CARBON LIFE-CYCLE AND ECONOMIC ANALYSIS OF FOREST CARBON SEQUESTRATION AND WOODY BIOENERGY PRODUCTION

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CARBON LIFE-CYCLE AND ECONOMIC ANALYSIS OF FOREST CARBON SEQUESTRATION AND WOODY BIOENERGY PRODUCTION

Thesis

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in the College of Agriculture at the University of Kentucky

By

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Lexington, Kentucky

2013

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ABSTRACT OF THESIS

CARBON LIFE-CYCLE AND ECONOMIC ANALYSIS OF
FOREST CARBON SEQUESTRATION AND
WOODY BIOENERGY PRODUCTION

Sequestering carbon in standing biomass, using woody bioenergy, and using woody products are the three potential ways to utilize forests in reducing greenhouse gases (GHGs) and mitigating climate change. These forestry related strategies are, however, greatly influenced by the existing markets and market based policies. This study focuses on the first two forest strategies. It investigates the combined impact of carbon and woody bioenergy markets on two different types of forests in the US – oak dominated mixed hardwood forests in the Central Hardwood Forests Region and loblolly pine forests in the southeastern US. A modification of the Harman model was used for the economic analysis of carbon sequestration and harvesting woody biomass for bioenergy. A forest carbon life-cycle assessment was used to determine the carbon emissions associated with management of forests and harvesting of wood products. Results from this study indicate that carbon payments and woody bioenergy production increase the land expectation value (LEV) for both forest types.

KEYWORDS: Climate change, Carbon and Bioenergy market, Hartman model, Life-cycle assessment, Land expectation value

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Chapter 1: Introduction

Climate Change

One of the major issues in today’s world, including the United States (US), is anthropogenic climate change (CC) which encompasses changes in temperature, precipitation, humidity, wind, and seasons over a long period of time. It has detrimental effects on the environment and has resulted in drought and desertification, melting of glaciers, rise in sea level, and changes in ecosystems (Mohajan, 2011; Schiermeier, 2008; Church, White, & Hunter, 2006; Klanderud & Birks, 2003). For example, in the US, over two thirds of the 150 glaciers in Glacier National Park that existed in 1850 disappeared by 1980 (Hall & Fagre, 2003). CC is mainly the result of rising concentrations of greenhouse gases (GHGs), such as carbon dioxide (CO₂), methane (CH₄), water vapors (H₂O), nitrous oxide (N₂O), chlorofluorocarbons (CFCs), and hydro fluorocarbons (HFCs) in the atmosphere, primarily from the anthropogenic sources (Pearce, 2005; Oreskes, 2004). Among these GHGs, CO₂ is the most prevalent (Tawil, 2012) and accounts for about 83.7% of the total GHG emissions in the US, the primary source being from human activities (Environmental Protection Agency [EPA], 2013). The total GHG emissions in the US in 2011 were 6,702.3 million metric tons of CO₂ equivalent (CO₂e) (EPA, 2013), which is the primary unit of measurement for the GHGs.

The major anthropogenic source of GHG emissions in the world and in the US is the combustion of fossil fuels such as coal, natural gas, and oil (EPA, 2013; Edenhofet et al., 2012; Tawil, 2012; Intergovernmental Panel on Climate Change [IPCC], 2007a; Houghton et al., 2001). In the US, from 1990 to 2011, CO₂ emissions from the combustion of fossil fuel increased at an average rate of 0.5% annually and in 2011,
around 94% of CO₂ emissions were accounted for by combustion of fossil fuels (EPA, 2013). Fossil fuels are basically used for activities such as electricity generation, transportation, industrial use, residential use, and commercial use (EPA, 2013). Among these, the use of fossil fuels for energy generation emitted the largest portion, about 41% of CO₂ emissions in 2011 (EPA, 2013). Land use change (such as conversion of forest land to agricultural and residential area) and changes in forestry practices is another significant contributor of CO₂ emissions. Around 17% of global CO₂ emissions in 2004 were accounted for by land use, land-use change, and forestry (IPCC, 2007b). In contrast in the US, land use, land use change, and forestry showed an increase in net CO₂ uptake of 13.9% from 1990 to 2011 (EPA, 2013). Another significant source of GHG emissions is agricultural activities such as use of fertilizers, burning of agricultural residues, and agricultural soil management. In the US these activities led to 6.9% of GHG emissions in 2011 (EPA, 2013).

How to reduce GHG emissions has always been a debated topic both in the public and private sectors (Shrum, 2007). Of growing interests among policymakers, society, and researchers is to reduce the GHG through forest management and utilization. In this regard, using renewable forest biomass as a source of energy is considered an important strategy to reduce demand for fossil fuels and GHG emissions to the atmosphere. In addition, forests themselves are one of the major sinks of CO₂, thus helping to reduce the amount of CO₂ in the atmosphere. Forestry practices such as afforestation, reforestation, and other forest management activities can play a significant role in increasing carbon storage in forest biomass.
Role of Forests in Carbon Cycle

The carbon cycle is the continuous movement of carbon in different forms among the biosphere, pedosphere, geosphere, hydrosphere, and atmosphere of the earth (Caulkins, n.d.). In the atmosphere, carbon is basically found in the form of CO₂ which is one of the major GHGs. Forests play an important role in the carbon cycle as it is both a source and sink for carbon. The forest carbon cycle is the movement of carbon between atmosphere and forests and forest soils during different activities.

When forests grow they take up CO₂ from the atmosphere and convert it into biomass through the process of photosynthesis. About one-half the weight of dry wood is carbon (Huang & Kronrad, 2006). The process of taking up the atmospheric carbon by green plants (including trees) and storing it as biomass is commonly referred to as carbon sequestration. In addition, forest soils also store huge amount of carbon from the atmosphere. When trees are harvested, wood products can still act as a carbon sink, potentially storing the carbon for a long period of time.

In contrast, during the process of respiration, trees take up oxygen (O₂) from the atmosphere and release CO₂. In addition, forest soils also releases CO₂ to the atmosphere during soil respiration. Stored carbon is lost to the atmosphere when wood products decay. A certain portion of the stored carbon is also released to the atmosphere when energy is produced from wood waste. In this way, forests continuously take up and release CO₂ in the atmosphere making them a significant part of the carbon cycle.

Forests and Climate Change Mitigation

It is now well established that forests play an important role in reducing GHGs and mitigating climate change. Because of this, there is increasing agreement that forests
should be an important part of any national or global strategy aimed at avoiding climate change (Tavoni, Sohngen, & Bosetti, 2007; Sohngen & Mendelsohn, 2003). Forest based mitigation strategies are considered highly cost-effective options to reduce net GHG emissions (Nepal, Grala, & Grebner, 2009; Richards, 2004; Sedjo, 2001; Sedjo, Sohngen, & Jagger, 2001). There are basically three ways in which forests can play an important role in mitigating climate change.

First, increasing the amount of carbon stored in forest biomass can potentially reduce net GHG emissions. About two-thirds of terrestrial carbon is sequestered in standing forests and forest soils, excluding the amount sequestered in rocks and sediments (Sedjo et al., 2001). Tropical forests absorb 4.8 billion tons of CO$_2$ every year and this accounts for 18% of the carbon emitted annually through the burning of fossil fuels (Lewis & Ryan, 2009). Thus, more of atmospheric carbon can be sequestered in woody biomass by adopting various forestry related activities such as afforestation, reforestation, reduction of deforestation, and improving forest management. Around 5 to 11 tons of CO$_2$ per hectare (ha) per year can be removed from the atmosphere by forest growth (Sohngen, 2009). In the US from 1990 to 2010, the increase in the forest area due to improved forest management practices and reforestation resulted in 31% increase in the net carbon sequestrated by forests (EPA, 2012a).

A second way is the substitution of woody bioenergy (energywood) for fossil fuels. Renewable bioenergy is considered environmentally friendly and can have less net GHG emissions because the CO$_2$ produced during biomass combustion is again absorbed by the growing trees in forests forming a closed loop carbon cycle (Forest Products Association of Canada [FPAC], 2009). Hence, forest biomass for energy production has
the potential to be carbon neutral (Washington State Department of Natural Resources [WDNR], 2010). In contrast, using fossil fuel for energy production is a one way process through which the carbon stored in the fossil fuel is released into the atmosphere. The advantages associated with woody bioenergy includes its potential to stimulate local and rural economies (Schubert et al., 2010); its ability to be processed into solid, liquid, and gaseous forms; and the existence of modern bioenergy consumption technologies that are clean and efficient (Hall & Scrase, 1998).

Finally, a third way is substituting woody products for other energy-intensive products (e.g. steel, concrete, iron). Trees after harvest are converted into different products such as structural lumber and furniture. These wood products can store carbon for decades and thus be used in construction and household items instead of more energy consuming products (Salwasser, 2006). For example, a typical 2,400 sq. ft. wooden frame house stores 29 metric tons of carbon (FPAC, 2009). According to Reid et al. (2004) utilizing a cubic meter of wood to replace other construction materials (e.g. concrete, blocks, or bricks) results in saving on average 0.75 to 1 ton of CO$_2$ emissions. Additional benefits with wood products include that they can easily be reused, recycled, or even used an energy source at the end of their service life (Malmsheimer et al., 2011). In 2003, a total of 12 to 19% of fossil fuel emissions in the US were offset by forest growth and harvested wood products (Ryan et al., 2010).

However, these forests related strategies to mitigate CC and reduce GHG emissions are highly influenced by the existence/non-existence of markets and market based policies. Studies have shown that market-based policies can reduce the GHG emissions at a lower cost than non-market regulations (Shrum, 2007).
Carbon Market

A carbon market generally refers to the trading (buying or selling) of carbon credits which are represented in terms of CO₂e. Establishing a carbon market is a climate change mitigation strategy as it works in two ways. On one hand, it encourages the landowners to manage and protect their forests thus resulting in more carbon sequestered in forest biomass. And on the other, it encourages GHG emitters to reduce the amount of emissions. Globally, around 10.3 billion tons of CO₂e were transacted in 2011 and the total value of the market increased annually by 11% to $176 billion (Kossoy & Guigon, 2012). The US has its own programs and policies for mitigation of GHG emissions through carbon markets (Ruddell, Walsh, & Kanakasabai, 2006) and, it is not bound to meet the target set by the Kyoto Protocol. There are basically two types of carbon markets in the US, one is the compliance carbon market and the other is the voluntary carbon market.

Compliance or regulatory carbon markets are mandatory where GHG emitters are obligated to reduce their emissions by a certain amount within a certain time period. This type of market is based on a cap and trade policy, which sets a limit on the amount of GHG emissions and issues permits equal to that amount. These permits are then traded among GHG emitters, thus creating a market for GHG reductions. Some of the existing compliance carbon markets in the US are Regional Greenhouse Gas Initiative (RGGI), Western Climate Initiative (WCI), and California’s Cap and Trade Program.

The RGGI is one of the mandatory markets initiated by nine states of the Northeast in 2009 with the aim to reduce GHG emissions from the power sector 10% below 2009 by 2019 (Malmsheimer et al., 2008). It has capped 165 million short tons of
CO₂ emissions in 2012 (Regional Greenhouse Gas Initiative [RGGI], 2012). The WCI was established in 2007 in the western region of the US and caps GHG emissions and uses tradable permits to incentivize development of renewable and lower polluting energy sources (Western Climate Initiative [WCI], 2010). Its aim is to reduce regional GHG emissions to 15% below 2005 levels by 2020 (WCI, 2007). The California Cap and Trade Regulation became effective from 2012 and for GHG emissions, the compliance obligation was implemented from January 2013 (Air Resources Board [ARB], 2013).

In contrast, voluntary carbon markets are unregulated (not mandatory) where GHG emissions are reduced voluntarily. Compared to compliance markets these types of markets are small. Buyers in the voluntary markets include companies (who buy offsets for their own operations or on behalf of their customers), individuals, organizations, and other entities, whereas sellers include retailers, wholesalers, and project developers (Green Markets International [GMI], 2007). Sellers generate carbon offsets and sell them to willing buyers without any carbon-specific requirements. The carbon transaction volume in voluntary carbon markets increased by 28% from 2009 to 2010 (Linacre, Kossoy, & Ambrosi, 2011). Some examples of currently existing and past voluntary carbon markets in the US are the Mountain Association for Community Economic Development (MACED), National Carbon Offset Coalition (NOCC), and Chicago Climate Exchange (CCX).

One of the currently existing voluntary markets, MACED serves as the aggregator of carbon offsets and sells the offsets produced through the Appalachian Carbon Partnership (Appalachian Carbon Partnership [ACP], 2011). They sell their carbon offsets either directly to private buyers or through a trading platform (ACP, 2011). The
other voluntary market, NCOC was founded in 2001 with the goal to help landowners and communities earn revenue by selling carbon credits and to reduce GHG (National Carbon Offset Coalition [NCOC], 2010). It is a member of the Big Sky Department of Energy Carbon Sequestration Partnership and is comprised of seven non-profit resource conservation organizations in Montana (Ruddell et al., 2006). NCOC is a CCX aggregator and offset projects include afforestation, urban forest planting, conservation tillage, grass planting, rangeland management, fuel switching, etc. (NCOC, 2010).

Similarly, CCX was one of the largest voluntary markets existed in the US from 2003 through 2010 (Chicago Climate Exchange [CCX], 2011). Here, the participants were legally bound to meet their previously agreed emission targets even though participation was voluntary (Malmsheimer et al., 2011). In 2006, it transacted 10.3 metric tons of CO₂e (Hamilton, Bayon, Turner, & Higgins, 2007) which was seven times higher than that of 2005 (Capoor & Ambrosi, 2008). A total baseline of 700 million metric tons of CO₂ was covered by this program (CCX, 2011). It launched the CCX Offsets Registry Program in 2011 (Intercontinental Exchange [IEC], 2013) and a total of 203,000 t CO₂e of CCX offsets were exchanged on the Offset registry (Kossoy & Guigon, 2012).

**Carbon Price**

Carbon pricing or putting a price on carbon is one of the most economically efficient and effective ways to reduce GHG emissions through the established carbon markets. Ideally, the carbon price across the world should be uniform as the damage done by a ton of CO₂e is same wherever it is emitted (Bowen, 2011). But in practice hundreds of diverse prices, ranging from less than $1/tCO₂e to over $100/tCO₂e, can be seen depending on the project standard, location, market types, and other environmental and
social co-benefits (Peters-Stanley, Hamilton, & Yin, 2012). The overall global average forest carbon price in 2011 was $9.2/tCO2e (Peters-Stanley et al., 2012).

In the US also exists diversity in the price of carbon. According to the Market Monitor Report for Auction 19 prepared by Potomac Economics (a contractor) for RGGI for March 2013, the clearing price of CO2 allowances was $3.08 per metric ton (Potomac Economics, 2013). RGGI Auction 18, held on December 2012, had the clearing price of $2.13 per metric ton (Potomac Economics, 2012). California Cap and Trade auctioned carbon permits at a price of $13.62 per metric ton in February 2013 (Point carbon, 2013a) which increased to $14.85 per metric ton in April 2013 (Point Carbon, 2013b). The voluntary carbon market, MACED sells the carbon offsets at a price of $5.57 per metric ton and $16.53 per metric ton depending on the volume being sold (Scott Shouse, personal communication, February 12, 2013). Similarly, the CCX at their closing in December 2010 had the price of $0.11 per metric ton (Nepal, Grala, & Grebner, 2012).

