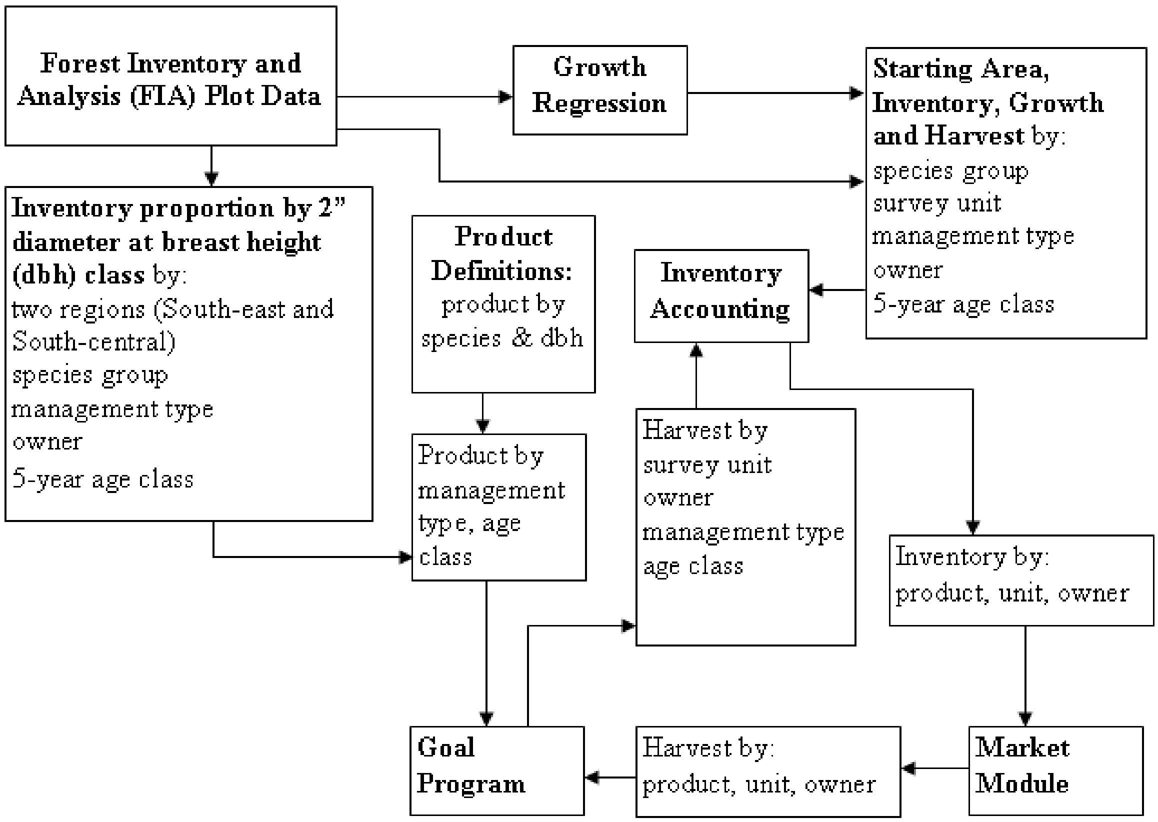


Figure 5.1 Data flows in Sub-Regional Timber Supply Model (derived from Abt et al. 2009).

