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Carbon sequestration and uneven-aged management of loblolly pine stands in the southern USA: a joint optimization approach

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CARBON SEQUESTRATION AND UNEVEN-AGED MANAGEMENT OF LOBLOLLY PINE STANDS IN THE SOUTHERN USA: A JOINT OPTIMIZATION APPROACH

A Thesis

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ABSTRACT

Forest carbon sequestration is regarded as a viable and cost effective option for reducing global greenhouse gas emissions. Several research studies analyzed the effects of joint management of carbon and timber under different even-aged forest management scenarios, and concluded that carbon benefits can alter forest management schedules significantly. However, research specifically focused on the inclusion of carbon sequestration benefits into uneven-aged management has received little attention. This study determined the optimum joint management regime of timber and carbon in uneven-aged loblolly pine stands in Louisiana, and assessed the management and financial effects resulting from the integration of carbon benefits into uneven-aged management. The USDA Forest Vegetation Simulator (FVS) –Southern (SN) variant was used to generate both growth and carbon data of uneven-aged loblolly pine stands. The generalized Faustmann model for uneven-aged management was applied to calculate the land expectation value (LEV) at every level of residual basal area and cutting cycle. In order to analyze the effects of changes in interest rate, stumpage prices, future land values, comparative static analyses were carried out at three different interest rates, stumpage prices and future land values.

This study determined the residual BA of 60 ft^2/acre and cutting cycle of 18 years as the optimum timber management regime of uneven-aged loblolly pine stands at the interest rate of 4% and 2010 stumpage prices in Louisiana. Changes in interest rates and stumpage prices altered the optimum management schedules significantly, but effects of changes in future land value were minimal. In the joint optimization of timber production and carbon sequestration, carbon benefits were found influential in both financial and management perspectives. At every level of interest rates, the joint management of timber and carbon increased the LEV, extended the cutting cycle, and shifted the residual stocking to higher level. The joint management of timber and carbon under uneven-aged management is profitable, and the carbon offsets would provide an important additional income source to landowners in the southern USA.

(Key words: Uneven-aged management, Forest carbon sequestration, Joint optimization)

CHAPTER 1. INTRODUCTION

1.1 Research Background

Forests are a crucial component of the global carbon cycle. Carbon dioxide (CO_2) is considered to be the most important greenhouse gas that plays a vital role in global warming and climate change (EPA, 2005). Forests absorb atmospheric CO_2 through photosynthesis and store it as carbon in biomass and the soil. Forest ecosystems not only fix additional carbon from the atmosphere but also act as a carbon reservoir over a period of decades (Sedjo, 2001). The Food and Agriculture Organization (2005) stated that global forest ecosystems store carbon more than the amount contained in the atmosphere. The three significant roles that forest trees play to reduce the carbon emission are carbon storage in biological ecosystems, carbon storage in long-lived (durable) wood products, and substitutes for fossil fuels (Richards et al., 2006).

A number of research studies stated that forest carbon sequestration is a viable and cost effective option for reducing global greenhouse gas emissions (Newell and Stavins, 1999; Sedjo, 2001; Richards and Stokes, 2004). Over the last 20 years, several forest carbon projects have been implemented as a mitigation measure of global greenhouse gas emissions with more than 20.8 million tons of CO_2 transacted (Waggie and Hamilton, 2011). Although some land use practices including deforestation are recorded as major sources of CO_2 emissions, the sequestered amount of CO_2 is estimated to be greater than the amount actually emitted (EPA, 2005). The Kyoto Protocol, a treaty of the United Nations Framework Convention on Climate Change (UNFCCC), establishes carbon sequestration as a valid strategy that participating countries can use to reduce their levels of greenhouse gas emissions. Terrestrial vegetation, mainly forests, currently sequesters about 24% of the greenhouse gasses released to the atmosphere (Ingerson, 2007). As the US forest-related carbon sink is increasing by about 699 million metric tons of CO_2 annually, US forests fix more carbon from atmosphere than they emit (Ingerson, 2007; EPA, 2005). Specifically, terrestrial carbon sequestration offsets approximately 11% of all GHG emissions from all sectors of the US economy annually (Depro et al., 2008). The US could potentially reduce its net CO_2 emissions by designing and implementing a large-scale forest carbon sequestration strategy (Richards et.al, 2006).

Uneven-aged forest management, which is comprised of trees of three or more age classes, is not only a viable alternative to meet the demand of softwood timber products in the southern USA (Murphy and Farrar, 1982; Schulte and Buongiorno, 1998) but also valuable from aesthetic as well as environmental perspectives. The varying stand structure provides the diversity of habitat options to wildlife and offers protection against natural disturbances. This system is equally worthwhile from watershed protection and soil conservation point of view. The other distinguished benefits of uneven-aged management are high sawtimber yields, and rehabilitation of under-stocked stands (Schulte and Buongionrno, 1998).

Several forestry practices could enhance the rate of forest carbon sequestration. The potential forest management practices which could escalate the sequestration rate include lengthening rotation, increasing the timberland (Sedjo, et.al, 2001), forest land preservation, agroforestry practices, and urban forestry (Stavins and Richards, 2005). Lengthening rotation not only holds more carbon by increasing the size of trees but also delays the emissions that occur with harvesting. Ericsson (2003) found a 13% increase in the accumulation of carbon when the rotation was extended by 20%. He also concluded that lengthening the rotation increased the potential of forest to substitute for fossil fuel by 12%.

A number of research studies concluded that integrating carbon benefits into forest management, i.e. joint management of timber production and carbon sequestration could change harvesting decisions and management practices. A carbon subsidy and tax policy could increase the amount of carbon sequestered in two ways: by prolonging the rotation to increase the amount of biomass in the existing forest stand, and by producing long-lived wood products such as sawtimber (Stainback and Alavalapati, 2002). A study conducted by Olschewski and Benitez (2009) in northwestern Ecuador revealed that a joint production of timber and carbon sequestration leads to a doubling of the rotation than the optimum financial rotation focused on timber production only. Likewise, van Kooten et al. (1995) analyzed the effects of carbon taxes and subsidies on the optimal forest rotation age and found that under some tax regimes, it is never optimal to harvest trees. Pohjola and Valsta (2007) also summarized that both rotation length and growing stock level have been increased in the joint production of timber and carbon stocks with thinning options. Huang and Kronrad (2006) also reported that the inclusion of carbon benefits into the plantation stands changes the optimal timber-carbon rotation length, but a number of factors such as interest rates and carbon prices determine the magnitude and direction of change.

1.2 Problem Statement

Even though numerous studies have analyzed the effects of carbon credits under various even-aged forest management types, research specifically focused on including the carbon sequestration benefits into uneven-aged management has received little attention. Several factors such as species, stand age, climate, topography, soil, and management practices can alter the rate of forest carbon sequestration substantially (EPA, 2005; Huang and Kronrad, 2006). With increasing global concerns directed at using forest carbon sequestration as a potential strategy to reduce greenhouse gas emissions, it becomes imperative to become familiar with the possible effects of carbon sequestration credits on various types of forest management. This study analyzes the financial and management alterations incurred from the joint management of carbon and timber in uneven-aged forest stands of loblolly pine. The findings of the study could provide crucial guidelines to landowners and researchers regarding the consequences of joint management of carbon and timber in uneven-aged forest stands of loblolly pines in the southern United States.

1.3 Objectives

The general objective of the study is to determine the financial and management impacts of carbon sequestration benefits in uneven-aged management of loblolly pine under different carbon price levels. The specific objectives are to

- determine the optimum management regime of uneven-aged loblolly pine stands without carbon sequestration benefits;
- determine the optimum management regime of uneven-aged loblolly pine stands with carbon sequestration benefits; and
- analyze the effects of changes in interest rate, stumpage prices, future land value and site productivity on the optimum level of residual basal area and cutting cycle.

CHAPTER 2. LITERATURE REVIEW

2.1 Forest Carbon Sequestration

Forest carbon sequestration is a process of absorbing the atmospheric CO_2 by plant species through photosynthesis and storing it as carbon in biomass and the soil. Forest trees, long-lived perennial plants, accumulate a huge amount of carbon as biomass over a long period of time. Growing forests can remove 5-11 tons CO_2 per hactare per year depending upon location and productivity (Sohngen, 2010). Young trees grow faster so that they capture more carbon through photosynthesis, and old growth trees have more biomass to store large stocks of carbon. A substantial amount of carbon is stored in the soil, as branches, leaves and other materials fall onto the forest floor. The global statistics shows that carbon stocks in soil are almost four times greater than carbon stocks in vegetation (CBO[1], 2007). The natural absorption and storage of CO_2 by vegetation and soil is collectively referred as biological sequestration. The US biological sequestration has a potential of sequestering 40 to 60 billion metric tons of CO_2 over the course of 50 years -equivalent to 0.8 billion to 1.2 billion metric tons per year (CBO, 2007).