**Woody Bioenergy Policy**

Woody biomass has been one of the most important traditional renewable sources of energy in the past and currently is considered as one of the most promising alternatives for fossil fuels. In the US, policies to promote and develop use of woody bioenergy date back to the 1970s (Guo, Hodges, & Young, 2012). However, with an increasing focus on climate change mitigation, maintaining forest health, and meeting the huge demand of energy, the utilization of woody biomass as a source of energy received increased attention in recent years. Federal and State governments promote the development and utilization of woody bioenergy through various policies such as incentives, rules and
regulations, subsidies, grants, education, and consultation (Guo et al., 2012; Becker, Moseley, & Lee, 2011; Guo, Sun, & Grebner, 2007).

The Biomass Research and Development Act of 2000 provided $49 million from 2000 to 2005 annually to improve biobased products (Guo et al., 2012). Similarly, the National Fire Plan of 2000 provided $43 million to reduce hazardous fuels from forests by using small-diameter woody biomass for electricity production (Guo et al., 2012).

The 2008 Farm Bill Title IX: Energy had several provisions targeted towards biobased products. Some of the provisions are: Biobased Markets Program, Forest Biomass for Energy, and the Community Wood Energy Program (Stubbs, 2010). The Biobased markets program basically established testing centers for biobased products which also includes forest products (Stubbs, 2010). Similarly, forest biomass for energy, authorized several developmental programs encouraging the use of forest biomass for producing energy with a $15 million annual budget appropriation from 2009 to 2012 (Stubbs, 2010). The community wood energy program authorized appropriations of annual $5 million from 2009 to 2012 for developing programs for the public to use woody biomass as the primary energy source (Stubbs, 2010).

A Renewable Portfolio Standard (RPS) is a regulation that requires a certain fraction of electricity to be produced from renewable sources of energy such as biomass, wind, solar, and geothermal. As of 2012, 36 states in the US have established RPS regulations, in addition to the District of Columbia and Puerto Rico (EPA, 2012b). The regulation varies from state to state; for example, Maine has the target to achieve 40% by 2017 whereas Rhode Island’s target is 16% by compliance year 2020 (McCarthy &
Hansen, 2013). Besides the US, Italy, Poland, Sweden, Belgium, United Kingdom, and Japan are some of the countries that have adopted this type of regulation (Rabe, 2006).

The Renewable Fuel Standard (RFS) established in 2005 by the Energy Policy Act mandates that national transportation fuel must use a minimum volume of biofuels each year from 2006 to 2012 (Schnepf & Yacobucci, 2013). RFS was extended through 2022 by the Energy Independence and Security Act of 2007 with the biofuels mandate volume of 36 billion gallons in 2022 (Schnepf & Yacobucci, 2013).

Thus, various programs at the federal and state level are promoting the use of woody bioenergy. Utilizing woody bioenergy to generate energy provides various economic and environmental opportunities. Despite this, there are operational and economic challenges related to its use, especially because of high harvesting and transportation costs, emerging non-woody bio-products, and other technological constraints (Guo et al., 2007).

Literature Review

*Forests Carbon Sequestration*

Forests sequester large quantities of carbon for a long period of time and thus help in reducing total availability of atmospheric carbon. Several studies have quantified the role of forests in carbon sequestration. For example, Han, Plodinec, Su, Monts, and Li (2007) in their study in the southeast and south-central US found that around 76 teragrams (Tg) of carbon is sequestered annually in forest biomass which can capture 13% of the total regional GHG emissions. Woodbury, Smith, and Heath (2007) revealed that the forestry sector in the US sequestered 159 million metric tons of carbon in 2005. According to Brown and Schroeder (1999), during the period between the late 1980s and
early 1990s, the eastern US forests (live trees, dead wood, and long-lived wood products excluding roots and soils) stored approximately 174 Tg of carbon annually. Thus, there is a growing interest to address the problem of increasing GHG emissions and associated CC is through forest management activities. Studies on the economics of forests carbon sequestration have shown that forestry activities can be cost effective in reducing atmospheric carbon (Nepal et al., 2009; Richards, 2004; Sedjo, 2001; Newell & Stavins, 2000).

*Carbon Implications of Woody Bioenergy*

Not only can standing forests reduce GHG concentrations in the atmosphere, but after harvesting, the forest biomass can be used to produce energy instead of fossil fuels which can efficiently reduce net GHG emissions. Woody biomass for energy is used in producing electricity and biodiesel. For electricity production, the woody bioenergy is either burned alone or co-fired with fossil fuels. Previous studies have demonstrated that the use of forest biomass instead of fossil fuels can contribute to a long term solution for the sequestration of CO₂. Zhang et al. (2009) compared the amount of emissions produced by the burning of coal, natural gas, and wood pellets for electricity production. The results showed that 100% wood pellet firing provided the greatest GHG benefit on a kilowatt-hour basis. Specifically, wood pellet firing reduced GHG emissions by 91% and 78% relative to coal and natural gas, respectively. In addition, they found that compared to coal, using 100% wood pellets reduced NO₂ emissions by 40-47% and SO₂ emissions by 76-81%.

Petersen and Solberg (2005) did a life cycle analyses of GHG emissions from wood and more energy intensive materials in Norway and Sweden. They found that
wood is a better alternative than other materials with regard to GHG emissions. Hughes (2000) stated that biomass is significantly lower in potential air pollutants than coal, as biomass has virtually no sulfur (often less than 1/100 that of coal), low nitrogen (less than 1/5 that in coal), and low ash. Similarly, Nienow, McMamara, and Gillespie (2000) argued that woody biomass is a renewable resource of energy that consumes CO₂ during its growth cycle and thus its use for energy production contributes no net CO₂ to the atmosphere. In this regard, they assessed woody biomass for co-firing with coal in northern Indiana. The results indicated that co-firing woody biomass at the power plant is a viable method to reduce the amount of air pollution. Ringe, Graves, and Reeb (1998) found that cofiring with up to 5% wood biomass decreased the emissions of marginally unacceptable coal supplies to an acceptable level i.e. within the selected potential emissions standard (0.6 to 1.2 %) in Kentucky. Hence, it can be said that use of forest biomass for energy production can be an effective way to reduce GHG emissions over fossil fuels.

Forest Carbon Life-Cycle Analysis

The forest carbon cycle basically consists of two cycles, the biological cycle and industrial cycle (Gower, 2003). The forest biological carbon cycle refers to the sum of all carbon fluxes (annual carbon sequestration or emissions) and the forest industrial carbon cycle is the net carbon emissions throughout the forest products life span from tree growth to disposal of wood products (White, Gower, & Ahl, 2005). Exclusion of the emissions associated with the production, transportation, and utilization of forest products will lead to erroneous conclusions about net carbon sequestered through forestry (Gower,
Thus, it is important to include the industrial carbon cycle along with the biological carbon cycle in CC studies (Skog & Nicholson, 2000).

Forest carbon life-cycle analysis (LCA) is an important tool in analyzing the GHG emissions over the entire life of forest stands, from its growth to the end use of its products. It can be described as assessing the emissions of GHG at all the stages of forest products from cradle (forest establishment) to grave (final fate) (Gower, 2003). Thus, the emissions must be taken into account from the entire life-cycle of the product which encompass the extraction and processing of the raw materials; manufacturing, transportation, distribution, use, re-use, maintenance, recycling, and final disposal (Lindfors, 1995; Consoli, 1993). Forest carbon LCA not only helps in identification of the carbon hot spots but also provides opportunities to reduce carbon emissions at the various stages of the forest product’s life. In addition, it also identifies the potential management opportunities to increase the biological carbon storage and assess the optimal disposal practices of end products (Gower, 2003).

Several studies used the LCA approach to quantify the total amount of emissions from fossil fuel burning and energy use associated with management of forests; harvesting and transportation of forest products; manufacturing, use, re-use, and disposal of products. One such study is by Dwivedi, Bailis, Stainback, and Carter (2012) where the results from LCA showed that the total global warming impact was 6539 kg CO$_2$e for managing a ha of intensively managed slash pine plantation in the southeastern US. Similarly, Dwivedi, Alavalapati, Susaeta, and Stainback (2009) in their study used the LCA to estimate the carbon emissions from forestry practices in the southeastern US. They considered the emission from site preparation, fertilization application, thinning,
and harvesting of stands. They used the Franklin Database available with SimaPro version 7.1 Multiuser to calculate the net emissions associated with the manufacturing of each material used and TRACI database to estimate the quantities of CO₂e emissions for each forestry practice. They found that the total emissions from different forestry practices from one hectare of slash pine plantation were 17662.78 kg CO₂e.

Markewitz (2006) used LCA approach in an intensively managed loblolly pine plantation in southeastern US to estimate the carbon emitted from fossil fuels utilized for silvicultural activities (site preparation, thinning, and fertilization). The results from the study showed that over a single 25 year rotation, total carbon emissions of around 3 Mg per ha was emitted from all the silvicultural activities considered. They stated that such systematic evaluation of fossil fuel carbon emissions from forest management activities, ranging from planting to harvesting, would ensure the net positive carbon balance. LCA was also used in the study by Johnson, Lippke, Marshall, and Comnick (2005) to account for the emissions from forest resource activities for the Southeastern and Pacific Northwest regions of the US. They basically evaluated the carbon emitted as a result of fuel used during the establishment, management, and harvesting of a forest stand. In their study, fuel consumed during the transportation of forest products was found to the largest contributor of the emissions and also, among the different fuels, diesel was found to produce the highest emissions outputs.

Similarly, White et al. (2005) used life cycle inventory to quantify the major carbon fluxes associated with the industrial roundwood production in northern Wisconsin. They found that the national, state, and non-industrial private forests have the carbon budgets of respectively, 0.10, 0.18, and 0.11 t C ha⁻¹ yr⁻¹ for the harvesting
process. Also, the dimensional lumber and two oriented strand board (OSB) products were found to be net carbon sources. Karjalainen and Askainen (1996) conducted research to estimate the amount of GHG emissions by machinery used in silvicultural and forest improvement work, wood harvesting, and timber transportation in Finland and the result showed total emissions of 1310 Gg of CO$_2$e on a 20-year time horizon.

Thus, LCA is an important tool to evaluate the environmental impact of forestry and forest products (Karjalainen et al., 2001). In addition, from an economic point of view, it is necessary to perform the LCA to estimate the total GHG emissions during the life span of forests and forest products. Non-industrial private forest (NIPF) landowners can currently get payments for sequestering carbon in forest biomass through existing carbon markets. Hence, they are also liable for the penalty associated with the release of carbon back to the atmosphere. And, the LCA approach will help determine the amount of GHG emissions until the end use of forest products produced from forestland.

Financial Implications of Net Carbon Payments and Woody Bioenergy Production

Several studies have analyzed the role of carbon payments on the land expectation value (LEV) and the optimal rotation age with and without integrating LCA (Dwivedi et al., 2009; Nepal et al., 2009; Stainback & Alavalapati, 2002; van Kooten, Binkley, & Delcourt, 1995). All these studies concluded that carbon payments increase both the LEV and the financial optimal rotation age.

Dwivedi et al. (2009) carried out research in which LCA was integrated with the modified Faustmann model to assess the impact of carbon payments on the optimum rotation age and profitability of 1 ha of privately owned slash pine plantation in the southern US. Results indicated that there is an increase in profitability to NIPF
landowners because of the carbon sequestered in forest biomass. Accordingly, the LEVs with carbon payments for thinning and without thinning scenarios were correspondingly, $1423 and $1702 per ha higher than the LEVs without carbon payments for thinning and without thinning scenarios respectively. They also highlighted that carbon prices will likely increase in the future because of the rising demand for carbon credits, and thus, the role of carbon payments will become more pronounced for NIPF landowners as it would provide a significant additional income opportunity to them.

Nepal et al. (2009) examined the financial returns to the forest owners managing loblolly pine stands in the interior flatwoods region in Mississippi under three production regimes – timber production only, carbon sequestration only, and joint production of timber and carbon. The result of the analysis indicated that the landowners received the highest return from a joint production of timber and carbon.

Stainback and Alavalapati (2002) analyzed the role of a carbon subsidy and penalty policy on slash pine plantations using a modified Hartman model and found a substantial increase in the LEV, suggesting that it would be beneficial to include carbon payments for private forestland owners. They also found that more of the land could be devoted to forestry instead of agricultural or urban development, as the carbon policy increases forestland value. Also, the optimal rotation age was found to be increased with an increase in the price of carbon. A similar study by van Kooten et al. (1995) also analyzed the role of carbon subsidies and penalties on the financial optimal rotation age in the Canadian northwest. They found that including the external benefits from carbon uptake resulted in longer optimal rotation ages.
There has been a growing concern on using forest biomass for energy production, and several studies have been done to analyze the economic returns to NIPF landowners from growing woody bioenergy. Like carbon payments, it was found that woody bioenergy production also increases profitability to landowners. In contrast, the optimal rotation age was found to decrease as the energywood price increased.

Catron (2012) investigated the economic implications of harvesting woody biomass for bioenergy in upland-oak dominated mixed hardwood in Kentucky. The overall results indicated the increase in the financial return to the NIPF landowners with an increase of bioenergy prices. On the other hand, energywood production was found to decrease the optimal rotation age of upland oak stands. Susaeta, Lal, Alavalapati, Mercer, and Carter (2012) analyzed the impacts of emerging woody bioenergy markets on the behavior of NIPF landowners in Florida. The results from the analysis suggest that bioenergy markets might financially benefit landowners.

Susaeta, Alavalapati, and Carter (2009) developed an integrated Black-Scholes and modified Hartman model to assess the impacts of bioenergy markets on slash pine plantation management. The study was conducted on non-industrial private forestlands in the southeastern US and they considered three scenarios – no thinning scenario, thinning for pulpwood scenario, and thinning for bioenergy scenario. The results indicated that LEV for the thinning scenario for bioenergy was greater and increased the land value by around 11.6% compared to the thinning for pulpwood scenario, and thus, inclusion of woody biomass as forest products can substantially benefit landowners. Nesbit, Alavalapati, Dwivedi, and Marinescu (2011) used a cost-benefit analysis to calculate the profitability of using slash pine forest biomass as a feedstock for ethanol production.
They found that emerging bioenergy markets increase forest land value by $28.56 to $37.50 per acre and is one of the most promising options for increasing financial returns to NIPF landowners.

It is well established from the above mentioned studies that carbon payments and energywood production increase forestland value. In addition, the former increases the optimal harvest age whereas the latter decreases it. However, there are only few studies conducted that have assessed the combined effect of carbon and energywood markets. One such study is by Dwivedi et al. (2012) in which the role of payments for carbon sequestration in wood products and avoided carbon emissions due to the use of forest biomass for electricity generation instead of fossil fuels on the profitability of NIPF landowners in a ha of intensively managed slash pine plantations in the southern US was analyzed. The results indicated that LEV was highest ($1299 per ha) when all carbon payments and penalties were considered along with the timber product benefits. This value was found to be 71% higher than the LEV when the benefits were considered only from timber products. Also, the impact of payments for avoided carbon emissions due to use of forest biomass for electricity generation instead of coal significantly increases LEV. Thus, their results showed that the emerging carbon and woody energy markets would greatly benefit NIPF landowners.