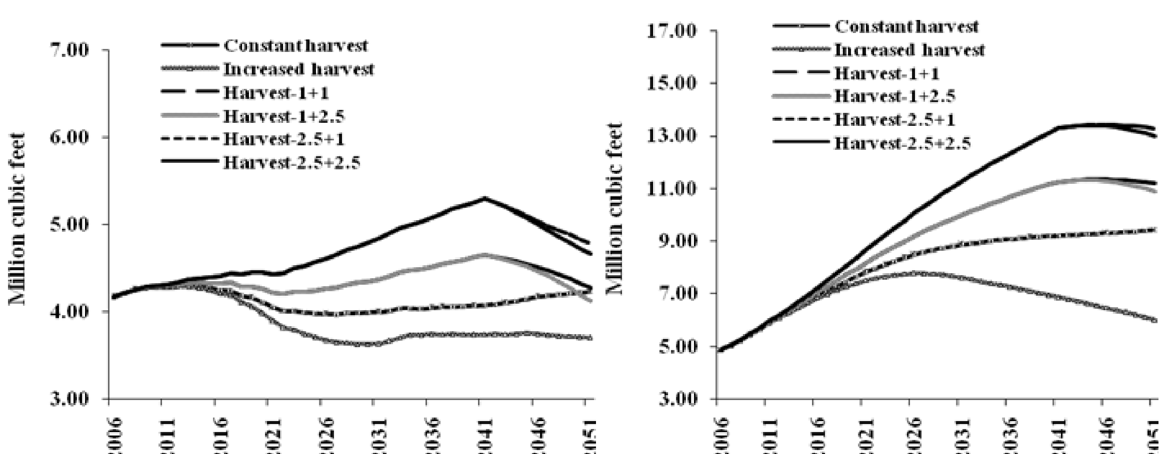


Figure 5.2 Inventory projection for softwood pulpwood (left) and sawtimber (right) in six different harvest scenarios in Mississippi.

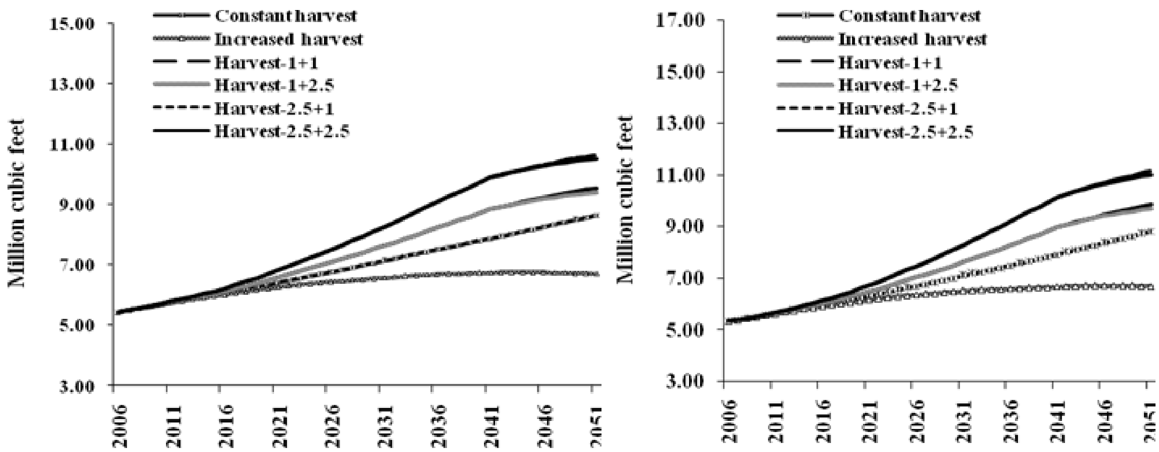


Figure 5.3 Inventory projection for hardwood pulpwood (left) and sawtimber (right) in six different harvest scenarios in Mississippi.

Table 5.1 Harvest scenarios representing future carbon policy alternatives used to estimate carbon accumulation in Mississippi during 2006-2051.

| Scenarios | Description |
|---|---|
| 1. Constant harvest | Baseline scenarios representing a constant harvest at 2006 level. |
| 2. Increased harvest | Harvest level projected by 2005 RPA assessment based on overall U.S. microeconomic conditions. The projected softwood harvest increase was 1.25%/year during 2010-2050, whereas hardwood harvest increase was 0.44%/year during 2010-2050. |
| 3. Mixed harvest | Represents harvest decrease in short-run (1-35 years) and increase in long-run (36-45 years) reflecting potential impacts of carbon policy. |
| A.Harvest-1+1 | Harvest decreased by 1%/year during 1-35 years and then increased by 1%/yr during 36-45 years. |
| B. Harvest-1+2.5 | Harvest decreased by 1%/year during 1-35 years and then increased by 2.5%/year during 36-45 years. |
| C. Harvest-2.5+1 | Harvest decreased by 2.5%/year during 1-35 years and then increased by 1%/year during 36-45 years. |
| D. Harvest-2.5+2.5 | Harvest decreased by 2.5%/year during 1-35 years and then increased by 2.5%/year during 36-45 years. |