Even though some studies criticize the role of biological sequestration in mitigating climate change, the net amount of carbon sequestered by forests and agricultural land is fairly significant. In some cases, biological sequestration is described as a source of carbon emission to the atmosphere. For instance, land use change, mainly tropical deforestation, accounts for around 20% of the world anthropogenic CO_2 emissions (IPCC, 2000). Deforestation is the second largest anthropogenic source of CO_2 to the atmosphere, right after the fossil-fuel combustion. CO_2 is either emitted quickly through burning or slowly through decaying over time. Some

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[1] Congressional Budget Office, Congress of the United States.

studies counter the role of forests in reducing atmospheric CO_2 stating that old-growth forests sequester little or no additional carbon (Gorte, 2007). If other greenhouse gases such as methane (CH_4) and nitrous oxide (N_2O) are considered, the agricultural sector is truly a net emitter of greenhouse gases. However, the total amount of carbon sequestered by forests and agriculture is significantly higher than the amount they actually emit. The US net biological carbon sinks (90% of which occurs on forests) offset 12% of the US annual greenhouse gas emissions from all sectors (EPA, 2005). In the US, land-use change was a major source of carbon emissions before early 20th century, but became a carbon sink after the 1950s (Stavins and Richards, 2005). Afforestation has dominated deforestation in the US since 1982, with a net gain in the US forest area of about 1.5 million hectare (Alig, 2003).

A substantial variation in the rate of forest carbon sequestrations has been recorded in several studies. The sequestration rate mainly depends on the management practices adopted, the species of tree involved, and the geographic regions (Stavins and Richards, 2005). De Jong et al. (2000) revealed that improved management of natural resources on communal land appears to be the most cost effective methods of sequestering carbon. In terms of geographic regions, forest carbon-uptake in the Great Plains can create carbon offsets at a lower cost (van Kooten et al., 2004). Some of the studies stated that the cost of carbon plays a vital role in the amount of carbon sequestered. Richards and Stokes (2004) critically reviewed a dozen carbon sequestration case studies, and estimated that 250 to 500 million tons of carbon per year may be sequestered in the price range of $10 to $150 per ton of carbon in the US. At $30 per ton $CO_{2,}$ forestry activities such as afforestation, forest management and avoided deforestation can sequester around 6.7 billion tons CO_2 per year (Sohngen, 2010).

Several forestry practices could enhance the rate of forest carbon sequestration. Richards and Stokes (2004) broadly categorized those forestry practices into two types; forest plantations, and methods of modifying forest management on existing forest stands i.e. improved forest management. Some of the common strategies to reduce greenhouse gas emissions are reducing deforestation and degradation, afforestation/reforestation, increasing the use of bio-energy to substitute for fossil fuels, and forest management activities to increase carbon density (Nabuurs et al., 2007). The forest management practices which could increase the sequestration rate are lengthening rotation and increasing the forest land (Sedjo, et.al, 2001; Sohngen and Mendelsohn, 2003), forest land preservation, agroforestry practices, and urban forestry (Stavins and Richards, 2005). Lengthening the rotation not only holds more carbon by increasing the size of trees but also delays the emissions that occur with harvesting. For instance, accumulation of carbon in biomass increased 13% over the baseline scenario when the rotation age was extended by 20% (Ericsson, 2003). Liski et al. (2001) also found that shortening the rotation towards the maximum mean annual increment lowers the amount of carbon stock of trees, but increases the carbon stock of soil because of increases in harvest residues and litter. Similarly, Kaipainen et al. (2004) used the CO2FIX model to analyze the effects of rotation length on the carbon stocks of trees, soil and wood products in different European forests, and reported that lengthening the rotation age increased the carbon stock of trees in each forest, but carbon in soil and wood products decreased in some cases.

Although forests have substantial contribution in mitigating climate change, there are various direct and indirect impacts of climate change which influence the forest ecosystem and its productivity. Increased temperature and CO_2 level affect numerous forest processes such as timber and wood-fuel production, carbon sequestration, water and air quality regulation and the maintenance of biodiversity and cultural services (Burgess et al., 2010). Higher level of CO_2 in the atmosphere and increasing rate of nitrogen releases from decomposition accelerated by warming could increase biological sequestration (CBO, 2007). Some field experiments and meta-analysis demonstrated that increasing CO_2 and temperature level may escalate plant growth by 25-50% (Joyce and Birdsey, 2000). However, large-scale disturbances on plant physiology and extreme weather events eventually temper the long-term response of plant growth under elevated CO_2 and temperature level (Galik and Jackson, 2009). Climate change could have substantial impact on forests by altering the growth of trees, causing dieback and species migration in forests. Sohngen and Sedjo (2005) categorized those effects of climate change into flow effects and stock effects. Stock effects are those which influence existing timber stands such as forest fires and pest infestations. Flow effects of climate change can alter the growth potential of forests in a long run.

2.2 Cost of Carbon Sequestration and Current Carbon Market

The cost of carbon sequestration is a ratio of economic inputs to carbon mitigation outputs which is commonly expressed in terms of monetary amount (Stavins and Richards, 2005). A number of studies analyzed the cost associated with biological carbon sequestration under various management and market assumptions. As several factors such as the cost of land, stumpage prices of timber, discounted rates applied, and study methods affect the cost and quantity of potential carbon sequestration, a wide range of cost of carbon sequestration has been obtained using various study techniques. Stavins and Richards (2005) analyzed eleven past case studies, and calculated a range of normalized marginal cost from \$7.5 to \$22.50 per metric ton of CO_2 sequestered per year. Van Kooten et al. (2004) used the meta-regression analysis to study forest carbon sinks, and calculated a range of average costs from \$31.84 to \$383.62/t CO_2 with a mean value of \$81.66/t CO_2[2]. In the market context of Texas, Huang & Kronrad (2001) estimated an average cost of sequestering additional ton of carbon ranges from \$0.74 to \$27.32 on the under-stocked land and \$4.18 to \$181.27 on the intensively managed land. Using the data from the Philippines, Zelek and Shively (2003) estimated \$3.3 per ton on the fallow land and \$62.5 per ton on the productive land as an opportunity cost of carbon storage via land modification. With a merged model of the US forest and agriculture sectors, Adams et.al (2001) derived a range of target carbon costs from \$5 to \$73 under different scenarios. When CO_2 prices are low, carbon sequestration in soil would contribute to overall mitigation substantially, whereas modifying forest management and afforestation would become relatively more prominent at the higher prices of CO_2 (CBO, 2007).

While accounting the meaningful carbon offsets, three key principles of the UNFCCC should be taken into account (Maness, 2009). The principle of additionality implies that only additional amount of carbon sequestered after the project is implemented should be counted as carbon offset credits. To calculate additional amount of carbon sequestered, business as usual (BAU) level has to be set first as a baseline. The principle of leakage concerns with the impacts of forestry projects outside the project boundary. Finally, the principle of permanence deals with the durability of forestry offsets which reduces the greenhouse emissions for a long period of time. Future uncertainty and requirement of the long-term agreement make this principle the most difficult to achieve in forestry projects (Maness, 2009).

Two distinct types of carbon markets exist globally: voluntary markets and regulatory (compliance) markets (Wagge and Hamilton, 2011). In the voluntary markets, without government-imposed obligations, individuals and industries can engage in activities to offset

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[2] 1 ton of carbon equals to 3.667 ton of CO2 (CCX, 2009).

their emissions. The voluntary carbon markets have two broad components: Chicago Climate Exchange (CCX) and Over-the-Counter (OTC) offset market (Hamilton et.al, 2010). CCX is the world's only voluntary but legally binding cap-and-trade carbon market system. However, OTC is a non-binding voluntary market, which does not assign any emissions cap. On the other hand, regulatory markets usually follow cap-and-trade mechanisms imposed by governments. As a regulatory system, Kyoto Protocol is a legally binding international agreement which has been ratified by 190 countries (Hamilton et.al, 2010). The Kyoto-signed countries have a common target of reducing emissions by 5.4% below the 1990 level.

The price of carbon per metric ton is fairly negligible compared to the cost of carbon sequestration explored by research studies. In 2009, the average price of a voluntary carbon credit is \$6.5/tCO_2 under the OTC market and \$1.2/tCO_2 under the CCX (Hamilton et.al, 2010). The historic data show that the largest value of US\$728 million was transacted in the voluntary carbon markets in 2008 (Figure 1). As the CCX recently closed its major operations, current carbon price under CCX system is \$0.05/ton (chicagoclimatex.com, 2011).

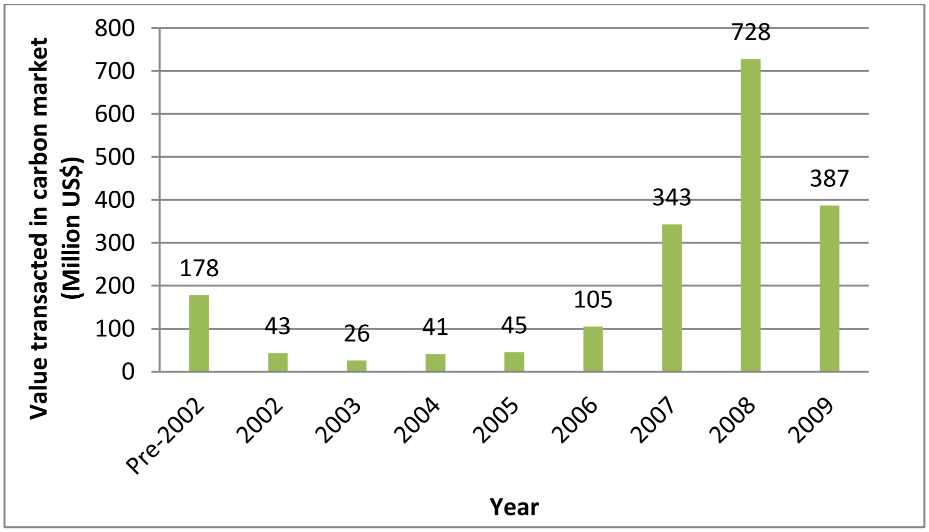

Figure 1. The historic monetary values transacted in the voluntary carbon markets. (Data source: Hamilton et.al, 2010).