**Research Rationale and Summary**

The above literature review suggests that establishing carbon and energywood markets increase LEV. However, only a few studies have incorporated the combined impact of both net carbon payments and energywood production on the optimal financial rotation age that maximizes LEV. Furthermore, none of the studies looked at the financial
implication of the combined effect of carbon and energywood markets incorporating LCA in oak-dominated mixed hardwood forests in the Central Hardwood Forest Region (CHFR) and the loblolly pine forests in the Southeast US. Thus, this study aims at partially fulfilling this research gap by assessing the impact of both net carbon payments and woody bioenergy production on LEV and the optimal rotation age using LCA.

Sensitivity analysis with range of carbon and energywood prices would help us determine how LEV and the optimal rotation age would be affected under various market conditions. With an increase of carbon and energywood prices LEV is assumed to increase. Also, increase of carbon and energywood prices assumes to increase and decrease respectively, the optimal rotation age. However, the magnitude of the increase/decrease can vary from small to large extent. A small variation in LEV or the optimal rotation age might not have much impact on the management regimes to be chosen or the supply of traditional forest products. But a large variation in LEV and the optimal rotation age could significantly impact the management decision to be taken and also the supply of traditional forest products. Hence, it is important to analyze the impact of range of carbon and woody bioenergy prices on the LEV and the optimal rotation age.

Thus, we conducted an economic analysis using a modification of the Hartman model (1976) to determine how net carbon payments and woody bioenergy production might affect the optimal rotation age that maximizes the LEV. We used the LCA approach to analyze the amount of carbon emissions from management of forests, harvesting of wood products, and the decay of wood products. For this study we analyzed both carbon payments (for carbon stored in aboveground forest biomass) and penalties (for carbon released) associated with forest management, harvest, and decay. Also, a
range of carbon and energywood prices were taken to perform a sensitivity analysis between the combination of these prices, LEV and optimal rotation age.

We looked at two different types of forests of the US. One is the oak-dominated mixed hardwood forests occurring in the CHFR and the other is loblolly pine forest plantations occurring in the Southeast US. The overall objective of this study was to build a stand level economic model for these two types of forests. The model developed can be used to assess forest management with various scenarios of carbon, energywood, and timber markets.

As expected, the results from the analysis showed that carbon payments and energywood production increase LEV for both forest types. In regard to the optimal rotation age, an increase in the carbon price tends to increase the optimal rotation age whereas, an increase in the energywood price tends to decrease the optimal rotation age. The details of the study for oak-dominated mixed hardwood forests and loblolly pine forests are presented in Chapter 2 and Chapter 3, respectively.
Chapter 2: Impact of Carbon Payments and Woody Bioenergy Production on Oak-dominated Mixed Hardwood Forests

This chapter focuses on determining how the carbon and woody bioenergy (energywood) markets affect the optimal rotation age that maximizes the LEV in the oak-dominated mixed hardwood forests of the Central Hardwood Forest Region (CHFR). For this study we chose three different product scenarios based on different types of policies that might emerge in the future in this region. The three product scenarios taken were: no pulpwood, pulpwood as energywood, and pulpwood and energywood. The first product scenario assume that all woody biomass less sawtimber is sold as energywood, the second product scenario assume that only the pulpwood sized material is sold as energywood, and the third product scenario assume that the residues left after extracting sawtimber and pulpwood are sold as energywood. Under each of these product scenarios we took two baseline scenarios depending on whether the net carbon payments are made from year zero (baseline 1 scenario) or the net carbon payments are made only after the baseline optimal rotation age (baseline 2 scenario). The detail of the scenarios, model used, results obtained, conclusions, and some future work are described in the following subheadings.

Study Area

We choose upland oak dominated mixed hardwood forests occurring in the CHFR for our study as none have yet investigated the economic benefits of carbon sequestration and forest based bioenergy production integrating the LCA from this region.

The CHFR is one of the largest broadleaf forest areas in the US covering over 100 million acres (Clark, 1989). The CHFR has oak-hickory as the dominated forest types,
others being the oak-pine, mixed hardwoods, and bottomland hardwoods (Sander & Fischer, 1989). The major oak species found are white oak, black oak, scarlet oak, northern red oak; other hardwood species occurring are black gum, yellow-poplar, red maple, sugar maple, white ash, black cherry, black walnut (Davis & Jacobs, 2005; Sander & Fischer, 1989). CHFR is economically and aesthetically important as it not only provides valuable raw wood products for the forest industry and energywood, but also provides scenic beauty, water, wildlife and recreation (Clark, 1989).

**Data Sources and Assumptions**

*Data Input for the Model*

Data required to develop the model were obtained from the literature and expert consultation. We used Gingrich (1971) to obtain the growth and yield data for upland oak stands for site index (SI) 65. SI represents the average height of the dominant or co-dominant tress in a stand at the base age and measures the potential productivity of the forests (Hanson, Azuma, & Hiserote, 2003). The growth and yield model gave the volume of sawtimber and pulpwood required for our model. The factor for converting merchantable volume (sawtimber plus pulpwood) to total aboveground tree biomass and for converting tree volume to carbon was obtained from Birdsey (1996). The stumpage prices for sawtimber and pulpwood were obtained from work done by Catron (2012). For this study we considered the sawtimber stumpage price of $244 per MBF and pulpwood stumpage price of $5 per ton. The detail description on obtaining these stumpage prices is presented in Appendix A.

After harvest, wood products were modeled to gradually start to decay at a rate based on half-lives and release carbon in the atmosphere. The half-lives were taken as
100 years, 2.6 years, and 1 year respectively, for sawtimber, pulpwood, and residues (Dwivedi et al., 2012). There are several types and models of machine that are used in harvesting operations, depending on the products to be extracted and terrain. We assumed that four types of machines were used to harvest the stand (feller buncher, skidder, knuckle boom loader, and chipper) based upon records from the Certified Master Logger Program Rainforest Alliance Smart Logging RA-SL-003285 documentation (Dr. Jeffrey Stringer, personal communication, March 28, 2013). We referred to the Wood Supply Research Institute: Auburn Stump to Mill Cost Program model (Dr. Mathew Smidt, personal communication, May 15, 2012) for the data for fuel consumed by machines during harvest of sawtimber and pulpwood. This model has, for each machine type and model, the data for fuel consumption (gallons per machine hour) and amount of wood products produced (tons per machine hour). The amount of fuel consumed by chipper to harvest energywood (residues) was taken to be 0.67 gallon per ton (Groover, 2011). Similarly, the data for the amount of carbon emitted per gallon of fuel consumed by machine during harvest was taken to be 10.5 kg (0.0105 metric tons) (Dr. Puneet Dwivedi, personal communication, June 27, 2012).

Assumptions and Specifications for the Model

Upland oak-dominated mixed hardwood forests are usually naturally regenerated and passively managed (Pelkki & Gracey, 1997). Passive management here indicates that there is minimal human intervention in the growth and development of the forests. Therefore, in this study we assumed there were no management or establishment costs. The residues from the harvest were assumed to be sold as energywood. Three forest products were assumed in the model – sawtimber, pulpwood, and energywood. In
computation of growth and yield data, we assumed that a standard cord of hardwood contains 80 cubic feet (cu ft) of solid wood (Wiant, 1989). All computations in the model used a real discount rate of 5% (similar to other economic studies such as Dwivedi et al., 2012; Catron, 2012; Nesbit et al., 2011).

We only considered the carbon stored in aboveground tree biomass. For the carbon LCA, we only considered carbon emissions from the machinery used during harvest of wood products. Carbon in the market is traded in the form of CO$_2$e, which can be obtained by multiplying the amount of carbon by 3.67 (Alabama Forestry Commission [AFC], n.d.). Hence, the term carbon mentioned in this chapter and Chapter 3 basically represents CO$_2$e. And, since we took the price of CO$_2$e in $ per metric ton, unless specified, CO$_2$e (now referred as carbon) is in metric tons. Sawtimber and pulpwood were assumed to decay releasing the stored carbon into the atmosphere; whereas energywood was considered to be sold for electricity production so does not decay. However, residues, if not sold as energywood was assumed to decay.

**Scenarios**

The impact of net carbon offset payments and energywood production on rotation age that maximizes LEV in the oak-dominated mixed hardwood forests was studied in three product scenarios – 1) *no pulpwood*, 2) *pulpwood as energywood*, and 3) *pulpwood and energywood* based on which part of the stand is sold as energywood. The common product in all these three scenarios is sawtimber.

In the first product scenario, i.e. *no pulpwood* scenario, we assumed that the pulpwood sized materials plus the residues are sold as energywood. This is the typical scenario where there is no or a limited pulpwood market e.g. Kentucky (Catron, 2012). In
the second product scenario, i.e. *pulpwood as energywood* scenario, we assumed that only the pulpwood sized materials are sold as energywood and the residues are allowed to decay in the forests. Some environmentalist may argue that removing residues from the forest floor may have detrimental effect in the environment and also in the long run deteriorates forest productivity. Thus, a new policy may emerge requiring residues from the biomass after harvest be left in the forests. Thus, we considered this product scenario where pulpwood sized materials would be sold as energywood and residues are left in the forest floor to decay. In the third product scenario, i.e. *pulpwood and energywood* scenario, we assumed that the pulpwood sized materials are sold as pulpwood and only the residues are sold as energywood. Existence of energywood markets may produce competition between energywood and other wood products. Choosing the third product scenario is thus in accordance with a policy that may limit the size of material that can be sold as energywood and other wood products to eliminate the competition among these products.

Under each of the above discussed three product scenarios, two baseline scenarios were considered depending on whether the net carbon benefits are obtained from year 0 (referred to as *baseline 1* scenario) or the net carbon benefits are considered only from the additional amount of the carbon sequestered in the growing stand (referred to as *baseline 2* scenario).

Thus, in *baseline 1* scenario, carbon payments which are obtained because of sequestering the atmospheric carbon into tree biomass was considered from year 0 and the penalty associated with carbon emissions associated with decay of products and also from harvesting is considered from year 0. Whereas, in *baseline 2* scenario, first the
optimal rotation age that maximizes the LEV only from timber and pulpwood production was calculated. This age was considered as the baseline rotation age. Only the additional carbon sequestered annually in tree biomass after this baseline optimal rotation age was considered and payments were made accordingly. Similarly, penalties due to carbon emissions from decay of products and machinery used during harvest were considered after this baseline optimal rotation age. For example, if the land value is maximized by selling traditional forest products at the rotation age of 56 years, then in the baseline 2 scenario, this 56 years would be the baseline optimal rotation age. And carbon payments are made only for additional carbon sequestered after this age. It means that the landowners have to extend the rotation age beyond 56 years (in above example) if they want to get carbon payments. Since carbon payments are made only after baseline optimal rotation age, we assume that the penalty associated with carbon emissions from decay of products and harvesting of stands are also considered after baseline optimal rotation age (in above example, after 56 years). The baseline 2 scenario might be the case where the carbon offset project requires that in order to participate in carbon trading programs, the forests need to sequester additional carbon than otherwise sequestered (Nepal et al., 2012; Ruddell, 2006). This is the additonality criterion and one of the ways to sequester the additional carbon in forest tree biomass is to increase the rotation length (Ruddell, 2006).

**Methods**

*Growth and Yield Model*

Yield table data from Gingrich (1971) was used to determine the amount of sawtimber and pulpwood for upland oak-dominated stands. According to Schnur (1937),
the SI 60 represents the average site and SI 70 represents the good site for the upland oak forests. According to Roach and Gingrich (1968), the predominant site class for Central States upland hardwoods is 55 to 74 and represents the medium site. Thus, for this study the SI 65 was taken which is an average site quality for upland hardwood stands. The growth and yield model has yield data for sawtimber and pulpwood from age 20 to 80 years at an interval of 10 years. Thus, the original yield data was fitted into the Equation 2.1.

$$v(t) = at^b e^{-ct}$$  \hspace{1cm} (2.1)

where $v(t)$ is the volume of sawtimber or pulpwood (unit per acre), $t$ refers to the stand age (years) mentioned throughout Chapter 2, and $a$, $b$, and $c$ are the parameters to be estimated. The values of these parameters are presented in Table B.1. in Appendix B, which were determined using non-linear regression in STATA 11.0. These parameters were in turn used in the Equation 2.1 to predict the volume of each product from the age 0 to 80 years at the interval of 1 year. Here yield data was extrapolated to age 0 from 20 and assumption was made that at age 0, the sawtimber and pulpwood yield would also be 0. At the younger ages, a tree does not produce sawtimber. And, the extrapolated results from age 20 to 0 years showed no sawtimber volume at these ages. The two graphs in Figure 2.1 show the original and fitted yield data for sawtimber and pulpwood. The sawtimber volume was in International ¼ inch broad feet which was converted into Doyle broad feet to match up the sawtimber price in $ per Doyle broad feet. For conversion, the International ¼ inch broad feet was divided by the factor 1.3 (Mercker, 2011), assuming that the average tree in the stand measures 22 inches in diameter at the breast height (dbh) with three 16 foot logs. Similarly, the equation gives the pulpwood
volume in cu ft which was converted into tons to match up with the pulpwood price in $ per ton. We used a general conversion factor which assumes a standard cord of hardwood contains 80 cu ft (Wiant, 1989) and 2.90 tons of solid wood (AFC, n.d.) Thus, pulpwood volume in cu ft was first divided by 80 to get the result in cords, this volume was finally multiplied by 2.90 to get the pulpwood volume in tons.

To find the volume of energywood (cu ft), first sawtimber and pulpwood volume (cu ft) was added to get merchantable volume (cu ft). Then, the total aboveground tree biomass (cu ft) was calculated by multiplying total merchantable volume by the factor 2.12 (Birdsey, 1996). This aboveground ratio (2.12) was obtained by taking the average of aboveground ratio from South Central, Mid-Altantic, and Central regions of the US where the CHFR are situated. Finally, the amount of energywood was obtained by subtracting merchantable volume from the total aboveground tree biomass.

Amount of Carbon Sequestered \(Q(t)\)

The amount of carbon (pounds) sequestered in the growing stand was calculated by multiplying the total aboveground tree biomass (cu ft) by a factor \(\beta (=19.74)\) (Birdsey, 1996). Like the aboveground ratio, \(\beta\) is also the average value from the South Central, Mid-Altantic, and Central regions of the US where the CHFR are situated. The carbon in pounds was converted into CO\(_2\)e in metric tons using appropriate conversion factors.

Amount of Carbon Emission Associated with Harvesting Operation \(H(t)\)

For a ton of merchantable volume (sawtimber and pulpwood) harvested, the total fuel consumed in gallon was determined using Equation 2.2.
\[ TF = \sum \frac{FCR}{PR} \]  

(2.2)

where, \( TF \) is the total fuel consumed during sawtimber and pulpwood harvest by all machines considered (gallons per ton), \( FCR \) is the fuel consumption rate of each machine type (gallons per machine hour), and \( PR \) is the production rate of each machine type (ton per machine hour). The data for \( FCR \) and \( PR \) are shown in Table C.1 in Appendix C. As mentioned earlier, for energywood harvest we use 0.67 gallons per ton fuel consumed by the chipper (Groover, 2011).

Total carbon emitted during harvest was obtained as shown in Equation 2.3.

\[ H(t) = (0.0105)[M(t)(TF) + E(t)(0.67)] \]  

(2.3)

where, \( H(t) \) refers to the amount of carbon emitted from harvesting operations (metric tons), \( M(t) \) is the merchantable volume harvested (tons), \( E(t) \) is the amount of energywood harvested (tons), and the factor 0.0105 is the amount of carbon emitted per gallon of fuel consumed by machine (metric tons).