Table 5.2 Carbon accumulated in five different forest management types in Mississippi from 2006 to 2051 under six different harvest scenarios.

| | | Forest management types | | | | | |
|---|---|---|---|---|---|---|---|
| Year | Scenarios | Plantation | Natural Pine | Mix Pine | Upland HW | Low land HW | All types |
| | Constant harvest | 116.65 | 75.46 | 44.69 | 152.78 | 116.72 | 506.30 |
| | Increased harvest | 116.65 | 75.46 | 44.69 | 152.78 | 116.72 | 506.30 |
| 2006 | Harvest-1+1 | 116.65 | 75.46 | 44.69 | 152.78 | 116.72 | 506.30 |
| | Harvest-1+2.5 | 116.65 | 75.46 | 44.69 | 152.78 | 116.72 | 506.30 |
| | Harvest-2.5+1 | 116.65 | 75.46 | 44.69 | 152.78 | 116.72 | 506.30 |
| | Harvest-2.5+2.5 | 116.65 | 75.46 | 44.69 | 152.78 | 116.72 | 506.30 |
| | Constant harvest | 128.31 | 74.27 | 46.55 | 162.93 | 115.45 | 527.51 |
| | Increased harvest | 128.31 | 74.27 | 46.55 | 162.93 | 115.45 | 527.51 |
| 2011 | Harvest-1+1 | 128.53 | 73.85 | 46.23 | 162.19 | 116.38 | 527.19 |
| | Harvest-1+2.5 | 128.44 | 74.31 | 46.69 | 162.82 | 116.15 | 528.41 |
| | Harvest-2.5+1 | 128.25 | 75.00 | 46.60 | 163.31 | 116.36 | 529.52 |
| | Harvest-2.5+2.5 | 128.25 | 75.00 | 46.60 | 163.31 | 116.36 | 529.52 |
| | Constant harvest | 140.04 | 76.86 | 51.39 | 185.32 | 115.09 | 568.70 |
| | Increased harvest | 140.02 | 74.84 | 51.28 | 182.69 | 112.17 | 560.99 |
| 2021 | Harvest-1+1 | 142.72 | 73.28 | 48.95 | 184.97 | 117.10 | 567.02 |
| | Harvest-1+2.5 | 142.95 | 78.98 | 52.62 | 187.61 | 117.80 | 579.96 |
| | Harvest-2.5+1 | 146.49 | 82.54 | 53.28 | 191.36 | 121.44 | 595.11 |
| | Harvest-2.5+2.5 | 146.49 | 82.54 | 53.28 | 191.36 | 121.44 | 595.11 |
| | Constant harvest | 141.22 | 82.49 | 56.64 | 210.71 | 111.25 | 602.30 |
| | Increased harvest | 142.19 | 75.07 | 54.10 | 202.59 | 101.56 | 575.50 |
| 2031 | Harvest-1+1 | 142.57 | 80.39 | 54.80 | 207.43 | 116.47 | 601.67 |
| | Harvest-1+2.5 | 150.75 | 87.93 | 58.55 | 217.80 | 119.13 | 634.16 |
| | Harvest-2.5+1 | 162.25 | 94.33 | 59.92 | 225.82 | 130.41 | 672.73 |
| | Harvest-2.5+2.5 | 162.25 | 94.33 | 59.92 | 225.82 | 130.41 | 672.73 |

Table 5.2 (Continued)