2.3 Uneven-aged Forest Management

Uneven-aged forest stands are comprised of trees of three or more categories which vary in size, age and species (Murphy and Farrar, 1982). It is synonymously called all-aged or all-sized management. Uneven-aged stands have a continuous and irregular forest cover with the trees of a wide range of sizes. Generally, an uneven-aged management system follows selection cutting of trees either individually or in groups (Williston, 1978; Peng, 2000). In balanced uneven-aged stands, the diameter distribution represents almost a reverse J-shape curve i.e. the reduction of number of trees in successive diameter classes follows a constant ratio which is commonly called q-ratio (Baker et al, 1996, Williston, 1978). Instead of the concept of rotation and planting density that are extensively applied in even-aged stands, cutting cycle and residual growing stock are the common variables to describe the uneven-aged stands (Murphy and Farrar, 1983; Bakers et al., 1996). Adams and Ek (1974) also stated that stand structure at the initial stocking level and cutting schedule are two pertinent factors to control uneven-aged forest management. The cutting cycle and residual stocking are interrelated; if the cutting cycle is increased, residual stocking must be decreased so that there will be space available for reproduction (Baker et al., 1996). As Chang (1981) expounded, since maximization of forest value basically resembles the maximization of land expectation value (LEV), uneven-aged management has a common management foundation with even-aged management.

Uneven-aged forest management is not only an attractive alternative to meet the demand of softwood timber products in the southern USA but also valuable from aesthetic as well as environmental perspectives (Murphy and Farrar, 1982; Schulte and Buongiorno, 1998). Approximately one million acres of industrial lands and over one million acres of non-industrial private lands have been managed under the selection system in the southern USA (Baker, 1985).

Besides the timber benefits from selection cuts, the continuous forest cover maintained by uneven-aged stands has multifarious social and economic values which are difficult or impossible to quantify in monetary terms. The varying stand structure provides the diversity of habitat options to wildlife, and offers protection against natural disturbances. Uneven-aged management is less vulnerable to complete destruction by fire, biotic or climatic agents than even-aged management (Baker and Murphy, 1982). This system is equally worthwhile from watershed protection and soil conservation points of view. The other distinguished benefits of the uneven-aged management are high sawtimber yields, and rehabilitation of under-stocked stands (Schulte and Buongionrno, 1998). It requires very little or no capital investment, and avoids the costly site preparation (Williston, 1978). Uneven-aged stands provide frequent cash flows from periodic selective harvesting which would be an attractive feature for non-industrial private landowners (Redmond and Greenhalgh, 1990). However, uneven-aged management is a complex system which requires more technical expertise to regulate the reproduction and timber harvest (Williston, 1978). Lack of interest, scarcity of suitable data for research efforts, and no direct applicability of rotation age are the major reasons that uneven-aged management has not been as widespread and straightforward as even-aged forest management (Murphy and Farrar, 1983; Peng, 2000).

Even though even-aged management is a dominant forest management system all around the world, uneven-aged management system can be economically superior to even-aged management under certain situations. With lower stumpage prices, higher interest rates, and less fixed costs associated with the selection harvest, uneven-aged management is financially more attractive than even-aged forest management (Chang, 1990). Similar findings are reported by Redmond & Greenhalgh (1990); the higher the discount rate and initial stocking level in under-stocked stands, the more uneven-aged alternatives supersede the even-aged system. They also found that uneven-aged management could be the best option for 30 and 50 percent stocked stands of loblolly-shortleaf pines, when the interest rate was 7.125 percent or higher. Likewise, low quality sites (site index less than 13) favor uneven-aged management so that even-aged stands should be converted to uneven-aged management in low productive lands (Orois et al., 2004). Uneven-aged forest supplies small but frequent economic returns, whereas even-aged stand produces large but infrequent revenues (Chang, 1990). When the value of initial stand was not considered, Guldin and Guldin (1990) found the highest net present value (NPV) incurred from uneven-aged stands of loblolly-shortleaf pines in southern Arkansas. The uneven-aged stand with high stocking level is found to be the most effective system to produce saw logs (Baker, 1987). While comparing the log-quality, Gudlin and Fitzpatrick (1991) revealed the better quality of saw logs from uneven-aged loblolly pine stands. As uneven-aged stands produce greater proportion and continuous supply of sawtimber basal area, they have higher board-foot yields (Guldin and Baker, 1988). In a recent study from Norway, Tahvonen et al. (2010) found that uneven-aged management overshadows even-aged management of Norway spruce, when regeneration and harvesting costs, interest rate, and the price differential between sawtimber and pulpwood are taken into account.

2.4 Uneven-aged Loblolly Pine Stands in the US South

Loblolly pine (*Pinus teada*) is the most planted commercial timber species in the southeastern USA. Loblolly pine stands are broadly categorized as a loblolly-shortleaf forest type which includes all combinations from pure loblolly to pure shortleaf pine (Schultz, 1997). It is the second largest softwood species by volume throughout the USA (Smith et al., 2007). It has covered 29 million acres of 14 southern states and makes up over one half of the standing pine volume (Baker and Langdon, 1990). Loblolly pine is not only an ideal species for site restoration and forest management but also the most versatile species in terms of its ability to reproduce and grow rapidly on diverse sites (Shultz, 1997). Recognizing its commercial and economic importance, several researchers have studied the ecology and management alternatives of loblolly pine in great detail. Past research studies showed that loblolly pine can be managed under various systems ranging from selection to intensive planation system. Although commercial forests are dominated by even-aged management, uneven-aged management of loblolly pine is also common to maintain an ecologically diverse mix of size classes in the US southeast (Lin, et.al, 1998). Uneven-aged loblolly pine stands are prevalent to produce the saw-timber sized trees (Baker, 1987). Crossett Experimental Forest in southern Arkansas, in which timber management was initiated since 1937, is a pioneer research site for uneven-aged loblolly-shortleaf pine forests in the US. Several papers have been published based on the data collected from this experimental forest mainly in 80's and 90's. Long-term case studies and rigorous field experiments have established the uneven-aged management of loblolly-shortleaf pines as a potential management alternative on poor to good sites (Baker et al., 1996). Since loblolly pine stands are extensive and grow rapidly in the southern USA, they have a great potential for sequestering carbon (Johnsen et al., 2004).

2.5 Optimization of Uneven-aged Forest Stands

Even though optimizing the management regime of forest stands is not a recently developed concept, very limited works have been conducted in uneven-aged compared to even-aged management. Optimization of uneven-aged management mainly involves selecting the optimal condition of variables to maximize management objectives. The major management variables considered while optimizing uneven-aged stands are cutting cycle and the sustainable diameter distribution in terms of residual stocking. Besides these two variables, Hann and Bare (1979) pointed out some other attributes for optimizing uneven-aged stands such as the optimal species mix, the optimal conversion strategy, and the optimal schedule of treatments.

A pioneer work in the optimization of uneven-aged forest was Duerr and Bond (1952). It was the first paper which dealt with the optimization of a selection forest fixing the cutting cycle to one year. This paper particularly discussed the way of optimizing timber stocking of a selection forest with a concept of maximizing marginal benefits. The greatest net return was determined at the point where marginal value growth percent equals the alternative rate of return. This paper also pointed out four major factors determining the optimal stocking of a selection stand; rate of growth, timber value per unit of volume, timber growing costs, and alternative rate of return.

Adams and Ek (1974) used mathematical programming techniques to determine the optimal diameter distribution for a given stocking level of uneven-aged forest stands. Setting the cutting cycle of 5 years, they vary the stand structure to determine the combination of diameter distribution and stocking level that maximizes the value growth. This paper mainly dealt with determining optimal structure, stocking, and transition strategies for uneven-aged stands.

Chang (1981) was the first paper to address the simultaneous determination of optimal growing stock and cutting cycle of uneven-aged stands. Using the Faustmann model, this paper not only derived a mathematical formula to calculate the maximum forest value (values of both land and trees) but also concluded that maximization of forest value was equivalent to maximization of land expectation value (LEV). Moreover, this paper discussed an economic implication of the optimal growing stock and cutting cycle using comparative static analyses. In addition, this paper used LEV as a measure of comparing uneven-aged with even-aged forest management. Later on, pointing out some limitations of Chang (1981), Hall (1983) generalized an even-aged present net worth model for all-aged stands, and developed a financial maturity model to optimize uneven-aged stands immediately after the harvest.