**Amount of Carbon Released from Each Wood Product and Residue Decay \( C(n) \)**

Using the exponential decay function as shown in Equation 2.4, first carbon remaining in wood products and residues through 100 years after harvest was estimated.

\[ N_n = N_0 \left( 2^{(-n/\text{hl})} \right) \]  

(2.4)

where, \( N_n \) is the amount of carbon left after \( n \) years of harvest (metric tons), \( N_0 \) is the amount of carbon left at the time of harvest (metric tons), \( n \) is the years after harvest (0 to 100 years), and \( \text{hl} \) is the half-lives of sawtimber, pulpwood, and energywood which were taken as 100 years, 2.6 years, and 1 year respectively (Dwivedi et al., 2012).
Then the amount of carbon emitted from the decay of products and residues at each year after harvest through 100 years were determined using Equation 2.5.

\[
C(n) = N_n - N_{(n-1)}
\]

(2.5)

where, \( C(n) \) refers to the carbon emissions values from decay of sawtimber, pulpwood, or residue at year \( n \) (metric tons), \( N_n \) is the amount of carbon left after \( n \) years of harvest (metric tons), \( N_{(n-1)} \) is the amount of carbon left after \((n-1)\) years of harvest (metric tons).

**Economic Model**

We used Equation 2.6, a modified Hartman (1976) model to determine the impact of carbon payments and energywood production on the optimal rotation age (\( t \)) that maximizes the land expectation value (LEV) of an acre of upland oak-dominated mixed hardwood forests.

\[
LEV(t) = \frac{pvc(t) + pvt(t)}{1 - e^{-rt}}
\]

(2.6)

where, \( LEV(t) \) is the land expectation value at a time \( t \) assuming benefits from forests to be perpetual ($ per acre), \( pvc(t) \) is the present value of net carbon benefits ($ per acre), \( pvt(t) \) is the present value of net timber benefits ($ per acre), \( r \) is the real discount rate, and \( t \) is the rotation age that maximizes LEV (year).

The net present value of carbon benefits \( pvc(t) \) on an acre of forestland for a single rotation period was determined using Equation 2.7.
\[ pvc(t) = \int_0^t P_c Q(t) e^{-rt} \, dt \]  
(2.7)

where, \( P_c \) is the price of carbon ($ per metric ton of CO2e), \( Q(t) \) is the amount of carbon sequestered with respect to the stand age (metric tons).

Similarly, the net present value of timber benefits \( pvt(t) \) on an acre of forestland over one rotation was determined using Equation 2.8.

\[ pvt(t) = P Y(t) e^{-rt} - P_c H(t) e^{-rt} - \sum_{n=0}^{100} C(n) P_c e^{-r(n+t)} \]  
(2.8)

where, \( P \) is the vector prices for sawtimber, pulpwood, and energywood ($ per unit), \( Y(t) \) is the vector of volume for sawtimber, pulpwood, and energywood (unit). \( H(t) \) is the amount of carbon emissions during harvesting operations (see Equation 2.3), and \( C(n) \) refers to the carbon emissions values from decay of sawtimber, pulpwood, or residue at year \( n \) (see Equation 2.5).

**Baseline 1 and Baseline 2 Scenarios**

The above mentioned steps (Equation 2.1 through Equation 2.8) were used to develop a model for both the baseline 1 and 2 scenarios under all three product scenarios (no pulpwood, pulpwood as energywood, and pulpwood and energywood).

The only difference in the model for the baseline 2 scenario is the assumption made that the land value would consider the net carbon payments only after the baseline optimal rotation age. So, in this scenario, first the volume of sawtimber and pulpwood was determined as described in the growth and yield model using Equation 2.1. Then, the optimal rotation age that maximizes the land value was calculated assuming only the sellable products to be traditional forest products (i.e., sawtimber and pulpwood). This
optimal rotation age was considered as the baseline optimal rotation age. And, the
amount of carbon sequestered, the amount of carbon emission associated with harvesting
operation, and the amount of carbon released from each wood product and residue decay
were calculated in the similar manner as described above (Equation 2.2 through 2.5) but
only after baseline optimal rotation age. Before this age the carbon stored in tree biomass,
carbon released from decay and harvesting was not accounted in the model. Using
Equation 2.7 and 2.8, the benefits from carbon stored in standing trees, penalty associated
with decay of timber products after harvest, penalty associated with harvesting wood
products, and benefits from selling timber products plus energywood were determined.
The first three calculations in the model were considered only after the baseline optimal
rotation age. And, finally using Equation 2.6, the LEV per acre was determined for the
baseline 2 scenario in each of the three product scenarios.

*Stand Level Supply (per acre per year)*

Stand level supply of sawtimber, pulpwood, energywood (per acre per year) and
carbon (per acre) as a function of carbon prices were estimated only for the *baseline 1*
and 2 scenarios under the *pulpwood and energywood* scenario. The amount of sawtimber
(or pulpwood or energywood) at the optimal rotation age that maximizes LEV was
divided by that age to get the supply of sawtimber (or pulpwood or energywood) over the
length of the rotation as shown in Equation 2.9. For carbon supply, the overall sum of
carbon stored in the stump up to the optimal rotation age was divided by that age as
shown in Equation 2.10. Here, the amount of sawtimber, pulpwood, and energywood
supply are considered in the harvested wood products whereas that of carbon supply is
considered for the standing tree biomass until the stand is harvested. Thus the carbon supply is not in per year basis in contrast to other wood product supply.

\[ S_{fp} = \frac{A_{fp}(t)}{t} \quad (2.9) \]

\[ S_c = \frac{\sum_0^t A_c}{t} \quad (2.10) \]

where, \( S_{fp} \) is the supply of sawtimber (or pulpwood or energywood) as a function of carbon prices (unit per acre per year), \( A_{fp} \) is the amount of sawtimber (or pulpwood or energywood) at the optimal rotation age (t), \( S_c \) is the supply of carbon as a function of carbon prices (metric tons per acre), and \( A_c \) is the amount of carbon over the length of the rotation age.

**Sensitivity Analysis**

The sensitivity analysis was conducted based on the different carbon and energywood prices in the existing markets in the US, obtained from literatures, and personal communication. For example, the RGGI has a clearing price of $3.08 per metric ton (Potomac Economics, 2013); the California cap and trade program auctioned the carbon permit at a price of $14.85 per metric ton (Point Carbon, 2013b), and the voluntary market MACED sells carbon offsets at prices $5.57 and $16.53 per metric ton depending on the volume being sold (Scott Shouse, personal communication, February 12, 2013). Hence, based on these different carbon prices in the market, for this study, a price of $0, $2, $5, $15, and $25 per metric ton were considered.

The information regarding the hardwood stumpage energywood prices were lacking. However, the prices for slash pine residues were found in some literatures. Thus,
for this study the energywood prices were based on the available data for pine residues sold as energywood. The prices for residues, sold as energywood, were $1.5 per ton (Dwivedi et al., 2012) and $5 per ton (Nesbit et al., 2011). The stumpage energywood price for hardwood species in the CHFR in the current context is $0 per ton (Dr. Jeffrey Stringer, personal communication, March 28, 2013). Hence, the prices considered for this study were $0 and $5 per ton.

Results and Discussion

The results for the LEV and optimal rotation age in the baseline 1 and 2 scenarios under three product scenarios at a range of carbon and energywood prices are shown in Table 2.1 through 2.4 and Figures 2.2 through 2.5. As expected, carbon payments and woody bioenergy production have positive impact on the LEV i.e. forests land value increased with the increase of carbon and energywood prices. In regard to the optimal rotation length, the carbon payments and energywood production react oppositely. Increase in carbon prices tend to lengthen the optimal harvest age whereas, increase in energywood prices tend to shorten the optimal harvest age. Similar results were seen in the other studies in regard to impact of carbon payments and/or energywood production on the LEV and optimal rotation age. Dwivedi et al. (2009) found increase in LEV and optimal rotation age on the 1 ha of privately owned slash pine plantation because of carbon payments. Nepal et al. (2009) found that LEV was highest when the benefits were considered from carbon payments and timber production in the loblolly pine stands. Catron (2012) found that increasing the energywood prices increased the LEV and decreases the optimal rotation age.
LEV and Optimal Rotation Age in the Baseline 1 Scenario under Three Product Scenarios

The result for the baseline 1 scenario in each of the three product scenarios (no pulpwood, pulpwood as energywood, and pulpwood and energywood) show that the carbon payments have more impact on the LEV than energywood production (see Table 2.1 and Figure 2.2). For example, forests land value in no pulpwood scenario increased by $73.47 per acre when the carbon price increased from $0 to $2 per metric ton at the energywood price $5 per ton. The maximum increase in the LEV is only $62.50 when the energywood price is increased from $0 to $5 per ton at the carbon price $0 per metric ton.

Among the three product scenarios, pulpwood as energywood scenario (i.e. selling pulpwood sized material as energywood and allowing residues to decay in forests) is the least optimal scenario to be chosen at all combinations of carbon and energywood prices considered. There may be several reasons that might have caused this result. First, in this scenario there is no economic benefit from residues as it is left in the forest floor to decay. Whereas, in the other two scenarios (no pulpwood and pulpwood and energywood), the residues were assumed to be sold as energywood. Hence, in addition to traditional product benefits there is also additional benefit from energywood production. Second, because the residues are allowed to decay, there is a penalty for the carbon emission from the decay. We found that the penalty for the decay of residues is greater compared to decay of pulpwood and sawtimber. This is because, the half life of residues is 1 year whereas that of pulpwood and sawtimber is 2.6 and 100 years respectively. This means that half of the carbon stored in residues, pulpwood, and sawtimber will be released in the atmosphere in 1, 2.6, and 100 years respectively. As a result, for a cubic
foot of biomass, the penalty associated with decay carbon emission, in descending order, is residues, pulpwood, and sawtimber. For example, at a carbon price of $2 per metric ton, the penalty associated with decay of a cubic foot of residues, pulpwood, and sawtimber is $0.59, $0.53, and $0.0077 per metric ton respectively.

At the energywood price of $5 per ton, the \textit{no pulpwood} (i.e. selling all biomass less sawtimber as energywood) was found to be the optimal choice for all carbon prices considered. At the energywood price of $5 per ton, both these (\textit{no pulpwood} and \textit{pulpwood and energywood}) scenarios are similar. In both these scenarios, it can be assumed that all biomass less sawtimber is sold at a price of $5 per ton producing the same benefits. The only difference is the penalty associated with the decay of pulpwood. In the \textit{no pulpwood} scenario, there is not any pulpwood production, hence, there is no penalty associated with its decay. In contrast, in \textit{pulpwood and energywood} scenario, there is the penalty associated with the carbon emissions from decay of pulpwood. Hence, the \textit{no pulpwood} scenario is the optimal choice at the energywood price $5 per ton and all carbon prices taken.

However, if the energywood price is considered to be $0 per ton, then the optimal scenario is either \textit{no pulpwood} or \textit{pulpwood and energywood} depending upon the carbon price. At lower carbon prices ($0, $2, and $5 per metric ton), the \textit{pulpwood and energywood} scenario was the optimal choice, whereas, when carbon price is increased beyond $5 per metric ton then, the \textit{no pulpwood} scenario was found to the optimal choice (see Table 2.1 and Figure 2.2). In the \textit{pulpwood and energywood} scenario (i.e. selling pulpwood sized material as pulpwood and selling residues as energywood), the additional benefit is from pulpwood production. At the same time, there is also the penalty
associated with the decay of pulpwood. But at lower carbon prices, the penalty is less than the benefits from selling pulpwood thus the **pulpwood and energywood** scenario is optimal. As the carbon price increases, so does the amount of penalty associated with pulpwood decay, and we found that the penalty amount far exceeds the benefit from selling pulpwood. As a result, at a higher carbon price (e.g. $15 and $25 per metric ton), the LEV of the **no pulpwood** scenario exceeded that of the **pulpwood and energywood** scenario. Thus the results for the **baseline 1** scenario showed that except at low carbon prices, it is more beneficial to sell the pulpwood sized materials as energywood along with the residues. This is because doing so there will be no penalty associated with carbon emissions from decay of pulpwood.

As expected, the carbon and energywood prices were also found to affect the optimal harvest length of the stand (see Table 2.1. and Figure 2.3). Comparing the optimal harvest age of the three products scenarios, it can be seen that the **pulpwood as energywood** scenario has the highest optimal rotation age at all combinations of carbon and energywood prices. At the energywood price of $5 per ton and all carbon prices, the **no pulpwood** scenario would be harvested early compared to others to get optimal benefits from this scenario. Whereas, at the energywood price of $0 per ton, the optimal harvest length is least for **pulpwood and energywood** scenario when the carbon prices are low and for **no pulpwood** scenario when the carbon prices are high.

**LEV and Optimal Rotation Age in the Baseline 2 Scenario under Three Product Scenarios**

The baseline optimal rotation age, that maximizes the LEV from sawtimber and pulpwood (depending upon scenario chosen) production was found to 61, 61, and 56
years respectively for no pulpwood, pulpwood as energywood, and pulpwood and energywood scenarios. It means that, the net carbon benefits (payments for sequestering carbon and penalty for releasing carbon) are considered only after these baseline optimal rotation ages in the model studied. And, the stand must be grown longer than the above mentioned rotation ages in each of the product scenarios to get net carbon benefits.

The results for the baseline 2 scenario in each of the three product scenarios (no pulpwood, pulpwood as energywood, and pulpwood and energywood) show that the energywood production has more impact on the LEV than carbon payments (see Table 2.2 and Figure 2.4). For example, land value in the pulpwood as energywood scenario increased by $8.05 per acre when the carbon price increased from $0 to $25 per metric ton at the energywood price $0 per ton. Whereas, increase in energywood price from $0 to $5 per ton at the carbon price $25 per metric ton increased the LEV by $18.14 per acre. It is more optimal (in each product scenario) to harvest early and get energywood benefits rather than waiting beyond baseline rotation ages to get some carbon benefits.

The pulpwood as energywood scenario is the least optimal scenario at all combinations of carbon and energywood prices considered. For example, at the highest carbon and energywood price taken, $25 per metric ton and $5 per ton respectively, the maximum LEV in the pulpwood as energywood scenario is only $75.16 per acre which is $36.31 and $49.05 per acre less compared to that of no pulpwood and pulpwood and energywood scenarios respectively. It can be explained in the similar manner as that of the baseline 1 scenario. When pulpwood is sold as energywood and residues are allowed to remain in forests, the reduction in benefits can be explained by two ways, one there is no benefits from selling residues, and the other, penalty associated with decay of
residues. In this scenario (pulpwood as energywood) we assume that the residues are left in the forest floor after harvesting, hence it will start decaying and will release carbon to the atmosphere. And, this emission has to be accounted in the model as a penalty. As previously mentioned in the results of the baseline 1 scenario, the penalty associated with decay of a cubic foot of residues is more compared to pulpwood and sawtimber decay. Same is the case with the baseline 2 scenario. Thus, more penalty due to decay of residues and not obtaining any economic benefits from selling residues (as woody bioenergy) results in the lowest LEV in the pulpwood as energywood scenario compared to no pulpwood and pulpwood and energywood scenarios.