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | Constant harvest | 137.97 | 86.53 | 60.86 | 235.04 | 108.99 | 629.37 |
| | Increased harvest | 135.45 | 73.62 | 57.52 | 212.28 | 97.47 | 576.34 |
| 2041 | Harvest-1+1 | 137.96 | 87.10 | 59.15 | 232.63 | 114.17 | 631.02 |
| | Harvest-1+2.5 | 154.66 | 96.37 | 63.29 | 249.53 | 122.80 | 686.65 |
| | Harvest-2.5+1 | 173.62 | 105.33 | 64.81 | 258.51 | 147.02 | 749.28 |
| | Harvest-2.5+2.5 | 173.62 | 105.33 | 64.81 | 258.51 | 147.02 | 749.28 |
| | Constant harvest | 137.08 | 89.94 | 63.58 | 256.71 | 110.61 | 657.92 |
| | Increased harvest | 135.87 | 65.95 | 56.25 | 213.29 | 99.74 | 571.10 |
| 2051 | Harvest-1+1 | 135.32 | 86.69 | 61.42 | 249.11 | 110.04 | 642.57 |
| | Harvest-1+2.5 | 148.07 | 100.02 | 65.81 | 276.10 | 116.56 | 706.57 |
| | Harvest-2.5+1 | 168.79 | 106.74 | 67.60 | 284.83 | 144.27 | 772.22 |
| | Harvest-2.5+2.5 | 168.78 | 106.73 | 67.59 | 284.82 | 144.23 | 772.14 |

Table 5.3 Carbon accumulated in wood products 100 years from harvest in five different physiographic regions in Mississippi during 2006-2051 under six different harvest scenarios.

| | | Physiographic regions | | | | | |
|---|---|---|---|---|---|---|---|
| Years | Scenarios | Delta | North | Central | South | South-West | All region |
| | Constant harvest | 0.11 | 0.38 | 0.50 | 0.41 | 0.28 | 1.68 |
| 2006 | Increased harvest | 0.11 | 0.38 | 0.50 | 0.41 | 0.28 | 1.68 |
| | Harvest-1+1 | 0.11 | 0.38 | 0.50 | 0.41 | 0.28 | 1.68 |
| | Harvest-1+2.5 | 0.11 | 0.38 | 0.50 | 0.41 | 0.28 | 1.68 |
| | Harvest-2.5+1 | 0.11 | 0.38 | 0.50 | 0.41 | 0.28 | 1.68 |
| | Harvest-2.5+2.5 | 0.11 | 0.38 | 0.50 | 0.41 | 0.28 | 1.68 |
| | Constant harvest | 0.67 | 2.32 | 2.96 | 2.36 | 1.73 | 10.05 |
| 2011 | Increased harvest | 0.68 | 2.33 | 2.97 | 2.37 | 1.73 | 10.08 |
| | Harvest-1+1 | 0.66 | 2.27 | 2.89 | 2.30 | 1.69 | 9.80 |
| | Harvest-1+2.5 | 0.66 | 2.27 | 2.89 | 2.30 | 1.69 | 9.80 |
| | Harvest-2.5+1 | 0.63 | 2.18 | 2.79 | 2.22 | 1.62 | 9.45 |
| | Harvest-2.5+2.5 | 0.63 | 2.18 | 2.79 | 2.22 | 1.62 | 9.45 |
| | Constant harvest | 1.73 | 6.42 | 7.86 | 5.97 | 4.83 | 26.81 |
| 2021 | Increased harvest | 1.84 | 6.85 | 8.36 | 6.32 | 5.17 | 28.55 |
| | Harvest-1+1 | 1.61 | 5.94 | 7.31 | 5.57 | 4.46 | 24.90 |
| | Harvest-1+2.5 | 1.61 | 5.94 | 7.31 | 5.57 | 4.46 | 24.90 |
| | Harvest-2.5+1 | 1.45 | 5.31 | 6.57 | 5.05 | 3.97 | 22.33 |
| | Harvest-2.5+2.5 | 1.45 | 5.31 | 6.57 | 5.05 | 3.97 | 22.33 |
| | Constant harvest | 2.73 | 10.65 | 12.70 | 9.41 | 8.09 | 43.59 |
| 2031 | Increased harvest | 3.08 | 12.10 | 14.30 | 10.48 | 9.24 | 49.20 |
| | Harvest-1+1 | 2.42 | 9.37 | 11.27 | 8.43 | 7.07 | 38.56 |
| | Harvest-1+2.5 | 2.42 | 9.37 | 11.27 | 8.43 | 7.07 | 38.56 |
| | Harvest-2.5+1 | 2.04 | 7.80 | 9.48 | 7.18 | 5.84 | 32.35 |
| | Harvest-2.5+2.5 | 2.04 | 7.80 | 9.48 | 7.18 | 5.84 | 32.35 |
| | Constant harvest | 3.70 | 14.97 | 17.53 | 12.78 | 11.38 | 60.37 |
| 2041 | Increased harvest | 4.41 | 18.03 | 20.72 | 14.82 | 13.79 | 71.76 |
| | Harvest-1+1 | 3.15 | 12.64 | 14.99 | 11.11 | 9.54 | 51.43 |
| | Harvest-1+2.5 | 3.15 | 12.65 | 14.99 | 11.12 | 9.54 | 51.45 |
| | Harvest-2.5+1 | 2.53 | 9.96 | 12.05 | 9.09 | 7.50 | 41.13 |
| | Harvest-2.5+2.5 | 2.53 | 9.97 | 12.06 | 9.09 | 7.50 | 41.15 |
| | Constant harvest | 4.65 | 19.34 | 22.36 | 16.14 | 14.64 | 77.15 |
| 2051 | Increased harvest | 5.84 | 24.50 | 27.62 | 19.50 | 18.73 | 96.19 |
| | Harvest-1+1 | 4.16 | 17.22 | 20.19 | 14.82 | 12.95 | 69.33 |
| | Harvest-1+2.5 | 4.26 | 17.70 | 20.73 | 15.19 | 13.31 | 71.19 |
| | Harvest-2.5+1 | 3.51 | 14.38 | 17.30 | 12.95 | 10.88 | 59.02 |
| | Harvest-2.5+2.5 | 3.62 | 14.85 | 17.85 | 13.33 | 11.24 | 60.89 |