Several studies determined the optimum management regimes of uneven-aged management using various techniques under various constraints in late 80's and afterwards. Haight et al. (1985) used a discrete-time optimal control technique to determine an optimal sequence of diameter distributions and selection harvests. Using a prognosis model for the first time, Bare and Opalach (1987) described an approach for determining the optimal sustainable diameter distribution and species composition in uneven-aged forest stands. Haight (1987) presented a general investment model to find the sequences of diameter-class harvesting rates that maximize the present value of existing uneven-aged stands. Hotvedt et al. (1989) determined the economically and biologically optimal level of residual basal area, the ratio of sawtimber to total merchantable basal area, and cutting cycle of uneven-aged loblolly-shortleaf pines maximizing the present net worth (PNW). Buongiorno and Lu (1990) developed a linear programming model to compute the best cutting cycle and residual stock in a regulated uneven-aged forest. Gove and Fairweather (1992) used a stochastic approach in optimizing the diameter distribution of uneven-aged forest management. Kant (1998), with a case study of uneven-aged private forests from Canada, estimated a matrix growth model and determined sustainable optimal harvesting regimes of uneven-aged stands. Schulte et al. (1999) identified the optimization models of uneven-aged loblolly pine maximizing soil expectation value, annual sawtimber production and the Shannon index of tree diversity. A couple of studies discussed the implications of converting forest stands from even-aged to uneven-aged management (Buongiorno, 2001; Nyland, 2003; Loewenstein, 2005).

Some of the recent works in uneven-aged forest management in Europe are Orois et al. (2004), Tahvonen (2009), Pukkala et al. (2009), Pukkala et al. (2010) and Tahvonen et al. (2010). Applying a size-structured transition matrix, Tahvonen et al. (2010) developed an optimization model for uneven-aged Norway spruce stands without any restriction on the forest management system. Pukkala et al. (2010) optimized the steady-state structure and management of uneven-sized Scots pine and Norway spruce stands in Finland. Tahvonen (2009) analyzed the optimal choice between even-aged and uneven-aged forest management systems, and showed that even-aged and uneven-aged systems may yield equal economic benefits. With an empirical analysis of Norway spruce, this study stated that increases in discount rate, timber price and regeneration cost may shift the optimal solution from even-aged to uneven-aged management. This study also expounded that uneven-aged management may produce about 30% more economic returns compared to even-aged management.

Chang and Gadow (2010) overcame a persistent shortcoming of the past studies in uneven-aged forest management by allowing the length of cutting cycle and harvest level to vary from one harvest to others. Extending the work of Chang (1998), they developed a generalized Faustmann formula for uneven-aged management which allows the number of years and residual stocking level to differ from one cutting cycle to others. Using comparative static analyses, they also determined the effects of interest rate and stumpage prices on the optimum cutting cycle and residual growing stock of uneven-aged stands.

2.6 Carbon Sequestration and Optimal Forest Management

The concept of optimizing forest management with both timber production and carbon sequestration is relatively new. The seminal work by Hartman (1976) discussed the inclusion of non-timber benefits into the optimal forest management for the first time. This paper analyzed the influence of non-timber forest benefits[3] on the optimal harvest age for a growing forest stand. He included non-timber values as a function of volume of standing trees in the Faustmann model, and concluded that such services provided by a standing forest may significantly alter the optimal harvesting decision.

Following the concept of Hartman (1976), several studies analyzed the possible consequences of the inclusion of carbon sequestration credits into optimum forest management regimes, and inferred that integrating carbon benefits into forest management could change the harvesting decisions and management practices substantially. Van Kooten et al. (1995) examined the effects of carbon subsidies and taxes on economically optimal harvest rotation. They included the carbon benefits as a function of the change in biomass, and calculated the optimum rotation age considering both commercial timber and carbon values. The study concluded that the carbon benefits can prolong the optimal rotation such that the length of rotation would be between the optimal rotation of the timber-only and carbon-only. Similar studies were conducted by Romeo et al. (1998) and Creedy and Wurzbacher (2001) with case studies of a beech forest in Spain and a forested catchment in Australia respectively. Both of them applied a Faustmann rotation model to maximize the net present value of timber and carbon benefits, and found the optimum rotation length moderately longer than the traditional financial rotation.

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[3] Hartman (1976) specified recreational and other services as non-timber benefits.

After the Kyoto Protocol and its mechanism established the forest carbon sequestration as a valid carbon offset, forest carbon sequestration has been receiving special attention in and outside the US. Using a modified Hartman model, Stainback and Alavalapati (2002) analyzed the impact of carbon credits on slash pine plantations in the southern US. They found the carbon subsidy and tax policy very influential in increasing the optimal rotation age, LEV and the supply of the sequestered carbon. Carbon benefits may increase the amount of carbon sequestered in two ways; by prolonging the rotation to increase the amount of biomass in the existing forest stand, and by producing long-lived end products such as sawtimber instead of pulpwood. Furthermore, Huang and Kronrad (2006) also reported that the inclusion of carbon benefits into the plantation stands changes the optimal timber-carbon rotation length, but a number of factors such as discount rates and carbon prices determine the magnitude and direction of changes. The joint optimization of timber and carbon in loblolly plantation could change unprofitable stands into profitable ones. Following the guidelines of CCX, Dwivedi et al. (2009) applied life cycle analysis and the modified Faustmann formula to assess the effects of carbon payments on the optimum rotation age and profitability of slash pine plantation in the southern US. They revealed a significant increment in the LEVs but no substantial alteration in the optimal rotation age while integrating carbon payments in slash pine management.

A number of studies analyzed the impact of carbon benefits on optimal forest management in the context of Europe and all over the world. Backeus et al. (2005) developed an optimization model for analyzing carbon sequestration impacts in forest biomass and forest products. With a case study from Sweden, they concluded that the monetary value of carbon storage not only increases the carbon sequestration in the forest but also decreases harvest levels. Likewise, Pohjola and Valsta (2007) used a joint production model of timber production and carbon sequestration in Finland, and summarized that both rotation length and growing stock level have been increased considerably by including carbon sequestration in the optimal management of Scots pine and Norway spruce stands. Chladna (2007) developed a stochastic real options model to determine the optimal rotation with and without carbon sequestration. With a case study for an even-aged forest in Austria, this study conducted sensitivity analyses to determine the effects of CO_2 prices, carbon crediting schemes and discount rates on the optimal rotation periods. A study conducted by Olschewski and Benitez (2009) in northwestern Ecuador compared the optimal Faustmann rotation of timber only with the optimal Hartman rotation of timber and carbon, and found that a joint production of timber and carbon sequestration leads to a doubling of the rotation. Similarly, Raymer et al. (2009) integrated carbon benefits into a forest optimization model, and applied it to a forest in Norway. They found 21% reduction in net present value of traditional timber revenue while maximizing the carbon benefits instead of traditional timber revenues. Likewise, Kothke and Dieter (2010) applied an adjusted Faustmann formula to analyze the effects of carbon sequestration rewards on optimal forest management in an even-aged spruce stand in Germany. They concluded that the profit from carbon sequestration revenues may even exceed potential timber revenues at the higher carbon prices.

Some of the recent studies took several constraints into account and analyzed the impact of carbon credits on the optimal forest management. Applying the linear programming technique, Baskent and Keles (2009) developed a multiple use forest management planning model including the economic value of timber production, water resources and carbon sequestration. They revealed that including carbon benefits into forest management planning significantly decreased the timber and water values due to long-term forest protection needed to sequester carbon. Daigneault et al. (2010) evaluated the impact of carbon credits on optimal management of a fireprone forest stand. Using a stochastic dynamic profit maximization model, they found that carbon benefits delay both thinning and final rotation age even for a fire-susceptible forest stand. In a recent study, Asante et al. (2011) included dead organic matter (DOM) pool into carbon benefits, and developed a dynamic programming model to determine the optimal joint management of timber and carbon. They revealed that at the higher carbon price (greater than CAD35/tCO2), the optimal harvest age is infinite. Moreover, they stated that the carbon in DOM pool alters the optimal harvest decisions significantly.

Almost all aforementioned literature discussed the effects of carbon sequestration benefits on the different even-aged forest management scenarios. Particularly, they analyzed how the joint management of timber and carbon influences the rotation age and profitability of managing forests under various constraints. Contrary to those studies, Goetz et al. (2010) considered size-structured i.e. uneven-aged forests of *Pinus sylvestris* to study the effects of carbon sequestration credits on optimal diameter distribution. With an integrated biophysical and economic model of uneven-aged forests, they analyzed the effects of various levels of carbon price, and revealed that the price of sequestered carbon has a significant influence on the optimal selective-harvesting regimes. They also reported an opposite relation between the amount of carbon sequestered and net benefits of timber production; an increase in the sequestered carbon goes with a decrease in the net benefits of timber production.

CHAPTER 3. METHODOLOGY

3.1 Data Generation

This study used the USDA Forest Vegetation Simulator (FVS) for generating total merchantable volume as well as total stand carbon. Southern (SN) variant of FVS was considered for necessary information needed to run simulation in SUPPOSE program of FVS.