Among the three product scenarios, at all carbon prices when the energywood price is $0 per ton, the pulpwood and energywood scenario is the optimal scenario. In this scenario, there is additional benefit from selling pulpwood compared to other two scenarios. Also, the penalty associated with pulpwood decay is less compared to present values from pulpwood production because the penalty is paid only after the baseline optimal rotation age (56 years) whereas pulpwood production benefits is obtained from year zero.

At the energywood price of $5 per ton, both no pulpwood and pulpwood and energywood scenarios are similar because in both of these scenarios, the price of biomass less sawtimber is $5 per ton and would yield the same wood product benefits. The only difference is the penalty associated with pulpwood decay in the case of the pulpwood and energywood scenario. LEV in both of these scenarios is $111.47 per acre up to the carbon price of $5 per metric ton (see Table 2.2). At these carbon and energywood price combinations, in both scenarios, it is more beneficial to get benefits from energywood
production resulting in the lowering of the optimal rotation age than their corresponding baseline optimal rotation age. Because of this there would not be any net carbon benefits (neither carbon sequestered nor the penalty associated with decay of products), resulting in the same LEV. Hence, at low carbon prices ($0, $2, and $5 per metric ton) when energywood price is $5 per ton, it does not make any difference whether the scenario chosen is no pulpwood or pulpwood and energywood. But, as the carbon price is increased to $15 and $25 per metric ton, the optimal LEV in pulpwood and energywood scenario exceeded that of no pulpwood scenario because of the extension of optimal rotation age beyond baseline optimal rotation age (56 years) in the former scenario to get some net carbon benefits.

The results for optimal rotation age (Table 2.2 and Figure 2.5) show that at the energywood price of $0 per ton, the optimal rotation age extends above the baseline optimal rotation age in each of the product scenario with an increase in carbon prices. It means that carbon prices in this case lengthen the rotation age. In contrast, at the energywood price of $5 per ton, the optimal harvest age is the same (with some exceptions) in each of the product scenarios, regardless of increase in the carbon payments.

Among all the three scenarios, the no pulpwood scenario has the highest optimal rotation age when the energywood price is $0 per ton at all carbon prices and is optimal to harvest early for the pulpwood and energywood scenario. At the energywood price of $5 per ton, the optimal rotation age is lowest in the no pulpwood scenario at all carbon prices. In this scenario, all biomass less sawtimber is sold as energywood. Hence, the stand is harvested early, even earlier than the baseline rotation age to get more benefits.
from energywood production. Similar is the case for the other two scenarios, with exceptions at the higher carbon prices ($15 and $25 per metric ton). At high carbon prices, for pulpwood as energywood and pulpwood and energywood scenarios it is optimal to increase the rotation age beyond the baseline optimal rotation age to get some net carbon benefits.

Comparisons between the Baseline 1 and 2 Scenarios

In each of the three product scenarios, both the baseline 1 and 2 scenarios show that carbon payments and energywood production increased the LEV. Comparing the baseline 1 and 2 scenarios, LEV is more and the stand is grown for a longer period in the former scenario. The carbon payments have more impact on the LEV in the baseline 1 scenario. In contrast, energywood production has more impact on LEV in the baseline 2 scenario. The pulpwood as energywood scenario was found to be the least optimal among the three scenarios in both the baseline 1 and 2 scenarios. At an energywood price of $5 per ton, at all prices of carbon, no pulpwood was the optimal choice in the baseline 1 scenario. In contrast, in the baseline 2 scenario, at the mentioned price ranges, pulpwood and energywood was the optimal choice along with no pulpwood scenario at the low carbon prices. Similarly, at the energywood price $0 per ton and at low carbon prices pulpwood and energywood scenario was the optimal choice in the baseline 1 scenario because of the additional benefit from selling pulpwood and low penalty associated with decay of pulpwood. And at high carbon price no pulpwood was the optimal choice in the baseline 1 scenario because there is no penalty for decaying of residue (as residues are sold as energywood) like there is in the pulpwood as energywood scenario. And, also there is no penalty associated with decaying of pulpwood like there is in the pulpwood
and energywood scenario. In contrast, in the baseline 2 scenario, at this energywood price ($0 per ton), at all prices of carbon, pulpwood and energywood was the optimal choice.

**Stand Level Supply as a Function of Carbon Prices**

**Sawtimber, Pulpwood, and Energywood Supply (unit per acre per year)**

The results for forest products (sawtimber, pulpwood, and energywood) supply as a function of carbon prices under energywood prices $0 and $5 per ton for the baseline 1 and 2 scenarios for pulpwood and energywood scenario are presented in Table 2.3 and 2.4, and Figure 2.6 through 2.8. The sawtimber supply is in MBF per acre per year, pulpwood supply is in tons per acre per year, and energywood supply is in tons per acre per year, the year being adjusted for the optimal rotation age. Sawtimber and pulpwood supply tend to react in opposite directions whereas pulpwood and energywood supply react more or less similarly in response to an increase in the carbon prices and at constant energywood prices in both the baseline 1 and 2 scenarios. In general, the supply of sawtimber increased with the increase of the carbon price whereas that of pulpwood and energywood supply decreased with the increase of the carbon price (with some exceptions), energywood price being held constant either at $0 or $5 per ton. Stainback and Alavalapati (2002) found similar results in the slash pine study, that the increase in carbon price increased the sawtimber supply and decreased the pulpwood supply.

With an increase of energywood price from $0 to $5 per ton, the supply of sawtimber decreased in both baseline 1 and 2 scenarios. The decrease in the sawtimber supply is more prominent when the carbon prices are low (see Figure 2.6) indicating that at lower carbon prices, the increase in energywood price tends to decrease the optimal rotation age by a greater amount. For example, in the baseline 1 scenario at a carton price
of $0 per metric ton, the increase in energywood price from $0 to $5 per ton reduced the optimal rotation age by 6 years whereas at a carbon price of $25 per metric ton, the decrease in optimal rotation age is only 3 years (see pulpwood and energywood scenario in Table 2.1). As a result there will be less sawtimber sized material in the stand when it is harvested early thus, decreasing the supply by greater extent.

Unlike sawtimber supply results in both baseline 1 and 2 scenarios, the supply of pulpwood and energywood increased (with some exceptions at low carbon prices) with the increase of energywood prices at each carbon price (see Figure 2.7 and 2.8). This can be explained by the decrease in optimal rotation age and thus, producing smaller (pulpwood and energywood sized) biomass. A study by Susaeta et al. (2012) showed similar results, where increase in the price of woody bioenergy increased the supply of both pulpwood and woody bioenergy and decrease in the supply of sawtimber. The exceptions of the pulpwood and energywood supply at the lower carbon prices even when the energywood price is increased from $0 to $5 per ton can be explained by the sharp decrease in the optimal rotation age. The result shows the backward bending supply curve and suggests that at these prices, it is financially optimal to harvest sooner and get more revenue even if the amount supplied is decreased.

*Carbon Supply (metric ton per acre)*

The result for carbon supply as a function of carbon prices under energywood prices $0 and $5 per ton for the baseline 1 and 2 scenarios for the pulpwood and energywood scenario are presented in Table 2.5 and Figure 2.9. As expected, the carbon supply increased with an increase in the carbon price in both scenarios. Also, at each carbon price, the increase in energywood price decreased the supply of carbon in both
scenarios. Comparing the two baseline scenarios, the carbon supply is greater in the
baseline 1 scenario, which is the obvious result because in the baseline 2 scenario net
carbon payments are made only after the baseline optimal rotation age (56 years) and the
carbon supply was also considered only after this age.

To facilitate comparison with the baseline 1 scenario, we modified the baseline 2
scenario by estimating the carbon sequestered in biomass from year zero even though the
net carbon payments are made only after the baseline optimal rotation age (56 years). The
result for this is presented in Table 2.5 and Figure 2.10 under baseline 2 modified
column. The results show that the baseline 2 modified scenario sequesters less carbon per
acre compared to the baseline 1 scenario. This is because in the baseline 2 scenario it is
optimal to harvest early to get benefits from energywood production resulting in less
carbon stored in the biomass and less carbon supply.

Conclusions

This study assessed the economic impact of a combination of net carbon
payments and energywood production on forests land value in the CHFR for two baseline
scenarios, one where net carbon payments are made from year zero (baseline 1 scenario)
and the other where net carbon payments are made from the baseline optimal rotation age
(baseline 2 scenario) and each under three different product scenarios, one where we
assume that all biomass less sawtimber is sold as energywood (no pulpwood), the other
where we assume that only the pulpwood sized material is sold as energywood
(pulpwood as energywood scenario), and the third where we assume that residues (all
biomass less sawtimber and pulpwood) is sold as energywood (pulpwood and
energywood scenario). The study also integrates the penalty associated with carbon
emissions from the decay of forest products and machinery used during harvesting operations, which were assessed using the life-cycle assessment approach. As expected, the results of the study indicate that net carbon payments and energywood production increase the LEV in all scenarios taken, also, the former lengthen the optimal financial harvest age whereas, the latter decrease the optimal rotation age of the stand. Several other studies where net carbon payments and/or energywood production were considered for the economic analysis showed similar results (Dwivedi et al., 2012; Catron, 2012; Nesbit et al., 2011; Stainback & Alavalapati, 2002; van Kooten et al., 1995). The results also indicated that the baseline 1 scenario has more LEV as compared to the baseline 2 scenario as the net carbon payments are made from year zero in the former. Results also suggest that it is optimal to harvest early in the baseline 2 scenario to get more benefits from energywood production as net carbon benefits do not start until the stand is grown beyond the baseline optimal rotation age in the no pulpwood, pulpwood as energywood, and pulpwood and energywood scenarios.

Comparing the three product scenarios, the results indicate that the pulpwood as energywood scenario is never optimal under the carbon and energywood prices taken for both the baseline scenarios. This is the scenario where we assume that pulpwood sized material is sold as energywood and the residues are left to decay. This will be the typical scenario where the concern is towards improving the forest productivity and where there exists no or only a limited pulpwood market. If this policy approach is taken and there exists both pulpwood and energywood markets, then there might exists competition on whether the pulpwood sized materials should be sold as pulpwood or energywood. One solution here is to sell the pulpwood volume as pulpwood if the price of per ton of
pulpwood is greater than energywood and to sell the pulpwood volume as energywood if
the price of pulpwood is less than that of energywood. Even if this is the case, whether or
not that would be the optimal approach is uncertain. This is because selling the pulpwood
sized materials as energywood, there is not any kind of penalty but if pulpwood volume is
sold as pulpwood then there is the penalty associated with its decay. Hence, the optimal
approach depends on whether the value from selling pulpwood outweighs the penalty
associated with its decay or not.

**Future Work**

CHFR tree species are greatly valued for the highly prized veneer (Davis &
Jacobs, 2005); hence, one future extension of this work could be including veneer as one
of the wood products along with sawtimber, pulpwood, and energywood. Also, CHFR are
one of the major sources of wildlife habitat and food (Davis & Jacobs, 2005). For
example, oak produces acorns which are one of the most valuable and energy rich foods
for the central hardwood mast-consuming wildlife communities (Thompson III &
Dessecker, 1997). Thus, in addition to timber products, non-timber benefits can also be
incorporated in future studies. We have considered only passive management for this
study. Healy, Gottschalk, Long, and Wargo (1997) suggested that to maintain oak forests
some sort of forest management must be required. Hence, different management
scenarios can also be included in the model.
Table 2.1. LEV ($ per acre) and optimal rotation age (years) at different energywood and carbon prices in the baseline 1 scenario under three product scenarios

<table>
<thead>
<tr>
<th>Energywood price ($/ton)</th>
<th>Carbon price ($/metric ton of CO₂e)</th>
<th>Baseline 1 scenario</th>
<th>Pulpwood as energywood</th>
<th>Pulpwood and energywood</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>No pulpwood</td>
<td>Baseline 1 scenario</td>
<td>Pulpwood as energywood</td>
</tr>
<tr>
<td></td>
<td></td>
<td>LEV ($/acre) Rotation age (years)</td>
<td>LEV ($/acre) Rotation age (years)</td>
<td>LEV ($/acre) Rotation age (years)</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>48.97 61</td>
<td>48.97 61</td>
<td>74.87 56</td>
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<td>2</td>
<td>125.43 62</td>
<td>116.35 64</td>
<td>142.49 59</td>
</tr>
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<td>5</td>
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<td>219.19 67</td>
<td>246.15 62</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>623.76 65</td>
<td>571.29 75</td>
<td>601.05 68</td>
</tr>
<tr>
<td></td>
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<td>1007.77 66</td>
<td>931.43 80</td>
<td>962.56 72</td>
</tr>
<tr>
<td>0</td>
<td>111.47 50</td>
<td>74.87 56</td>
<td>111.47 50</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>184.94 53</td>
<td>139.58 59</td>
<td>175.77 54</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>296.70 55</td>
<td>239.40 63</td>
<td>276.01 58</td>
</tr>
<tr>
<td></td>
<td>15</td>
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<td>585.07 71</td>
<td>624.22 65</td>
</tr>
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<td>25</td>
<td>1055.55 61</td>
<td>941.07 79</td>
<td>981.90 69</td>
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</tbody>
</table>

Baseline 1 scenario assumes that net carbon benefits are obtained from year zero

Three product scenarios: No pulpwood scenario assumes all biomass less sawtimber is sold as energywood; Pulpwood as energywood scenario assumes only the pulpwood sized biomass is sold as energywood and residue is decay; Pulpwood and energywood scenario assumes pulpwood sized biomass is sold as pulpwood and residue is sold as energywood.

Note: The bold and the italicize numbers in each row in the above table represents the highest LEVs and optimal rotation age among three product scenarios considered at a combination of each energywood and carbon price.
Table 2.2. LEVs ($ per acre) and optimal rotation age (years) at different energywood and carbon prices in the baseline 2 scenario under three product scenarios

<table>
<thead>
<tr>
<th>Energywood price ($/ton)</th>
<th>Carbon price ($/metric ton of CO₂e)</th>
<th>Baseline 2 scenario</th>
<th></th>
</tr>
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<tbody>
<tr>
<td></td>
<td></td>
<td>No pulpwood</td>
<td>Pulpwood as energywood</td>
</tr>
<tr>
<td></td>
<td></td>
<td>LEV ($/acre)</td>
<td>Rotation age (years)</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>48.97</td>
<td>61</td>
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<tr>
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<td>2</td>
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<tr>
<td></td>
<td>25</td>
<td>111.47</td>
<td>50</td>
</tr>
</tbody>
</table>

Baseline 2 scenario assumes that net carbon benefits are obtained only after baseline optimal rotation age, which is the age that maximizes LEV from traditional forest products production. The baseline optimal rotation age was 61, 61, and 56 years respectively for no pulpwood, pulpwood as energywood, and pulpwood and energywood scenarios.

Three product scenarios: No pulpwood scenario assumes all biomass less sawtimber is sold as energywood; Pulpwood as energywood scenario assumes only the pulpwood sized biomass is sold as energywood and residue is decay; Pulpwood and energywood scenario assumes pulpwood sized biomass is sold as pulpwood and residue is sold as energywood.