Table 5.4 Projected removals of softwood pulpwood, softwood sawtimber, hardwood pulpwood, and hardwood sawtimber during 2006-2051 in six harvest scenarios in Mississippi.

| Products | Scenarios | Projection year | | | | | |
|---|---|---|---|---|---|---|---|
| | | 2006 | 2011 | 2021 | 2031 | 2041 | 2051 |
| Softwood pulpwood | Constant harvest | 0.20 | 0.20 | 0.20 | 0.20 | 0.20 | 0.20 |
| | Increased harvest | 0.20 | 0.20 | 0.23 | 0.25 | 0.27 | 0.29 |
| | Harvest-1+1 | 0.20 | 0.19 | 0.17 | 0.15 | 0.20 | 0.22 |
| | Harvest-1+2.5 | 0.20 | 0.19 | 0.17 | 0.15 | 0.20 | 0.26 |
| | Harvest-2.5+1 | 0.20 | 0.17 | 0.13 | 0.10 | 0.20 | 0.22 |
| | Harvest-2.5+2.5 | 0.20 | 0.17 | 0.13 | 0.10 | 0.20 | 0.26 |
| Softwood sawtimber | Constant harvest | 0.30 | 0.30 | 0.30 | 0.30 | 0.30 | 0.30 |
| | Increased harvest | 0.30 | 0.31 | 0.35 | 0.39 | 0.42 | 0.45 |
| | Harvest-1+1 | 0.30 | 0.29 | 0.26 | 0.23 | 0.30 | 0.34 |
| | Harvest-1+2.5 | 0.30 | 0.29 | 0.26 | 0.23 | 0.31 | 0.40 |
| | Harvest-2.5+1 | 0.30 | 0.27 | 0.21 | 0.16 | 0.30 | 0.34 |
| | Harvest-2.5+2.5 | 0.30 | 0.27 | 0.21 | 0.16 | 0.31 | 0.40 |
| Hardwood pulpwood | Constant harvest | 0.16 | 0.16 | 0.16 | 0.16 | 0.16 | 0.16 |
| | Increased harvest | 0.16 | 0.16 | 0.19 | 0.21 | 0.22 | 0.24 |
| | Harvest-1+1 | 0.16 | 0.15 | 0.14 | 0.12 | 0.16 | 0.18 |
| | Harvest-1+2.5 | 0.16 | 0.15 | 0.14 | 0.12 | 0.16 | 0.21 |
| | Harvest-2.5+1 | 0.16 | 0.14 | 0.11 | 0.08 | 0.16 | 0.18 |
| | Harvest-2.5+2.5 | 0.16 | 0.14 | 0.11 | 0.08 | 0.16 | 0.21 |
| Hardwood sawtimber | Constant harvest | 0.16 | 0.16 | 0.16 | 0.16 | 0.16 | 0.16 |
| | Increased harvest | 0.16 | 0.16 | 0.19 | 0.20 | 0.22 | 0.24 |
| | Harvest-1+1 | 0.16 | 0.15 | 0.14 | 0.12 | 0.16 | 0.18 |
| | Harvest-1+2.5 | 0.16 | 0.15 | 0.14 | 0.12 | 0.16 | 0.21 |
| | Harvest-2.5+1 | 0.16 | 0.14 | 0.11 | 0.08 | 0.16 | 0.18 |
| | Harvest-2.5+2.5 | 0.16 | 0.14 | 0.11 | 0.08 | 0.16 | 0.21 |