3.1.1 Forest Vegetation Simulator (FVS)

FVS is a family of forest growth and yield simulation models designed to predict forest stand dynamics (Dixon, 2002). It is a semi-distant-independent, individual-tree growth model which is extensively applied throughout the USA. The FVS predictions are commonly used to explore the effects of alternative management actions (Crookston and Dixon, 2005). It consists of 20 geographic-specific variants to represent the particular locations. As the Southern (SN) variant was developed using new growth equations with Forest Inventory and Analysis (FIA) data to cover all southern states, this study used FVS to simulate stand level data for uneven-aged loblolly pine stands. Furthermore, as CCX approves all FVS variants as eligible growth and yield models to account for the carbon offsets of any forest stands, using FVS SN variant as a data generation model is practically relevant.

Table 1 presents the parameters considered to generate the data using FVS. The growth data was simulated for the basal area class of 50 to 90 ft^2/acre with a maximum diameter of 18 inches. The initial diameter distribution and number of trees were generated fixing the q-ratio at 1.4. As Murphy and Farrar (1982, 1983) found 80-90 feet as a common range of site indices for loblolly-shortleaf pines in the US South, this study used site index of 85 feet as an average site index. Total simulated data were split into sawtimber (board feet Doyle) and pulpwood (cubic feet), as market prices of sawtimber and pulpwood vastly differ.

Table 1. The parameters used in FVS simulation

Attributes	**Specification**
Variant	Southern (SN)
Species	Loblolly pine (LP)
Management Specification	Uneven-aged, individual- tree selection
Q-ratio	1.4
Site Index	85 feet (base age 50)
Cutting cycle	30 years
Minimum diameter	5 inches
Maximum diameter	18 inches
Common cycle length	1 year

3.1.2 Quantify the Carbon Content

The SUPPOSE simulation program of FVS directly estimates the amount of carbon stored in uneven-aged forest stands. The stand-carbon report tabulates both aboveground and belowground carbon content of forest stands. The principle of additionality was taken into account while calculating the carbon offsets in uneven-aged loblolly pine stands. The same SUPPOSE file of growth data simulation was used in the modeling of carbon content in uneven-aged loblolly pine stands.

3.2 Optimization of Uneven-aged Stands

The method of maximizing LEV was applied to optimize uneven-aged management of loblolly pine stands.

3.2.1 Calculate LEVs without Carbon Benefits

The generalized Faustmann formula for uneven-aged management, developed by Chang and Gadow (2010), was applied to calculate the LEVs of uneven-aged stands of loblolly pine. The generalized Faustmann formula maximizes the LEVs of uneven-aged stands by considering an infinite number of cutting cycles. Unlike the classical Faustmann formula for uneven-aged management developed by Chang (1981), the generalized Faustmann model calculates the optimum length of cutting cycle and the residual basal area, which can vary from one cutting cycle to next cycle. The Faustmann formula for the first cutting cycle is

$$LEV_1 = e^{-r_1 t_1}[V_1(Q_1(t_1, g_1)) + LEV_2] - v_1(g_1) - K_1 \qquad (1)$$

where

LEV_1 is the land expectation value (timber only) at the beginning of 1st cutting cycle;

g_1 is the desirable level of residual stocking in ft^2/acre;

$v_1(g_1)$ is the value of the residual growing stock (\$/acre) at the beginning of the 1st cutting cycle;

$V_1(Q_1(t_1,g_1))$ is the stumpage value (\$/acre) at the time of harvest;

k_1 is the fixed cost(\$/acre) associated with timber harvest;

r_1 is the interest rate (%) corresponding to 1st cutting cycle; and

LEV_2 is the land expectation value (\$/acre) at the beginning of 2nd cutting cycle.

For the stumpage prices of sawtimber and pulpwood, 2010 market prices of Louisiana were taken into account. The market stumpage prices of sawtimber and pulpwood in Louisiana are \$256.71/MBF and \$27.83/cord respectively (LDWF, 2010). For the baseline management schedules, an interest rate of 4%, LEV_2 of \$1000/acre and fixed cost (k) of \$15/acre were assumed for computing the generalized LEV_1. The generalized LEVs at every combination of residual basal area and elapsed age were calculated. The combination of residual basal area and cutting cycle that has the maximum LEV_1 was selected as the optimal management regime of uneven-aged loblolly stands. As Chang (1990) stated a requirement of a minimum harvest of 1 MBF of sawtimber or 4 cords of pulpwood, this study also incorporated such requirement of minimum harvest while selecting the optimal management regimes.

3.2.2 Calculate LEVs with Carbon Benefits

Considering carbon as an annual source of income from uneven-aged stands, the LEV_1 with carbon credits at every combination of residual basal area and cutting cycle was calculated using the following Faustmann formula:

$$LEV_1 = e^{-r_1 t_1}[V_1(Q_1(t_1, g_1)) + \int_0^{t_1} A_{1,j} e^{r_1(t_1-j)} dj + LEV_2] - v_1(g_1) - K_1 \qquad (2)$$

where

LEV_1 is the land expectation value (timber and carbon benefits) at the beginning of 1st cutting cycle;

$A_{1,j}$ represents annual income sources of first cutting cycle i.e. carbon credits; and

Other attributes of equation 2 were assumed as of equation 1.

To calculate the additional amount of carbon sequestered, the business as usual (BAU) level was calculated first as a baseline beyond which the carbon credits were taken into account. The optimal residual basal area considering only timber production was considered as a baseline stocking. Only the additional amount of carbon above the baseline residual stocking was counted as carbon credits. Though most of the previous literature assumed a wide range of carbon prices from \$5 to \$100 (Stainback and Alavalpati, 2002; Huang and Kronrad, 2006), this study assumed the price of carbon to be \$5, \$10, \$20 or \$40 per metric ton. The maximum levels of LEVs for each level of carbon prices were recorded to compare the scenarios with timber-only management schedules.

3.3 Effects of Carbon Sequestration Benefits

In order to identify and analyze the financial and management effects of including carbon benefits, the maximum LEVs without and with carbon credits were compared. The carbon prices of \$5, \$10, \$20, and \$40 were assumed, and the generalized LEVs were calculated at every price levels. The changes in the maximum LEVs (\$/acre) explored the financial effects, and changes in residual BA and the cutting cycle denoted the management effects of carbon credits in the baseline management scheme of uneven-aged loblolly stands.

3.4 Comparative Static Analyses

Sensitivity analyses were carried out to determine the effects of interest rate, future land value (LEV_2) and stumpage prices of trees to be harvested. Three interest rates, stumpage prices, and LEV_2 were chosen to calculate the maximum LEVs. Interest rates of 4% (baseline), 6%, and 8% were used to calculate the maximum LEVs. Likewise, stumpage prices of sawtimber and pulpwood of \$256.71/MBF and \$27.81/cord (baseline), \$350 and \$35 (40% increases in baseline) and \$450 and \$45 (80% increases in baseline) were assumed, and the maximum LEVs were calculated in each price range using the generalized Faustmann formula. Similarly, future land values (LEV_2) of \$500, \$1000 (baseline), and \$2000/acre were chosen.

In order to analyze the effects of site productivity on joint management regimes, a low productive site with site index of 50 feet (base age 50) and a highly productive site with site index of 120 feet (base age 50) were selected. Both growth and carbon data for each level of site index were generated separately, and optimum management regimes were determined using the generalized Faustmann formula.

3.5 Joint Optimum Management Regimes with Biological Considerations

From a practical point of view, the higher stocking of uneven-aged stands may not support regeneration for the next cutting cycle. Farrar (1984) and Baker et al. (1996) explained that regeneration of the next crop in selection stands of loblolly-shortleaf pines may be restricted if basal area rises above 80 ft^2/acre at the end of the cutting cycle. Unlike even-aged management, land area in selection stands is required for trees of all sizes from seedlings to mature trees. This study also set the maximum basal area of 80 ft^2/acre immediately before the harvest, and determined the joint optimization of carbon and timber at every combination of carbon price and interest rate.

CHAPTER 4. RESULTS AND DISCUSSION

4.1 FVS Simulated Growth and Carbon Data

Figure 2 depicts the total volume associated with various levels of residual BA and elapsed time. Under all levels of residual BA, total volume increased up to the age of 55 years. However, at the lower levels of residual BA, total volume continued increasing up to the age of 80 years. After the age of 80 years, every level of residual BA gradually converged to total volume of around 8500 ft^3/acre. Moreover, Figure 2 shows a sharp growth rate from starting to the age of around 50 years for every level of residual BA.