Note: The bold and the italicize numbers in each row in the above table represents the highest LEVs and optimal rotation age among three product scenarios considered at a combination of each energywood and carbon price.
Table 2.3. Stand level supply of wood products as a function of carbon prices and at energywood prices $0 and $5 per ton in the baseline 1 scenario under the pulpwood and energywood scenario

Baseline 1 scenario

<table>
<thead>
<tr>
<th>Energywood price ($/ton)</th>
<th>CO₂e price ($/metric ton)</th>
<th>Rotation age (years)</th>
<th>Sawtimber (MBF/acre/year)</th>
<th>Pulpwood (ton/acre/year)</th>
<th>Energywood (ton/acre/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>56</td>
<td>0.052</td>
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<td>0.061</td>
<td>1.572</td>
<td>1.886</td>
</tr>
<tr>
<td>5</td>
<td>5</td>
<td>62</td>
<td>0.069</td>
<td>1.555</td>
<td>1.892</td>
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<td>15</td>
<td>68</td>
<td>0.079</td>
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<td>1.773</td>
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<td>1.574</td>
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</tr>
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<td>0.058</td>
<td>1.575</td>
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<td>25</td>
<td>69</td>
<td>0.080</td>
<td>1.479</td>
<td>1.849</td>
</tr>
</tbody>
</table>

Baseline 1 scenario assumes that net carbon benefits are obtained from year zero.

Pulpwood and energywood scenario assumes pulpwood sized biomass is sold as pulpwood and residue is sold as energywood.
Table 2.4. Stand level supply of wood products as a function of carbon prices and at energywood prices $0 and $5 per ton in the baseline 2 scenario under pulpwood and energywood scenario.

<table>
<thead>
<tr>
<th>CO₂e price ($/metric ton)</th>
<th>Rotation age (years)</th>
<th>Sawtimber (MBF/acre/year)</th>
<th>Pulpwood (ton/acre/year)</th>
<th>Energywood (ton/acre/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>56</td>
<td>0.052</td>
<td>1.577</td>
<td>1.864</td>
</tr>
<tr>
<td>2</td>
<td>58</td>
<td>0.058</td>
<td>1.575</td>
<td>1.880</td>
</tr>
<tr>
<td>5</td>
<td>60</td>
<td>0.064</td>
<td>1.568</td>
<td>1.890</td>
</tr>
<tr>
<td>15</td>
<td>65</td>
<td>0.075</td>
<td>1.528</td>
<td>1.884</td>
</tr>
<tr>
<td>25</td>
<td>68</td>
<td>0.079</td>
<td>1.493</td>
<td>1.860</td>
</tr>
<tr>
<td>0</td>
<td>50</td>
<td>0.034</td>
<td>1.548</td>
<td>1.773</td>
</tr>
<tr>
<td>2</td>
<td>50</td>
<td>0.034</td>
<td>1.548</td>
<td>1.773</td>
</tr>
<tr>
<td>5</td>
<td>50</td>
<td>0.034</td>
<td>1.548</td>
<td>1.773</td>
</tr>
<tr>
<td>15</td>
<td>61</td>
<td>0.066</td>
<td>1.562</td>
<td>1.892</td>
</tr>
<tr>
<td>25</td>
<td>65</td>
<td>0.075</td>
<td>1.528</td>
<td>1.884</td>
</tr>
</tbody>
</table>

Baseline 2 scenario assumes that net carbon benefits are obtained only after baseline optimal rotation age, which is the age that maximizes LEV from traditional forest products production. The baseline optimal rotation age was 56 years for the pulpwood and energywood scenario, which assumes all biomass less sawtimber and pulpwood, is sold as energywood.
Table 2.5. Stand level supply of carbon as a function of carbon prices and at energywood prices $0 and $5 per ton in the baseline 1 and 2 scenarios under the pulpwood and energywood scenario

<table>
<thead>
<tr>
<th>Energywood price ($/ton)</th>
<th>CO₂e price ($/metric ton)</th>
<th>Baseline 1</th>
<th>Baseline 2</th>
<th>Baseline 2 modified</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Baseline 1</td>
<td>Baseline 2</td>
<td>Baseline 2 modified</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>66.98 (56)</td>
<td>0.00 (56)</td>
<td>66.98 (56)</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>73.50 (59)</td>
<td>0.14 (58)</td>
<td>71.33 (58)</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>86.86 (62)</td>
<td>0.27 (60)</td>
<td>75.65 (60)</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>92.31 (68)</td>
<td>0.50 (65)</td>
<td>86.22 (65)</td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>99.99 (72)</td>
<td>0.58 (68)</td>
<td>92.31 (68)</td>
</tr>
<tr>
<td>5</td>
<td>0</td>
<td>53.98 (50)</td>
<td>0.00 (50)</td>
<td>53.98 (50)</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>62.63 (54)</td>
<td>0.00 (50)</td>
<td>53.98 (50)</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>71.33 (58)</td>
<td>0.00 (50)</td>
<td>53.98 (50)</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>86.22 (65)</td>
<td>0.32 (61)</td>
<td>77.80 (61)</td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>94.28 (69)</td>
<td>0.50 (65)</td>
<td>86.22 (65)</td>
</tr>
</tbody>
</table>

Baseline 1 scenario assumes that net carbon benefits are obtained from year zero.

Baseline 2 scenario assumes that net carbon benefits are obtained only after baseline optimal rotation age, which is the age that maximizes LEV from traditional forest products production. The baseline optimal rotation age was 56 years for the pulpwood and energywood scenario, which assumes all biomass less sawtimber and pulpwood is sold as energywood.

Baseline 2 modified scenario is the modification of the baseline 2 scenario, where carbon supply was estimated from year zero even though the net carbon payments are made only after the baseline optimal rotation age (56 years).

Note: The italicized values in bracket represents the optimal rotation ages for the pulpwood and energywood scenario.
Figure 2.1. Comparison of original and fitted yield data for sawtimber (bdft) and pulpwood (cu ft).

The R squared ($R^2$) for fitted sawtimber yield data was found to be 0.9994 and that for fitted pulpwood yield was found to be 0.9983.
Figure 2.2. LEV ($ per acre) as a function of carbon and energywood prices in the baseline 1 scenario under three product scenarios (no pulpwood, pulpwood as energywood, and pulpwood and energywood).

The y-axis represents the LEV in $ per acre. The upper x-axis represents the carbon price in $ per metric ton of CO$_2$e and the lower x-axis represents the energywood price in $ per ton.
Figure 2.3. Optimal Rotation Age (years) as a function of carbon and energywood prices in the baseline 1 scenario under three product scenarios (no pulpwood, pulpwood as energywood, and pulpwood and energywood).

The y-axis represents the optimal rotation age in years. The upper x-axis represents the carbon price in $ per metric ton of CO$_2$e and the lower x-axis represents the energywood price in $ per ton.
Figure 2.4. LEV ($ per acre) as a function of carbon and energywood prices in the *baseline 2* scenario under three product scenarios (*no pulpwood*, *pulpwood as energywood*, and *pulpwood and energywood*).

The y-axis represents the LEV in $ per acre. The upper x-axis represents the carbon price in $ per metric ton of CO₂e and the lower x-axis represents the energywood price in $ per ton.
Figure 2.5. Optimal Rotation Age (years) as a function of carbon and energywood prices in the baseline 2 scenario under three product scenarios (no pulpwood, pulpwood as energywood, and pulpwood and energywood).

The y-axis represents the optimal rotation age in years. The upper x-axis represents the carbon price in $ per metric ton of CO₂e and the lower x-axis represents the energywood price in $ per ton.
Figure 2.6. Sawtimber supply (MBF per acre per year) as a function of carbon prices and at energywood prices $0 and $5 per ton in the baseline 1 and 2 scenarios under pulpwood and energywood scenario. The y-axis represents the sawtimber supply in MBF per acre per year and the x-axis represents the carbon price in $ per metric ton of CO$_2$e.
Figure 2.7. Pulpwood supply (ton per acre per year) as a function of carbon prices and at energywood prices $0 and $5 per ton in the baseline 1 and 2 scenarios under the pulpwood and energywood scenario. The y-axis represents the pulpwood supply in ton per acre per year and the x-axis represents the carbon price in $ per metric ton of CO$_2$e.
Figure 2.8. Energywood supply (ton per acre per year) as a function of carbon prices and at energywood prices $0 and $5 per ton in the baseline 1 and 2 scenarios under the pulpwood and energywood scenario. The y-axis represents the energywood supply in ton per acre per year and the x-axis represents the carbon price in $ per metric ton of CO$_2$e.
Figure 2.9. Carbon supply (metric tons per acre) as a function of carbon prices and at energywood prices $0 and $5 per ton in the 
baseline 1 and 2 scenarios under the pulpwood and energywood scenario.

The y-axis represents the carbon supply in metric tons per acre per year and the x-axis represents the carbon price in $ per metric ton of CO$_2$e.
Figure 2.10. Carbon supply (metric tons per acre) as a function of carbon prices and at energywood prices $0 and $5 per ton in the baseline 1 and 2 modified scenarios under the pulpwood and energywood scenario.

The y-axis represents the carbon supply in metric tons per acre per year and the x-axis represents the carbon price in $ per metric ton of CO$_2$e.
Chapter 3: Impact of Carbon Payments and Woody Energy Production on Four Different Management Regimes of Loblolly Pine Forests

This chapter investigates the economic impact of carbon sequestration and woody bioenergy (energywood) production on the LEV and optimal rotation age in the loblolly pine forests in the southeastern US. We analyzed the impact on four different management regimes - no thinning nor fertilization, thinning only, fertilization only, and thinning and fertilization. The detail of the scenarios, model used, results obtained, conclusions, and some future work are described in the following subheadings.

Study area

Loblolly pine, also known as oldfield pine, North Carolina pine, Arkansas pine, and shortleaf pine, is the second most common species in the US (Nix, 2012; Baker & Langdon, 1990) and is one of the most commercially important species in the southeast (Susaeta et al., 2012). It comprises around half of the total standing pine volume in the south occupying a total of about 11.7 million hectares (Baker & Langdon, 1990). It ranges from southern New Jersey to central Florida and west to eastern Texas and is found in variety of topographies such as Coastal Plain (upper and lower), Piedmont hills, and Interior Highlands (Baker & Langdon, 1990). This study focuses on intensively managed loblolly pine plantations occurring in the Lower Coastal Plains of Florida, Georgia, North Carolina, and South Carolina.

Data Sources and Assumptions

Data Input for the Model

Several sources of information were collected from the literature and personal communication with experts. A growth and yield model from Harrison and Borders
(1996) was used to predict sawtimber, chip-n-saw, and pulpwood yields for loblolly pine plantations in the lower coastal plain of Florida, Georgia, North Carolina and South Carolina. This model gives the total volume of the stand and the volume of each product considered.

The stumpage prices of merchantable wood products (sawtimber, chip-n-saw, and pulpwood) were obtained from Susaeta et al. (2012). They considered the stumpage prices from 1994 to 2011 and reported three categories - high, medium, and low, all of which were adjusted to 2010 dollars. However, for this study, the average of high, medium, and low stumpage prices for each of the products was used. Thus, the stumpage prices considered for sawtimber, chip-n-saw, and pulpwood were $1.08, $0.65, and $0.28 per cubic foot respectively.

The amount of carbon emissions from different silvicultural practices in intensively managed loblolly pine forests was determined from Dwivedi et al. (2012). They determined the carbon emissions from various silvicultural operations in intensively managed slash pine plantations using life cycle assessment based on International Organization for Standardization (ISO) guidelines. The silvicultural practices in their study include site preparation (chopping, piling, burning, diskimg, bedding, herbicide application, and planting); fertilization; and harvesting (felling and bunching, skidding, delimbing, loading, and chipping). The site preparation cost and the fertilization cost was also obtained from Dwivedi et al. (2012). In addition to this, we refer to Susaeta et al. (2012) for the thinning operations and intensity in the managed loblolly pine stands, and cost associated with yearly management and thinning of the stands. The half life of
sawtimber, chip-n-saw, and pulpwood were taken 100, 30, and 2.6 years respectively (Dwivedi et al. 2012).

Assumptions

We assumed that the loblolly pine stand produces three products: sawtimber, chip-n-saw, and pulpwood. And, the residues are sold as the energywood. For most of the data needed for our study, we referred to the study by Dwivedi et al. (2012) which assesses the economic impact of carbon payments in the slash pine plantations. We assumed that the slash and loblolly pine stands in the same region have similar management and harvesting regimes and thus the carbon emissions from silvicultural operations was assumed to be similar.

We assumed that nitrogen and phosphorus were applied as fertilizers at the age of 12 years at the amount of 150 and 50 pounds per acre respectively. This assumption is similar to other existing studies and guidelines. For example, a study by Susaeta et al. (2012) in loblolly pine considered the application of fertilization thrice at the ages (5, 11, and 16 years). According to North Carolina Forest Service [NCFS] (2012), application of fertilization in the loblolly pine stands at mid-rotation (8 to 20 years) would increase the tree growth and the amount for most sites is 150 to 200 pounds of nitrogen plus 25 pounds of phosphorus. In the loblolly pine growth and yield model by Harrison and Borders (1996), nitrogen and phosphorus fertilizers were applied in site prepared loblolly pine plantations ranging from the ages 10 to 16 years.

In the Plantation Management Research Cooperative (PMRC) model it is mentioned that thinning can be completed using three methods: row thinning, selective thinning, and row-select combination with thinning intensities set at 33, 40, and 50
percent (Harrison & Borders, 1996). For our study, we assumed the selective thinning method and that the thinning operations were conducted twice at the ages 11 and 16 years and at each thinning 33% of trees were removed similar to a study by Susaeta et al. (2012).

The real discount rate was assumed to be 5%. And, only the forest products – sawtimber, chip-n-saw, and pulpwood was assumed to decay and release carbon back to the atmosphere based on exponential half-lives. The energywood (or residues) was assumed to be sold for electricity production.

**Scenarios**

This study attempts to assess the impact of carbon offset payments and woody energy production on the land expectation value (LEV) and determine the optimal management regime. We analyzed four management regimes (scenarios) which were: 1) *No thinning nor fertilization* 2) *Thinning only* 3) *Fertilization only* 4) *Thinning and fertilization*. In *no thinning nor fertilization* we assumed that the stands were left unthinned and unfertilized. In the *thinning only* scenario, we assumed the stands were thinned twice at ages 11 and 16 years. Similarly, in the *fertilization only* scenario, we assumed that the growing stand was treated with nitrogen and phosphorus fertilizers at the age of 12 years. And, in the *thinning and fertilization* scenario, we assumed that the fertilizers were applied in conjunction with the thinning operation. Here, the stand was first thinned at the age of 11 years and at the age of 12 years fertilizers were assumed to be applied and finally, at the age of 16 years the second thinning was made.
Methods

Growth and Yield Model

To determine the yield from intensively managed loblolly pine stands in the lower coastal plain, the whole-stand level growth and yield model developed by Harrison and Borders (1996) was used. The stand yield for each merchantable product class (sawtimber, chip-n-saw, and pulpwood) was determined using Equation 3.1.

\[ v_m = V \exp \left[ b_1 \left( \frac{t_d}{D_q} \right)^{b_2} + b_3 TPA^{b_4} \left( \frac{d}{D_q} \right)^{b_5} \right] \]  (3.1)

where, \( v_m \) and \( V \) are the merchantable and total stand yield respectively (cubic foot per acre), \( t_d \), \( d \), and \( D_q \) are in inches the top diameter, the diameter at breast height (dbh), and the quadratic mean diameter respectively (QMD). The value of the parameters \( b_1 \), \( b_2 \), \( b_3 \), \( b_4 \), and \( b_5 \) are presented in Table D.1 in Appendix D. Equation 3.1 gives the stand volume of trees with a dbh equal or greater than \( d \) up to a top of \( t \) over bark (o.b.). Here, the sawtimber consists of trees larger than 11.5 inches to an 8 inch top (o.b.), chip-n-saw consists of trees between 8.5 and 11 inches to a 4 inch top (o.b.), and pulpwood consists of trees larger than 4.5 inches to a 2 inch top (o.b.) (Harrison and Borders 1996).