# CHAPTER VI

# CONCLUSIONS

The overall objective of this dissertation was to explore financial feasibility and physical potential for sequestering carbon in Mississippi forests and wood products. To this end, the studies in chapter II and III have produced valuable information on financial viability and trade-offs associated with managing forest stands jointly for timber and carbon sequestration for two commercially important species, loblolly pine and cherrybark oak based on Chicago Climate Exchange (CCX ) forestry offset protocols. The study also determined financial feasibility of increasing carbon sequestration in wood products by extending rotation lengths of loblolly pine stands. Finally, the study investigated future carbon sequestration potential in Mississippi forests and harvested wood products based on harvest levels representing potential impacts of future carbon policy. The findings can be useful to forest landowners considering enrollment in carbon offset protocols as well as researchers and policy makers interested in management of forest resources for increased carbon sequestration. The important findings, major strengths, limitations and the future research recommendations of are summarized in the following sections.

## 6.1 Important findings

Study results presented in Chapter II and III indicated that without carbon payments, harvest age generating the largest NPV was 35 years for loblolly pine and 50 years for cherrybark, with corresponding NPVs of \$5,126/ha, and \$534/ha, respectively.

When enrolled in carbon contracts these harvest ages still generated the largest NPVs from managing the stand jointly for timber and carbon sequestration for carbon prices from \$4.25/t $CO_2$e to \$20/t $CO_2$e. Enrollment in two subsequent CCX 15-year contracts generated the largest revenues (\$6,032/ha) for a loblolly pine. However, enrollment in three CCX 15-year contracts generated the largest joint revenue (\$1,128/ha) in case of cherrybark oak. Two moderate intensity thinnings carried out at ages of 16 and 25 years, with each thinning removing 38% of the merchantable volume fared better in terms of total joint revenue in case of loblolly pine, whereas an unthinned stand generated the largest joint revenue in case of cherrybark oak.

Analysis of the financial trade-offs (Chapter III) revealed that managing stands with rotations maximizing physical quantity of carbon (50 years for loblolly pine and 80 years for cherrybark ok) reduced timber revenue by \$561/ha for loblolly pine and \$168/ha for cherrybark. These reductions in revenues represent amounts of money landowners would have to forgo to increase carbon sequestration and can be considered as the subsidy needed to motivate them to manage their stands for increased carbon sequestration. In contrast, managing the stands at rotation ages maximizing timber revenue (35 years for loblolly pine and 50 years for cherrybark oak) reduced the quantity of sequestered $CO_2$e by 363 t/ha for cherrybark oak and 297 t/ha for loblolly pine. These amounts were 38% less when compared to the amounts at harvest ages maximizing physical quantities of sequestered carbon.

Evaluating feasibility of increasing rotation length to increase carbon in wood products (Chapter IV) revealed a potential to increase carbon accumulation by 16 t/ha to 67 t/ha for rotation increases from five to 65 years, respectively. However, carbon prices of \$50/ $tCO_2e$ and \$110/$tCO_2e$ would be needed to provide a sufficient incentive to forest landowners to extend rotation by five and 10 years, respectively.