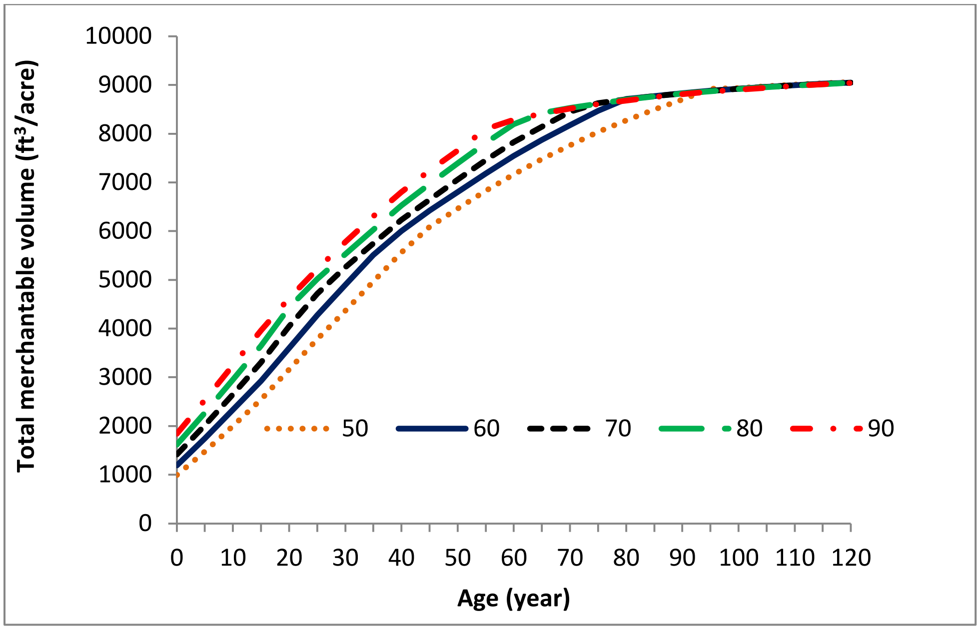

Figure 2. Projected total volume of uneven-aged loblolly pine stands.

Figure 3 shows the total stand carbon for different levels of residual BA generated using FVS. Even though total volume remains stable after 70 years of age, total amount of carbon increases up to the age of 90 years. This means total biomass is still increasing even though the total volume remains constant. After 90 years, every level of basal area converged to the total stand carbon of around 100 M ton per acre.

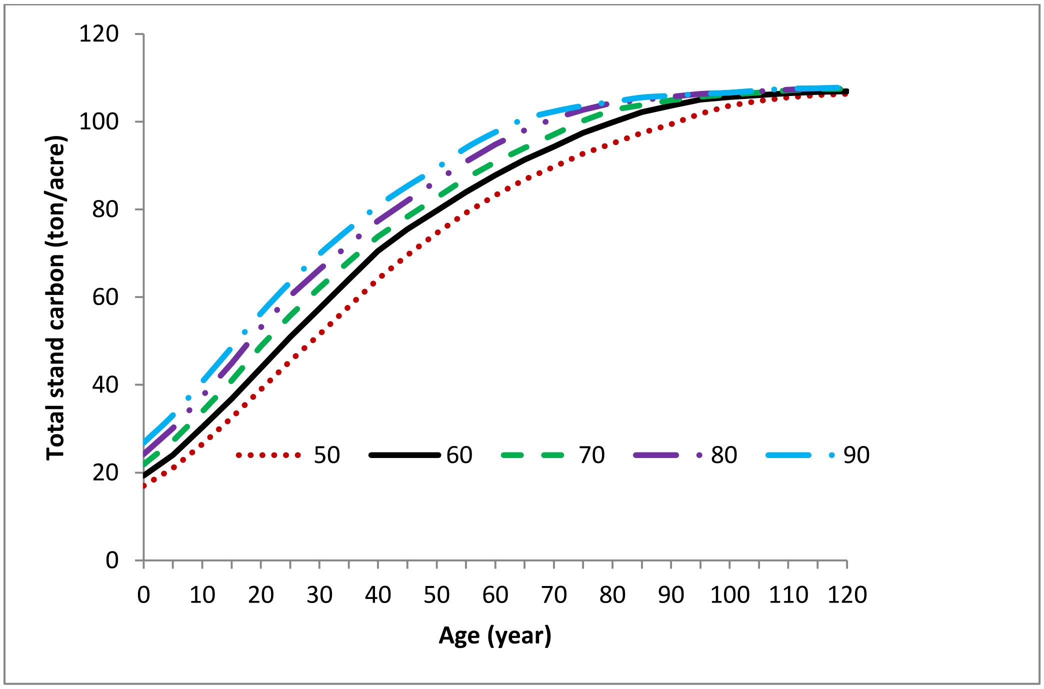

Figure 3. FVS predicted total stand carbon (M ton/acre) associated with various levels of residual BA.

4.2 Optimum Management Regime (Timber Only)

Figure 4 depicts the generalized LEVs associated with different residual BAs and cutting cycles at the interest rate of 4%[4] and stumpage price of $257/MBF and $27/cord for sawtimber and pulpwood respectively. The LEVs curves fluctuated substantially such that there were no common trends of LEVs for various combinations of elapsed time and residual BA. The fluctuation in the LEVs provided several local maximum points. When only timber production was considered, the global maximum LEV was $1312.24/acre at the combination of residual BA of 60 ft^2/acre and cutting cycle of 18 years. At the interest rate of 4% and 2010 timber stumpage

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[4] Figure 4 shows how the optimum management schedules were determined at 4% interest rate. Other cases are presented in Table 2.

prices of Louisiana, the optimum management regime of loblolly pine stands was 60 ft^2/acre of residual BA and 18 years of cutting cycle.

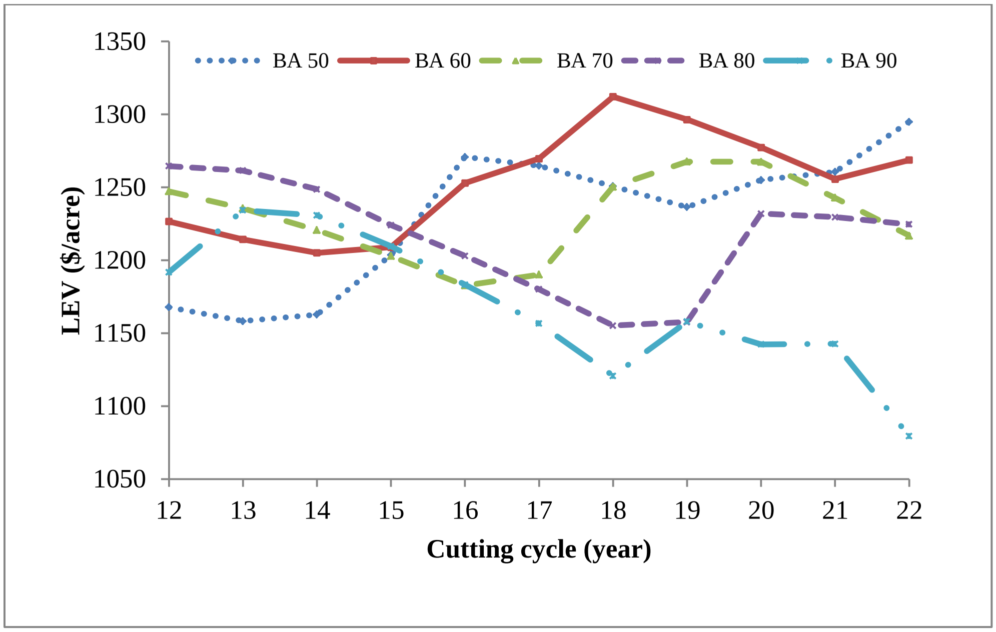

Figure 4. Generalized LEVs ($/acre) associated with different residual BA and cutting cycle at the stumpage prices of $257/MBF(sawtimber), $27/cord (pulpwood) and 4% interest rate.

4.3 Sensitivity Analyses

4.3.1 Effect of Changes in Interest Rate

Among the attributes used in the Faustmann formula, interest rate was the most influential factor in determining the optimal management regimes for uneven-aged loblolly pine stands. When only timber production was considered, the optimal cutting cycle as well as residual BA decreased with an increase in the interest rate. When the interest rate was increased from 4% to 6%, the maximum LEV fell from $1312.24/acre to $911.49/acre (Table 2). Likewise the optimal cutting cycle shortened sharply from 18 years to 5 years, but optimal residual BA remained unchanged at 60 ft^2/acre. However, a further increase in interest rate from 6% to 8% reduced the residual BA from 60 to 55 ft^2/acre, but had no effect on optimal cutting cycle. As interest rate went up from 4% to 6%, the maximum LEV decreased by 30%, and decreased another 20% when interest rate jumped up from 6% to 8%. Chang (1981) also found similar results that the higher the interest rate, the shorter the optimum cutting cycle and the lower the optimum growing stock level.

Table 2. Increase in interest rate decreased maximum LEV, cutting cycle and residual BA.

Interest rate (%)	**Maximum LEV ($/ acre)**	**Cutting Cycle (years)**	**Residual BA (ft^2/acre)**
4	1312.24	18	60
6	911.49	5	60
8	732.71	5	55

Though the cutting cycle was relatively longer at the 4% interest rate, the cutting cycle of 5 years is reasonable at the higher interest rates. Uneven-aged stands should have frequent selection harvests so that space is available for regeneration. Most of the previous studies also calculated the optimum cutting cycle of 4 to 10 years for uneven-aged loblolly-shortleaf pine stands (Chang, 1990; Hotvedt et al., 1989; Baker et al., 1996).