The total yield \( (V) \) of the stand was calculated using Equation 3.2.

\[ \ln (V) = b_0 + b_1 \ln (TPA) + b_2 \ln (HD) + b_3 \ln (BA) + b_4 \ln (TPA/A) + b_5 \ln (BA/A) \]  (3.2)

where, \( TPA \) is the number of trees (per acre), \( HD \) is the average dominant height (feet), \( BA \) is the basal area (square feet per acre), and \( A \) is the age of the stand (years). The value of the parameters \( b_0 \), \( b_1 \), \( b_2 \), \( b_3 \), \( b_4 \), and \( b_5 \) are shown in Table D.1 in Appendix D. The equations used to determine \( TPA \), \( HD \), and \( BA \) are presented in Appendix E.
The QMD was calculated using Equation 3.3.

\[
QMD = \sqrt{BA/(TPA*k)}
\]  

(3.3)

where, \( k (= 0.005454) \) is a constant (Curtis and Marshall 2000).

**Growth Response to Thinning**

The basal area after thinning was projected using Equation 3.4.

\[
BA_t = BA_{ut}(1 - CI_2)
\]

(3.4)

where, \( BA_t \) and \( BA_{ut} \) are the projected basal area of the thinned and unthinned counterpart respectively (square feet per acre), \( CI_2 \) is the projected competition index which was determined in Appendix F.

**Growth Response to Fertilization**

Adjustments were made to the dominant height and the basal area to account for fertilization application at the age of 12 years. The adjustment terms which were added to the dominant height and the basal area were determined as shown in Equation 3.5 and 3.6 respectively.

\[
R_{HD} = (0.00106N + 0.2506PZ) Y_t e^{-0.1096Y_t}
\]

(3.5)

\[
R_{BA} = (0.0121N + 1.3639PZ) Y_t e^{-0.2635Y_t}
\]

(3.6)

where, \( R_{HD} \) and \( R_{BA} \) are the adjustment terms for dominant height (feet) and basal area (square feet per acre) respectively, in response to fertilization application, \( N \) is the amount of nitrogen applied (pounds per acre), \( PZ \) is taken 1 if fertilized with phosphorus; 0 otherwise, and \( Y_t \) is the years since treatment. For our study, \( PZ \) is taken to be 1 as we have considered the application of phosphorus.
**Amount of Energywood**

We considered the residue is sold as energywood. Hence, the energywood (residue) is the amount left after taking out the merchantable (sawtimber, chip-n-saw, and pulpwood) volume from the total aboveground biomass. The total aboveground tree biomass was determined by multiplying the merchantable volume by the factor 1.12 (AFC, n.d.).

**Amount of Carbon Sequestered \( (Q(t)) \)**

The amount of carbon stored in the aboveground tree biomass during the stand growth was determined using Equation 3.7.

\[
Q(t) = V(t) \beta
\]

where, \( V(t) \) is the total aboveground tree biomass (cu ft), \( \beta (=0.02592) \) is the factor that converts \( V(t) \) in cu ft into the CO₂e in metric tons for the loblolly pine plantation in the southeast US. The value of the factor \( \beta \) was obtained from Birdsey (1996).

**Amount of Carbon Emitted from Management and Harvesting of Stand**

The amount of carbon emissions from site preparation and planting was taken as 0.456 metric tons per acre (Dwivedi et al., 2012). And, emission from nitrogen and phosphorus fertilization application during age 12 years was taken as 1.258 metric tons per acre (Dwivedi et al., 2012). Similarly, the amount of carbon emitted from machinery used during the harvesting operations was taken as 0.654 metric tons per acre (Dwivedi et al., 2012).
Amount of Carbon Emitted from Decay of Each Wood Product \( C(n) \)

The wood products (sawtimber, chip-n-saw, and pulpwood) were assumed to decay according to the half-lives and release carbon gradually. First, the amount of carbon remained in the each of the wood products through 100 years of harvest was estimated using the exponential decay function as shown in Equation 3.8.

\[
N_n = N_0 \left(2^{-n/h_l}\right)
\]

where, \( N_n \) is the amount of carbon left after \( n \) years of harvest (metric tons), \( N_0 \) is the amount of carbon left in the tree biomass at the time of harvest (metric tons), \( n \) is the years after harvest (0 to 100 years), and \( h_l \) is the half-life of each wood product (100, 30, and 2.6 years respectively for sawtimber, chip-n-saw, and pulpwood - Dwivedi et al., 2012).

Then the amount of carbon emitted from the decay of products and residues at each year after harvest through 100 years were determined using Equation 3.9.

\[
C(n) = N_n - N_{(n-1)}
\]

where, \( C(n) \) refers to the carbon emissions values from decay of sawtimber (or chip-n-saw or pulpwood) at year \( n \) (metric tons), \( N_n \) is the amount of carbon left after \( n \) years of harvest (metric tons), \( N_{(n-1)} \) is the amount of carbon left after \( (n-1) \) years of harvest (metric tons).

Economic Analysis

A modification of the Hartman model (1976) was used to estimate the LEV and determine the optimal management regime for the loblolly pine plantation under the
impact of net carbon payments and energywood production. The forestland value is determined using Equation 3.10.

\[
LEV(t) = \frac{pvc(t) + pvt(t) - pvm(t)}{1 - e^{-rt}}
\]  

(3.10)

where, \(LEV(t)\) is the land expectation value at a time \(t\) assuming benefits from forests to be perpetual ($ per acre), \(pvc(t)\) is the net present value of carbon benefits ($ per acre), \(pvt(t)\) is the net present value of timber benefits ($ per acre), \(pvm(t)\) is the net present value of management cost over one rotation ($ per acre), \(t\) is the age of the stand that maximizes forest land value (years), \(r\) is the real discount rate.

The net present value of the carbon benefits \((pvc(t))\) on an acre of forestland over one rotation is estimated using Equation 3.11.

\[
pvc(t) = \int_0^t P_c Q(t)e^{-rt} dt - P_c Q_f e^{-rt} - P_c C_m
\]  

(3.11)

where, \(P_c\) is the price of carbon ($ per metric ton), \(Q(t)\) is the amount of carbon stored in tree biomass (metric tons), \(Q_f\) is the amount of carbon released from fertilization use (metric tons), \(C_m\) is the amount of carbon released during site preparation and planting (metric tons).

Net present value of management cost \((pvm(t))\) on an acre of forestland over one rotation is estimated using Equation 3.12.
\[ pvm(t) = \int_0^t Y(t)e^{-rt} dt + T_t e^{-rt} + F_t e^{-rt} + C_t \]  

(3.12)

where, \( Y(t) \) is the yearly management cost ($/acre/year), \( T_t \) is the marking cost for thinning ($/acre), \( F_t \) is the fertilization cost ($/acre), \( C_t \) is the site preparation and planting cost ($/acre).

Net present value of the forest product harvest benefits \( pvt(t) \) over one rotation age is determined using Equation 3.13.

\[ pvt(t) = PQ(t)e^{-rt} - \sum_{n=0}^{100} P_c C(n)e^{-r(n+t)} - P_c H_t e^{-rt} \]  

(3.13)

where, \( P \) is the vector of prices for sawtimber, chip-n-saw, pulpwood, and energywood ($ per unit), \( Q \) is the vector of volume for sawtimber, chip-n-saw, pulpwood, and energywood (unit), \( C(n) \) refers to the carbon emissions values from decay of sawtimber (or chip-n-saw or pulpwood) at year \( n \) (metric tons), \( H_t \) is the amount of carbon emitted during harvesting (metric tons).

**Sensitivity Analysis**

Sensitivity analysis was conducted based on different carbon and bioenergy prices in the existing markets in the US, obtained from literature and personal communication. For example, the RGGI has a clearing price of $3.08 per metric ton (Potomac Economics, 2013); the California cap and trade program auctioned the carbon permit at a price of $14.85 per metric ton (Point Carbon, 2013b), and the voluntary market MACED sells carbon offsets at prices $5.57 and $16.53 per metric ton depending on the volume being sold (Scott Shouse, personal communication, February 12, 2013). Hence, based on these
different carbon prices in the market, for this study, a price of $0, $2, $5, $15, and $25 per metric ton were taken.

For this study the energywood price range is based on the available data for pine residues sold as energywood. The prices for residues, sold as energywood, were $1.5 per ton (Dwivedi et al. 2012) and $5 per ton (Nesbit et al. 2011). Hence, the prices considered for this study were $0 and $5 per ton.

**Results and Discussion**

Summary of the results for LEV and optimal rotation age of four management regimes under different carbon and energywood prices considered are shown in Tables 3.1 and 3.2 and Figures 3.1 and 3.2. The results show that in each of the management regimes, as expected, the LEV increased with an increase of carbon and energywood prices. This result was similar to the results obtained in other studies like Dwivedi et al. (2012), Nesbit et al. (2011), Susaeta et al. (2009), Stainback and Alavalapati (2002), where net carbon payments with/without integrating LCA and/or energywood production increase the LEV. It can be seen that carbon payments have higher impact on LEV and in contrast, energywood production has a negligible impact on LEV. For example, in the *thinning and fertilization* scenario, at the energywood price of $0 per ton, the increase in carbon price from $0 to $2 per metric ton increased the LEV by $91.69 per acre, whereas at the carbon price of $0 per metric ton, the increase in energywood price from $0 to $5 per ton increased the LEV by $24.39 per acre.

The results for optimal rotation age shows that in each of the four management scenarios, the increase in carbon payments gradually increased the optimal rotation age as expected. Contrary to our expectation and other studies (Catron, 2012; Schaberg et al.,
2005), the increase of energywood price has no impact on optimal rotation age, with few exceptions. The above LEV results show that energywood production does not increase the land value as much as sequestering carbon in forest biomass. This result is the reason for the negligible decrease in the optimal rotation age even when the energywood price was increased.

Land Expectation Value (LEV) Comparison among Four Management Regimes

The results obtained showed that LEV is highest for the thinning only scenario and lowest for the fertilization only scenario at all combinations of carbon and energywood prices. Thus, it can be said that thinning only is financially the best management regime and fertilization only is the financially worst management regime to be chosen. Among the four scenarios, the arrangement from best to least management regimes to be chosen are, thinning only followed by thinning and fertilization, no thinning nor fertilization and fertilization only.

In the no thinning nor fertilization management regime there is no penalty for carbon emissions from fertilization use nor cost associated with fertilization and thinning of the stands. Despite this, the LEV in this scenario is less compared to the thinning only scenario where there is costs associated with thinning of the stands and the thinning and fertilization scenario where there is costs associated with application of fertilization and thinning of the stands as well as penalties associated with carbon emissions from fertilization. For example, the results showed that, at a carbon price of $15 per metric ton and energywood price of $5 per ton, the LEV in the no thinning nor fertilization scenario is $130.75 and $92.17 per acre less compared to the thinning only and thinning and fertilization scenarios respectively.
The total aboveground biomass in the no thinning nor fertilization scenario is higher compared to the thinning only and thinning and fertilization scenarios. Thus, the carbon benefits are more in the no thinning nor fertilization scenario as compared to the other two management regimes. For example, at the rotation age of 35 years, when the carbon price was $25 per metric ton, the discounted carbon benefits for the no thinning nor fertilization were $95.29 and $54.91 per acre more than thinning only and thinning and fertilization scenarios respectively. Also, at same rotation age, the benefits from selling energywood at the price of $5 per ton yields $14.85, $13.89, and $14.07 per acre respectively for no thinning nor fertilization, thinning only, and thinning and fertilization scenarios. The LCA showed the penalty associated with carbon emissions in the no thinning nor fertilization was $17.25 per acre less compared to the thinning and fertilization scenario. In addition, the management cost for the no thinning nor fertilization scenario was $14.54 and $69.42 per acre less compared to the thinning only and thinning and fertilization scenarios respectively. A study by Nepal et al. (2009) on thinned and unthinned loblolly pine stands showed similar results for the carbon accumulation and penalty associated with carbon release. In their study, the unthinned stand was found to accumulate twice as much carbon as that of thinned stands. And, the penalty for releasing carbon during thinning and final harvest was found to be greater in the thinned scenario as compared to the unthinned scenario.

We found that the present value of merchantable volume is more in the thinning only and thinning and fertilization scenarios as compared to the no management nor fertilization scenario. The sawtimber volume is more in the thinning only and thinning and fertilization scenarios, in contrast, chip-n-saw and pulpwood volumes are more in the
no management nor fertilization scenario. In addition, the price of a cubic foot of sawtimber is more than chip-n-saw and pulpwood, which resulted in more overall merchantable present value in the thinning only and thinning and fertilization scenarios. For example, at the rotation age of 35 years, the net present value of merchantable volume in the no thinning nor fertilization, thinning only, and thinning and fertilization regimes were respectively $495, $624, and $633 per acre. It was also found that the penalty for carbon emissions from the decay of wood products (sawtimber, chip-n-saw, and pulpwood) is higher in the no management nor fertilization scenario as compared to other two scenarios. We assumed that the half of the carbon stored in biomass will be released from the decay of sawtimber, chip-n-saw, and pulpwood in 100, 30, and 2.6 years of harvest, respectively. Thus, for a cubic foot of wood products, the carbon emissions and hence associated penalty, in descending order are pulpwood, chip-n-saw, and sawtimber. Since, the volume of chip-n-saw and pulpwood is higher in the no thinning nor fertilization scenario, it has a high penalty associated with emissions from decay. For example, at the carbon price of $25 per metric ton, the overall discounted penalty associated with decay emissions at 35 years are approximately $239, $157, and $155 per acre respectively for the no thinning nor fertilization, thinning and fertilization, and thinning only scenarios. The results show that the benefits from carbon payments, energywood production, lower management costs, and no penalty from fertilization use in the no thinning nor fertilization scenario are outweighed by the benefits from selling traditional wood products and the smaller penalty for the decay of these products in the thinning only and thinning and fertilization scenarios.
The smaller LEV in the *fertilization only* scenario as compared to the other three scenarios can also be explained similarly. The *fertilization only* scenario has the highest total aboveground biomass, chip-n-saw, and pulpwood volumes of all four scenarios. Thus, a smaller present value of wood products and a high decay penalty associated with these merchantable products in this scenario causes the LEV to be smaller as compared to the other three scenarios. Also, the LCA showed that the penalty for carbon emissions from harvesting and fertilization use were higher in the *fertilization only* scenario compared to other scenarios. Similarly, LEV in the *thinning and fertilization* scenario is smaller compared to the *thinning only* scenario. This is because of the inclusion of fertilization costs and penalties associated with emissions from fertilization use in the *thinning and fertilization* scenario. The application of fertilization in this scenario increases the total biomass but not by a huge amount. Hence, though the *thinning and fertilization* scenario has a higher present value from wood products, energywood, and carbon payments, it too has a high penalty associated with carbon emissions and stand management resulting in a smaller LEV compared to the *thinning only* scenario.