Finally, evaluation of future carbon sequestration potential for Mississippi forest sector based on six harvest levels (Chapter V) indicated a potential to sequester from 571 to 772 Tg of carbon in forests, and 59 to 96 Tg of carbon in harvested wood products by 2051. A carbon policy resulting in a reduced harvest at 2.5% /year in short- run (1-35 years) and increased harvest by 1%/year in long-run (36-45 years) achieved the largest increase in forest carbon (266 Tg). In contrast, an increased harvest scenario projected by 2005 RPA assessment based on population and economy growth, forest products trade, and overall macroeconomic and resource conditions in the U.S. sequestered the largest amount of carbon in wood products (94 Tg).

## 6.2 **Major strengths**

In contrast to past literature that discussed economic aspects of forest carbon sequestration based on hypothetical carbon payment scenarios, chapters II and III of this study were based on CCX carbon offset protocols. Therefore, the results are more relevant for understanding financial viability and trade-offs associated with enrollment in existing carbon programs. Landowners interested in participation in carbon offset programs can use it to evaluate financial attractiveness of enrolling into such programs.

The economics of carbon sequestration in wood products received relatively little attention in the literature despite their substantial potential for $CO_2$ mitigation. Chapter IV of this study has made a contribution in this area by investigating financial feasibility of sequestering carbon in wood products by extending rotation length of loblolly pine stands in Mississippi. Finally, chapter V examined the potential impact of future carbon policies on carbon accumulation in Mississippi forests and harvest wood products. Although this issue was largely discussed in global context, the local impacts of such policies have been explored only to a limited extent.

## 6.3 Limitations

This study used FVS, a distance independent growth and yield model for projecting timber volume at different rotation ages. There is error inherent to all growth and yield models. Therefore, the results presented in this study are dependent on the accuracy of the FVS in projecting tree growth and yield. Despite that the results might be overestimated due to potential estimation error, the results would still provide useful information to landowners on financial viability of enrolling in carbon contracts.

The study utilized 2008 average sawtimber and pulpwood prices. Published price data for different log dimensions were not available at the time of analysis. The average sawtimber and pulpwood prices used in the analysis may not account for the potential increase in revenues due to price premium for large diameter logs.

The study results presented in chapters II and III were derived based on the contractual framework of CCX. Although, CCX closed in December 2011, the results are still useful in evaluating financial attractiveness of participating in other carbon programs. Longer rotations in loblolly pine stands are associated with potential biological risks such as vulnerability to southern pine beetle. In addition, there is risk of fire and wind damage in older loblolly pine stands. The results presented in this study did not take into account such risks and, therefore, should be interpreted with caution.

## 6.4 Future research recommendations

Several future research recommendations can be made based on this study. First, the study used only selected management regimes (e.g., one site index, three planting densities, nine thinnings, and seven harvest ages for loblolly pine) and 9 harvest ages for cherrybark oak to examine financial viability of managing stands jointly for timber and carbon sequestration. Additional research is needed to account for alternative site indices, planting densities, thinning scenarios, and silvicultural treatments. For example, it would be useful to investigate financial viability of increasing carbon sequestration by using genetically improved planting stock.

This study analyzed financial implications of enrolling Mississippi forest landowners into CCX carbon offset protocols. Similar analysis can be conducted to determine financial incentives available to NIPF landowners from other carbon offset protocols existing in the U.S., such California Action Reserve (CAR), and Regional Greenhouse Gas Initiative Program (RGGI).

Further research is also needed to determine the impact of price premium for large diameter logs (within a diameter range operationally acceptable by mills) on revenues generated from managing forests for increased carbon sequestration. This study assumed that there was no catastrophic loss in the sequestered carbon. Further research is needed to account for potential biological and physical risks associated with longer rotations used to promote greater carbon accumulation.

Although the study results give a valuable insight into the potential impact of future carbon policies on carbon accumulation by Mississippi forest sector and on forest products market further research incorporating additional harvest and demand scenarios for the whole southern region will further improve understanding of this topic.