4.3.2 Effect of Changes in Market Stumpage Prices

The analysis showed that changes in stumpage prices also alter the optimum management regimes significantly. In most of the combinations of interest rate and stumpage prices, increase in stumpage prices increased the maximum LEVs and residual BA, and prolonged the optimum cutting cycles (Table 3). Chang and Gadow (2010) also found that increases in the stumpage prices lengthened the cutting cycle and increased the residual basal area. The higher the interest rate, the less effect of stumpage prices on the optimum level of management regimes and LEV. At 4% interest rate, increases in stumpage prices of sawtimber and pulpwood led to higher LEV and longer cutting cycle, but it had no effect in the optimum level of residual BA (Table 3). As the stumpage prices of sawtimber and pulpwood increased by about 30% from $256/MBF, $27/cord (baseline market prices) to $350/MBF, $35/cord respectively, both maximum LEV and cutting cycle increased by around 40%, but optimum residual BA remained unchanged. Further increase in stumpage prices had no effect on optimum level of residual BA and cutting cycle. However, the maximum LEV increased substantially i.e. increase in stumpage prices from $256/MBF, $27/cord to $450/MBF, $45/cord (increased by around 75%) led to increase in the maximum LEV from $1312.24 to $2489.35/acre (nearly 90%).

Table 3. Increase in stumpage prices of sawtimber and pulpwood increased LEV, Cutting cycle and Residual BA.

Interest rate (%)	**Stumpage price ($)**	**Maximum LEV ($/acre)**	**Cutting cycle (years)**	**Residual BA (ft^2/acre)**
4	256, 27*	1312.24	18	60
	350, 35	1872.32	26	60
	450, 45	2489.35	26	60
6	256, 27	911.49	5	60
	350, 35	1071.63	6	80
	450, 45	1408.72	12	85
8	256, 27	732.71	5	55
	350, 35	870.22	5	60
	450, 45	1022.78	5	60

*stumpage value of sawtimber ($/MBF) and pulpwood ($/cord) respectively.

At 6% interest rate, results indicated that an increase in stumpage prices from $256/MBF, $27/cord to $350/MBF, $35/cord led to slight increases in the maximum LEV and cutting cycle, but optimum residual BA increased by 33%. However, further increase in stumpage prices to $450/MBF, $45/cord led to increase the maximum LEV, optimum cutting cycle and residual BA. On the other hand, at 8% interest rate, there were negligible effects of increases in the stumpage prices (Table 3). The optimum cutting cycle remained unchanged at 5 years, and both residual

BA and the maximum LEV experienced a slight increase, as stumpage prices were increased by around 75%. The residual BA moved to 60 ft^2/acre and maximum LEV increased to \$1022.78/acre when the stumpage prices increased from \$256/MBF, \$27/MBF to \$450/MBF, \$45/cord.

4.3.3 Effect of Changes in Future Land Value

Table 4 depicts the effects of changes in future land value on the optimum uneven-aged management schedules of loblolly pine stands. At the interest rate of 4%, increases in future land values shortened the cutting cycle and increased the LEV without any impact on residual stocking (Table 4). When the future land value increased from \$500 to \$1000/acre, cutting cycle shortened to 18 years with an increase in the LEV by 20%. The cutting cycle reduced to 5 years dramatically when the LEV_2 increased from \$1000 to \$2000/acre. However, no change in the optimal residual stocking occurred.

Table 4. Effects of changes in future land value (LEV_2) on optimum uneven-aged management schedules.

Interest rate (%)	**Future land value (\$/acre)**	**Maximum LEV (\$/acre)**	**Cutting cycle (years)**	**Residual BA (ft^2/acre)**
4	500	1121.53	26	60
	1000	1312.24	18	60
	2000	1929.45	5	60
6	500	541.08	5	60
	1000	911.49	5	60
	2000	1652.31	5	60
8	500	397.55	5	55
	1000	732.71	5	55
	2000	1403.03	5	55

At the higher interest rates, changes in the future land value did not alter the optimum level of cutting cycle and residual basal area, though financial returns changed substantially (Table 4). At the interest rate of 6%, when the future land value increased from $500 to $2000/acre, the maximum LEV increased three fold. Likewise, at the interest rate of 8%, financial returns increased from $397 to $1403/acre when the LEV_2 increased from $500 to $2000/acre.

4.4 Joint Optimum Management of Timber Production and Carbon Sequestration

Including carbon sequestration benefits in the generalized Faustmann formula as an annual source of income significantly altered the optimum management regimes of uneven-aged loblolly pine stands. Regardless of the effect of interest rate, the inclusion of carbon credits increased the maximum LEVs, prolonged the optimum cutting cycle, and shifted the optimal residual BA to the higher level. Moreover, at the higher interest rates and per unit carbon prices, the effects were more influential from both financial and management points of view. The carbon sequestration credits even dominated the total timber revenues at the higher interest rates.

At the interest rate of 4%, the optimum cutting cycle lengthened by 5 years and the residual stocking increased by 30 ft^2/acre when the carbon credit at $5/ton was included (Table 5). Likewise, the gain in maximum LEV was more than 100% from $1313.24 to $2663.60/acre when the carbon price was $10/ton. A further increase in carbon price to $20/ton prolonged cutting cycle to 30 years and the maximum LEV soared by more than three fold. As the carbon price was doubled every time from $5 to $40/ton, the difference in maximum LEV was also nearly double. For instance, as the price increased from $5 to $10/ton, the net gain in maximum LEV was around $800/acre. When the price doubled from $10 to $20/ton, around $1800/acre was added to the maximum LEV. And the difference in the maximum LEV was around $3700/acre when the price rate was $40/ton.

Table 5. The optimum joint management schedules at different prices of carbon benefits. The carbon price of $0/ton denotes the optimum management regime when only timber value is considered.

Interest rate (%)	**Carbon Price ($/M ton)**	**Maximum LEV ($/acre)**	**Cutting cycle (years)**	**Residual BA (ft^2/acre)**
4	0	1312.24	18	60
	5	1883.23	23	90
	10	2663.60	24	90
	20	4465.58	30	90
	40	8146.15	30	90
6	0	911.49	5	60
	5	1084.17	6	90
	10	1470.62	14	90
	20	2647.98	24	90
	40	5459.36	30	90
8	0	732.71	5	55
	5	833.32	6	90
	10	1102.68	6	90
	20	1983.86	23	90
	40	4860.37	30	90

Similar results were found for the case of 6% interest rate as well (Table 5). As the carbon prices increased to $40/ton, the maximum LEV increased almost six fold ($911.49 to $5459.36/acre), and the optimum cutting cycle and residual BA increased to 30 years and 90 ft^2/acre respectively. However, when the carbon price was $5/ton, the cutting cycle lengthened by one year to 6, but residual BA increased by 50% to 90 ft^2/acre.

At the interest rate of 8%, up to the price of $10/ton, optimum cutting cycle wasn't affected much, but residual BA increased from 55 to 90 ft^2/acre (Table 5). When the price doubled from $10 to $20/ton, the cutting cycle prolonged by four times to 23 years with a gain of around $800/acre in the maximum LEV. When carbon price was $40/ton, the optimum residual BA increased to 90 ft^2/acre and cutting cycle prolonged to 30 years with the maximum LEV of $4860.37/acre.

These results are similar with the findings of Goetz et al. (2010), which also analyzed the joint management of carbon and timber in uneven-aged forest stands. However, Goetz et al. (2010) just analyzed the effects of carbon credits on the optimum stocking in terms of number of trees, and did not consider the effects on the cutting cycle of uneven-aged stands. Stainback and Alavalapati (2002), and Huang and Kronrad (2006) also found similar effects of carbon credits in even-aged southern pines stands; lengthening the optimum harvest age, substantial gain in the financial returns, and converting financially unprofitable land to profitable one.

4.5 Joint Optimization of Timber and Carbon in Less Productive Sites

In the lower site index of 50 feet (base age 50 years), carbon benefits play a significant role in joint optimum management regimes. Obviously, less productive lands have lower financial returns. In the schemes of timber-only, i.e. when carbon price is $0/ton, interest rate did not affect the cutting cycle and residual BA much. The optimum cutting cycle was 6 years for all combinations, and residual BA decreased to 50 ft^2/acre, when interest rate increased from 4% to 8%. However, the maximum LEV decreased substantially from $953.84 to $562.64/acre as the interest rate increased from 4% to 8% (Table 6). The lower the interest rate, the higher the financial returns.

Table 6. The joint optimum management regimes in a site index of 50 feet (base age 50).

Interest rate (%)	**Carbon Price ($/M ton)**	**Maximum LEV ($/acre)**	**Cutting cycle (years)**	**Residual BA (ft^2/acre)**
4	0	953.84	6	60
	5	1243.25	16	90
	10	1889.16	27	90
	20	3499.07	30	90
	40	6806.59	30	90
6	0	739.13	6	50
	5	929.73	7	90
	10	1426.65	16	90
	20	3091.91	30	90
	40	6797.16	30	90
8	0	562.64	6	50
	5	623.79	7	90
	10	950.88	7	90
	20	1960.19	22	90
	40	4885.99	30	90

Similar to the scenario of 85 feet site index (baseline value), joint management schemes for site index of 50 feet had longer cutting cycles and higher levels of residual BA compared with timber-only management regimes. At the interest rate of 4%, when the carbon price is $5/ton, optimum cutting cycle lengthened to 16 years with a gain of around $300/acre in the maximum LEV (Table 6). Similarly, optimum residual basal increased from 60 to 90 ft^2/acre. There was a huge gain in the maximum LEV at the carbon price of $40/ton. At the interest rates of 6% and 8% also, optimum residual BA increased and cutting cycle lengthened by including carbon credits as an additional source of income. At the carbon price of $5/ton or more, the optimum residual BA shifted to 90 ft^2/acre in every cases. At the interest rate of 8%, up to the carbon price of $10/ton, optimum cutting cycle lengthened by only one year but residual BA increased to 90 ft^2/acre.