The results also showed that, at lower carbon prices the LEV difference among the four management regimes are greater where as when the carbon prices increased, the difference in LEV among these regimes are smaller. For example, if we considered two management regimes, *thinning only* and *thinning and fertilization*, then, at a carbon price of $2 per metric ton and an energywood price of $5 per ton, the difference in LEV is $66 per acre. As the carbon price increased to $5, $15, and $25 per metric ton keeping the energywood price the same, the LEV difference decreased to $59.90, $38.58, and $17.48 per acre respectively. Similarly, at a constant energywood price of $0 per ton, when the
carbon price is increased from $0 to $25 per metric ton, the difference in LEV between
the *thinning only* and *fertilization only* scenarios decreased from $236.90 to $35.76.

**Optimal Rotation Age Comparison among Four Management Regimes**

The optimal financial rotation age for the *no thinning nor fertilization* and *fertilization only* scenarios were found to be higher compared to the *thinning only* and *thinning and fertilization* scenarios with few exceptions at low carbon prices. Also, the stand harvest is delayed more in the *no thinning nor fertilization* and *fertilization only* scenarios. For example, the increase in carbon price from $0 to $25 per metric ton, increased the optimal harvest age by 11 years in both the *no thinning nor fertilization* and *fertilization only* scenarios, whereas, the optimal rotation age was increased only by 5 years in the case of the *thinning only* and *thinning and fertilization* scenarios.

**Conclusions**

Results indicate that carbon payments and energywood production along with the traditional forest products (sawtimber, chip-n-saw, and pulpwood) increase the forest land value in all the four management scenarios considered – *no thinning nor fertilization, thinning only, fertilization only*, and *thinning and fertilization*. Though there has been an increase in LEV as a result of carbon payments and energywood production, the results also indicate that an increase in the price of carbon increased the LEV by a greater amount compared to an increase in the price of energywood in all four management scenarios.

As expected and similar to other studies (K.C., 2012; Stainback & Alavalapati, 2002), in all the four scenarios, an increase in the net carbon payments increased the optimal harvest age. This might indicate an increase in the supply of traditional forest
products in the markets especially sawtimber. In contrast to the other studies (Catron, 2012; Schaberg et al., 2005), an increase in energywood price did not decrease the optimal harvest age. In our results, the optimal rotation age was found to be unaffected by the increased economic return from energywood production. This might indicate that the production of energywood would not affect the supply of traditional forest products. Similar results were found in a study by Snider and Cubbage (2006), where the economic analysis showed that wood chip markets do not significantly shorten the optimal rotation age and the supply of sawtimber.

The results of the analysis also indicated that the thinning only scenario is the optimal management regime followed by thinning and fertilization, no thinning nor fertilization and fertilization only at all combinations of carbon and energywood prices. These results suggest that providing financial incentives for net carbon sequestration and energywood production could induce forestland owners to thin their stands. The results also indicated that the thinning and fertilization scenario has the lowest optimal financial rotation age, along with thinning only scenario with few exceptions at the highest and lowest carbon prices considered. This suggests that if the forestland owners chose to thin their stands, then depending upon the price of carbon, they will get the financial returns 1 to 5 years sooner than if they manage their stand through application of fertilization only or when they do not do either thinning or fertilization.

**Future Work**

This work could be expanded in future to include various other associated factors. In this study we assume that 100% of the traditional wood products obtained at the time of harvesting would be converted into various processed wood products. However, in
practice conversion of harvested wood products in the mills would generate residues such as bark, chunks, slabs, and sawdust depending upon the conversion efficiencies of the timber products. These mill residues can be sold as energywood for electricity generation. And selling unutilized mill residues along with the harvested residues as energywood might impact LEV and the optimal rotation age. For the carbon life-cycle assessment, we considered only carbon emissions associated with site preparation, management, and harvesting of forest stands. Thus, there are still various carbon emissions stages that could be added in this study such as carbon emissions associated with transportation, carbon recycled in various wood products, and carbon accumulated in landfills.

Likewise, the landowners typically have to bear the other costs associated with carbon offset programs such as the costs verification, registration, de-registration, and retirement (Scott Shouse, personal communication, February 12, 2013). These costs can be included in the model in future studies. Other costs such as property taxes can also be included in the study.
Table 3.1. LEV ($ per acre) at different energywood and carbon prices under four management regimes

<table>
<thead>
<tr>
<th>Energywood price ($/ton)</th>
<th>Carbon price ($/metric ton of CO$_2$e)</th>
<th>LEV ($ per acre)</th>
<th>No thinning nor fertilization</th>
<th>Thinning only</th>
<th>Fertilization only</th>
<th>Thinning and fertilization</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>-40.26</td>
<td>196.64</td>
<td>-94.28</td>
<td></td>
<td>126.34</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>59.03</td>
<td>283.30</td>
<td>5.93</td>
<td></td>
<td>218.03</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>211.37</td>
<td>415.52</td>
<td>159.85</td>
<td></td>
<td>356.40</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>741.40</td>
<td>865.87</td>
<td>696.27</td>
<td></td>
<td>828.12</td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>1292.97</td>
<td>1328.73</td>
<td>1255.27</td>
<td></td>
<td>1311.47</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>-18.22</td>
<td>221.56</td>
<td>-71.52</td>
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<td>150.73</td>
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<tr>
<td></td>
<td>2</td>
<td>80.24</td>
<td>308.22</td>
<td>27.91</td>
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<td>242.22</td>
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<td>5</td>
<td>231.46</td>
<td>439.83</td>
<td>180.71</td>
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<td>379.94</td>
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<td></td>
<td>15</td>
<td>758.18</td>
<td>888.92</td>
<td>713.74</td>
<td></td>
<td>850.34</td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>1307.66</td>
<td>1350.50</td>
<td>1270.13</td>
<td></td>
<td>1333.03</td>
</tr>
</tbody>
</table>

Note: The bold numbers and the italicize numbers in each row in the above table represents the highest and lowest LEVs respectively among the four management scenarios considered at a combination of each energywood and carbon price.
Table 3.2. Optimal Rotation Age (years) at different energywood and carbon prices under four management regimes

<table>
<thead>
<tr>
<th>Energywood price ($/ton)</th>
<th>Carbon price ($/metric ton of CO₂e)</th>
<th>Optimal Rotation Age (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No thinning nor fertilization</td>
<td>Thinning only</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(years)</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>31</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>32</td>
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<td></td>
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<td>41</td>
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<tr>
<td>5</td>
<td>0</td>
<td>29</td>
</tr>
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<td></td>
<td>2</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>32</td>
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<td>15</td>
<td>36</td>
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<td></td>
<td>25</td>
<td>40</td>
</tr>
</tbody>
</table>
Figure 3.1. LEV ($ per acre) at different energywood and carbon prices under four management regimes.

The y-axis represents the land expectation value in $ per acre. The upper x-axis represents the carbon price in $ per metric ton of CO$_2$e and the lower x-axis represents the energywood price in $ per ton.
Figure 3.2. Optimal Rotation Age (years) at different energywood and carbon prices under four management regimes.

The y-axis represents the optimal rotation age in years. The upper x-axis represents the carbon prices in $ per metric ton of CO$_2$e and the lower x-axis represents the energywood prices in $ per ton.
Appendices

Appendix A: Sawtimber and Pulpwood Stumpage Prices for Hardwood Forests

The stumpage prices for hardwood sawtimber and pulpwood for the model in Chapter 2 were obtained from work done by Catron (2012). In that study the author obtained the stumpage price (high, average, and low) data for sawtimber of each commercially important species for each region of Kentucky, East, Central, and West, from the James W. Sewall Company through personal communication with Christopher Will. The stumpage prices were by the species and does not consider grade. These price data were based on a quarterly stumpage price survey conducted for the 6 years period from 2005 to 2010. The author converted these prices to 2012 dollars. Each region was assumed to have three site indexes – SI 55, SI 65, and SI 75. The author obtained the species composition of typical stands of site qualities 50-60, 60-70, and 70-80 from the Forest Inventory and Analysis (FIA) Database 5.1, USDA Forest Service. Then, for each site index for each price region the author first obtained the proportion of total sawtimber volume of each species. The proportion of total sawtimber volume of each species was then multiplied by the relevant stumpage prices (high, average, and low). And, finally the weighted average sawtimber prices (high, average, and low) were obtained for each region. Thus, all together there were 27 sawtimber stumpage prices. For simplicity, in this study the average of these 27 stumpage sawtimber prices were taken which was found to be $244 per MBF. In a similar manner, the author obtained the stumpage prices (high, average, and low) of pulpwood (pine pulpwood, soft hardwood pulpwood, and hard hardwood pulpwood) for each region (East, West, and Central) from James W. Sewall Company. Like sawtimber stumpage prices, there were 27 pulpwood stumpage
prices. And, for this study we took the average of these 27 pulpwood stumpage prices which was $5 per ton.
Appendix B: Parameters Estimated for Predicting Sawtimber and Pulpwood Yield for Hardwood Forests

The values of parameters $a$, $b$, and $c$ that can be applied to Equation 2.1 in Chapter 2 to predict the yield for sawtimber and pulpwood for upland oak-dominated mixed hardwood stands is shown in Table B.1. These values are estimated using non-linear regression in STATA 11.0.

Table B.1. Values of parameters estimated

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Sawtimber (International ¼ inch bdft)</th>
<th>Pulpwood (cubic feet)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a$</td>
<td>5.14E-18</td>
<td>0.0076</td>
</tr>
<tr>
<td>$b$</td>
<td>14.49376</td>
<td>3.856281</td>
</tr>
<tr>
<td>$c$</td>
<td>0.1837198</td>
<td>0.0508014</td>
</tr>
</tbody>
</table>
Appendix C: Production and Fuel Consumption Rate of Machines used in Harvesting of Hardwood Forests

The data for the production rate and fuel consumption rate for each of machine type and model used for harvesting oak-dominated mixed hardwood forests are presented in Table C.1. These values are used to calculate the total fuel consumed for harvesting of sawtimber and pulpwood volume per ton as shown in Equation 2.2 in Chapter 2.

The selection of the machine model was based on the Certified Master Logger Program Rainforest Alliance Smart Logging RA-SL-003285 documentation (Dr. Jeffrey Stringer, personal communication, March 28, 2013) plus Wood Supply Research Institute: Auburn Stump to Mill Cost Program model (Dr. Mathew Smidt, personal communication, May 15, 2012). Accordingly, the selected machine models were TigerCat, CAT, BARKO, and Conehead respectively for, feller buncher, skidder, knuckle boom loader, and chipper, as shown in Table C.1.

Table C.1. Data for production and fuel consumption rate

<table>
<thead>
<tr>
<th>Machine type</th>
<th>Model</th>
<th>Production rate (ton/PMH)</th>
<th>Fuel consumption rate (gallon/PMH)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feller buncher</td>
<td>TigerCAT</td>
<td>20</td>
<td>6</td>
</tr>
<tr>
<td>Skidder</td>
<td>CAT</td>
<td>25</td>
<td>7</td>
</tr>
<tr>
<td>Knuckle boom loader</td>
<td>BARKO</td>
<td>25</td>
<td>5</td>
</tr>
</tbody>
</table>
Appendix D: Parameters for Loblolly Pine Growth and Yield Model

The parameter estimates for predicting merchantable yield and total yield per acre, used in Equation 3.1 and 3.2 respectively in Chapter 3 for the loblolly pine plantations in the lower coastal plain are presented in Table D.1. (Harrison and Borders 1996).

Table D.1. Parameter estimates for merchantable and total yield per acre for lower coastal loblolly pine plantations

<table>
<thead>
<tr>
<th>Parameter estimates</th>
<th>Merchantable product yield (cubic feet per acre)</th>
<th>Total yield (cubic feet per acre)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$b_0$</td>
<td>-</td>
<td>-1.520877</td>
</tr>
<tr>
<td>$b_1$</td>
<td>-1.034486</td>
<td>0.20068</td>
</tr>
<tr>
<td>$b_2$</td>
<td>3.940848</td>
<td>1.207586</td>
</tr>
<tr>
<td>$b_3$</td>
<td>-5.062955</td>
<td>0.703405</td>
</tr>
<tr>
<td>$b_4$</td>
<td>-0.422892</td>
<td>-5.139064</td>
</tr>
<tr>
<td>$b_5$</td>
<td>6.004646</td>
<td>6.744164</td>
</tr>
</tbody>
</table>
Appendix E: Equations to Determine Dominant Height, Trees per Acre, and Basal Area of Loblolly Pine Forests

The dominant height, trees per acre, and the basal area of the intensively managed loblolly pine plantations in lower coastal plain as determined in growth and yield model by Harrison and Borders (1996) are shown respectively, in Equation E.1, E.2, and E.3. which in turn are used in Equation 3.2 in Chapter 3 to determine total tree biomass.

\[
HD = SI_{25} \left[ 0.30323 \left(1 - e^{-0.014452A}\right) \right]^{-0.8216} \tag{E.1}
\]

where, \(HD\) is the average dominant height (feet) and \(SI_{25}\) is the site index at 25 years (= 60 feet).

\[
TPA_2 = 100 + \left[ (TPA_1 - 100)^{-0.745339} + 0.0003425^2 SI_{25} \left( A_2^{1.97472} - A_1^{1.97472} \right) \right] \left( \frac{1}{0.745339} \right) \tag{E.2}
\]

where, \(TPA_2\) is the number of trees survived as a function of time (per acre), \(TPA_1\) is the initial density of stand (500 per acre), \(A\) is the age of the stand (year).

\[
ln(BA) = b_0 + \frac{b_1}{A} + b_2 ln(TPA) + b_3 ln(HD) + b_4 \frac{ln(TPA)}{A} + b_5 \frac{ln(HD)}{A} \tag{E.3}
\]

where, \(BA\) is the basal area (square feet per acre). The value of parameters \(b_0, b_1, b_2, b_3, b_4,\) and \(b_5\) used are 0.0, -42.689283, 0.367244, 0.659985, 2.012724, and 7.703502 respectively.
Appendix F: Equation to Determine Projected Competition Index for a Thinned Loblolly Pine Stand

The projected competition index for a thinned stand of the intensively managed loblolly pine plantations in the lower coastal plain as determined in growth response due to thinning by Harrison and Borders (1996) is shown in Equation F.1 which in turn is used in Equation 3.4 in Chapter 3 to determine projected basal area of thinned stand.

\[
CI_2 = CI_1 e^{-\beta(A_2-A_1)}
\]  
(F.1)

where, \( CI_2 \) is the projected competition index, \( CI_1 \) is the competition index which is expressed as a proportion of the basal area of a thinned stand to unthinned counterpart and determined as shown in Equation F.2, \( A \) is the age of the stand, and \( \beta \) is the parameter estimates (= 0.110521) for lower coastal plain.

\[
CI_1 = 1 - \frac{BA_{at}}{BA_u}
\]  
(F.2)

where, \( BA_{at} \) is the basal area in the thinned stand (per acre) and \( BA_u \) is the basal area in unthinned stand of the same age (per acre). \( BA_{at} \) is determined as shown in Equation F.3.

\[
BA_{at} = BA_u - BA_u \left( \frac{TPA_s}{TPA_{ut}} \right)^{1.2345}
\]  
(F.3)

where, \( TPA_s \) is the trees per acre removed by selective thinning and \( TPA_{ut} \) is the trees per acre before thinning.
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