4.6 Joint Optimization of Timber and Carbon in More Productive Sites

Similar trends in the effects of inclusion of carbon benefits into uneven-aged optimization of loblolly pine were found in high productive sites as well. Table 7 depicts the optimum joint management schedules of carbon and timber at the various rates of carbon price in the high productive lands of site index120 feet. The analyses showed that higher interest rates decreased the optimum residual BA and cutting cycle with a significant financial loss.

Table 7. The joint optimum management regimes in a site index of 120 (base age 50).

Interest rate (%)	**Carbon Price ($/M ton)**	**Maximum LEV ($/acre)**	**Cutting cycle (years)**	**Residual BA (ft^2/acre)**
4	0	2156.92	23	60
	5	2826.07	26	90
	10	3842.15	30	90
	20	5893.78	30	90
	40	9997.03	30	90
6	0	1163.00	15	60
	5	1560.38	11	90
	10	2146.69	19	90
	20	3474.90	26	90
	40	6642.65	30	90
8	0	909.57	4	55
	5	1104.36	5	90
	10	1487.45	11	90
	20	2779.36	30	90
	40	6132.20	30	90

Compared with the baseline case of site index 85 feet, significantly large gains in the maximum LEVs at every price levels were found. For example, at the interest rate of 4%, the maximum LEV increased fivefold, as the price of carbon increased from \$0 to \$40/ton. Similarly, increasing carbon prices lengthened cutting cycle and increased residual BA in more productive lands. In contrast, the optimum cutting cycle decreased from 15 to 11 years when carbon price increased from \$0 to \$5/ton at the interest rate of 6%.

The analyses of different site indices depicted that the joint management of timber and carbon favored to less productive lands. In some combinations, financial returns from less productive lands even exceeded the values from more productive lands. For instance, at 6% interest rate and \$40/ton carbon price, the maximum LEV was \$6797.16/acre for SI 50 (Table 6), but \$5459.36/acre for SI 85 (Table 5), and \$6642.65/acre for SI 120 (Table 7). Huang and Kronrad (2006) also concluded that the joint management of timber and carbon is more profitable in lower productive sites.

4.7 Joint Optimization of Timber and Carbon with Biological Considerations

When the BA of 80 ft^2/acre as the maximum stand density immediately before the harvest was taken into account (Farrar, 1984), the optimum residual BA of 60-65 ft^2/acre was found in most of the scenarios. Accordingly, the cutting cycles were also found to be shorter than the baseline cases. Carbon benefits were less influential in the joint optimum management schedules, though financial returns increased substantially.

At the interest rates of 6% and 8%, including carbon benefits into the management did not affect cutting cycle of 5 years, but a minimal increase in the optimum residual BA (Table 8). However, joint management increased the financial returns substantially. At the interest of 8%, more than 70% increase in the maximum LEV from $732.71 to $1261.74/acre was recorded at the carbon price of $40/ton. At the interest rate of 4%, the maximum LEV increased by around 50% from $1178.69 to $1787.80/acre, when the carbon price was $40/ton.

Table 8. Joint optimum management regimes of carbon and timber with a biological consideration.

Interest rate (%)	**Carbon Price ($/M ton)**	**Maximum LEV ($/acre)**	**Cutting cycle (years)**	**Residual BA (ft^2/acre)**
4	0	1178.69	10	50
	5	1191.51	6	60
	10	1276.69	6	60
	20	1447.06	6	60
	40	1787.80	6	60
6	0	911.49	5	60
	5	931.60	5	65
	10	970.30	5	65
	20	1047.70	5	65
	40	1202.51	5	65
8	0	732.71	5	55
	5	771.93	5	65
	10	841.90	5	65
	20	981.85	5	65
	40	1261.74	5	65

4.8 Implications of Longer Cutting Cycle and Higher Residual Stocking

The uneven-aged management schedules with longer cutting cycle and higher level of residual stocking definitely favor the carbon sequestration up to a certain level by delaying the timber harvesting and increasing tree biomass in forests. The analyses showed that the optimum cutting cycle of 30 years and residual basal area of 90 ft^2/acre when the carbon price was $40/ton. This study revealed a relationship between cutting cycle and residual basal area; the longer the cutting cycle, the higher the level of residual growing stock. In contrast, Baker et al. (1996) stated that if cutting cycle is lengthened, residual stocking must be decreased to provide space for regeneration. Likewise, Farrar (1984) considered the BA of 80 ft^2/acre as the maximum stand density in uneven-aged loblolly pine stands. From a practical point of view, the management regime with cutting cycle of 30 years and residual basal area of 90 ft^2/acre is quite unfamiliar for uneven-aged loblolly pine stands. Principally, uneven-aged stands should have frequent financial returns from recurrent selection harvests. Unreasonably delaying the timber harvesting will increase mortality and may reduce net carbon storage in the long run (Huang and Kronrad, 2006).

CHAPTER 5. SUMMARY AND CONCLUSIONS

This study analyzed the possible financial and management effects of carbon sequestration benefits on uneven-aged stands of loblolly pine in the southern US. It used the USDA FVS- SN variant to generate both growth and carbon data simultaneously. FVS is a recently revised family of growth and yield models, which has been approved by CCX to calculate the carbon offsets from any forest stands. This study has specific importance among researchers because it applied the generalized Faustmann formula to calculate the joint LEV of carbon sequestration and timber production in uneven-aged loblolly pine stands for the first time. Applying the generalized Faustmann formula to optimize uneven-aged forest management provides flexible management schedules so that the length of cutting cycle and level of residual growing stock can vary from one cutting cycle to the next. As the study considered the stumpage prices and interest rate of the market in Louisiana, the applicability of the findings is limited to Louisiana and nearly states with similar markets.

At the interest rate of 4% and 2010 timber stumpage prices in Louisiana, this study found the residual BA of 60 ft^2/acre and cutting cycle of 18 years to be the optimum timber management regime of uneven-aged loblolly pine stands. Sensitivity analyses depicted that changes in interest rate and stumpage prices have significant effects on the uneven-aged management schedules of loblolly pine stands, but the future land value was found less influential. Increase in interest rate reduced the LEV, cutting cycle length, and residual stocking level, but increase in stumpage prices increased the LEV and residual stocking with a longer cutting cycle. Though changes in the future land value did not affect the management schedules, it has a substantial influence on financial returns.

In the joint optimization of timber production and carbon sequestration in uneven-aged loblolly pine stands, carbon benefits were found influential from both financial and management perspectives. At every level of interest rates, the joint management of timber and carbon increased the LEV, extended the cutting cycle, and increased residual stocking. Likewise, this study showed that including carbon benefits into the management could increase the LEV almost seven fold when the carbon price is $40/ton. The higher the carbon price, the longer the cutting cycle, and the higher the residual basal area. This study also concluded that carbon benefits influenced uneven-aged management in both higher and lower productive lands. However, the financial gain was more prominent in the lower productive sites. With 80 ft^2/acre of basal area as the maximum stand density, the carbon benefits were found to be less influential on the optimum management schedules of uneven-aged loblolly pine stands.

Forest carbon sequestration is one of the emerging environmental services, which is considered as a cost effective mechanism to reduce atmospheric CO_2 level. Similar to the previous studies, this study also found that carbon sequestration could play a crucial role in optimum management of forest stands. Carbon sequestration benefits could not only alter the optimum management schedules of uneven-aged loblolly pine stands substantially but also increase financial returns manifold. Incorporating carbon sequestration into uneven-aged management could be an important additional source of income for landowners. Since this study followed the CCX guidelines and generated the data from a CCX-approved growth model, the findings have practical implications for landowners in the US South. Moreover, this study established the fact that carbon benefits might be one of the crucial benefits among the multiple benefits of uneven-aged forest management. At the higher interest rates, carbon benefits even dominated the total timber revenues.

As this study is the first one which jointly optimized the timber and carbon in uneven-aged forest management in the US, further studies should be conducted to elaborate and confirm the findings. This study used a hypothetical q-ratio while generating data from FVS model. The results might be more interesting and practically applicable if the field inventory data from uneven-aged loblolly pine stands were used as initial stand data. Since this study only took the principle of additionality into account, it is recommended that further studies should consider the other principles of carbon accounting such as permanence and leakage along with the principle of additionality. Several studies already analyzed the joint management effects of carbon and timber in even-aged southern pines. It would be highly useful to landowners as well as policymakers if there is a comparative study of joint management of timber and carbon in even-aged versus uneven-aged southern pine stands under similar site and market conditions.

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