LIFE CYCLE IMPACT OF LOBLOLLY PINE (*Pinus taeda*) MANAGEMENT ON CARBON SEQUESTRATION IN THE SOUTHEASTERN UNITED STATES

By

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A THESIS PRESENTED TO THE GRADUATE SCHOOL
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To my parents

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TABLE OF CONTENTS

APPENDIX

LIST OF TABLES

LIST OF FIGURES

Abstract of Thesis Presented to the Graduate School
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Global warming is primarily due to increasing greenhouse gases, mainly carbon dioxide in the atmosphere. One strategy to slow down the concentration of carbon dioxide is to store carbon in forests but carbon emissions and other environmental impacts occur during forest management. Diesels, fertilizers and other inputs have been the sources of emissions during silvicultural operations. This study analyzed cradle to gate LCA approach to assess the environmental impact of loblolly management and carbon balance model to calculate the C production from the plantation.

Diesel use in transportation and silvicultural practices consumed the highest amount of energy. Environmental impact and carbon emissions from the transportation and diesel use in harvesting machinery were higher. Use of the fertilizer had a significant effect on environmental categories in high intensity management. It was found that fertilizer's contribution on environmental impact increases when the management shifts from lower to higher intensity of management. Among the three macro nutrient used, nitrogen has the highest impact on the highest number of environmental categories.

It was found that the carbon cost from silvicultural practices is minimal compare to *in situ* carbon production at the end of the rotation. Seed orchard and nursery management had an insignificant effect on carbon emission and other environmental impacts. The total C cost due to silvicultural activities was found to be 1.2% and 0.4% of the total *in situ* in high and low intensity management and the contribution is increased to 2.5% and 1.4% while considering transportation. The C cost of high intensity was three times higher than low intensity management.

Forest management practices with the better application rate and efficient use of fertilizers could reduce the fertilizers' effect. Increasing the fuel efficiency of trucks and harvesting machine and using the size and power capacity of the harvesters with the tree size to be harvested decreases the fuel use. Proper route planning during the transportation could increase the loading factor which eventually reduces diesel consumption during the transportation. Also, use of the biofuel and other renewable source of energy could reduce the emissions from diesel consumption.

CHAPTER 1
INTRODUCTION

Background

The earth is warming up, and there is scientific consensus that people are the primary actors to the results of the climate change. There is a compelling case adopting policies to mitigate the adverse effect of global warming and climate change (McCarthy, 2001). Impact of climate change can primarily be categorized into three types namely ecological, social, and economic. The ecological impacts include shift in vegetation types and corresponding biodiversity (Elliott and Baker, 2004), change in forest density (Smith et al., 2007), and increased incidence of wildfires, diseases, and pests (Gan, 2004). Social impacts are comprised of changes in risk distribution, declines in human health, and relocation of the population (Karl et al., 2009). Similarly, increased risk and uncertainty of agriculture production (Smith et al., 2007), and changes in the supply of ecosystem goods and services (Scott and Huang, 2007) are major economic impacts. Global warming, a major challenge to the 21st century, is primarily attributed due to the increase the concentration of greenhouse gases (GHG) mainly carbon dioxide (CO_2), methane, and nitrous oxide in the atmosphere. The main contributor to the enhanced greenhouse effect is CO_2. Globally it accounts for over 60 percent of the enhanced GHG effect and in the industrialized countries it makes up more than 80 percent of the total emissions. The CO_2 emissions due to fossil fuel use increased the concentration of atmospheric CO_2 to 377 ppm (parts per million) in 2006 from 280 ppm in 1750 (Blasing and Smith, 2006). The continued increase of CO_2 along with other GHGs has elevated the earth's surface temperature by blocking the thermal infrared radiation.

Further addition of gases in the next 65 years could cause the earth temperature to rise up to 5°C or at least 1°C (Cox et al., 2000).

One strategy to slow down the increasing GHGs concentration in the atmosphere is to increase the storage of the carbon (C) in forests (Gorte, 2009) which might be able to reduce the deposition rate of atmospheric C (Sedjo 1989). The recognition that CO_2 is increasing in the atmosphere has increased recognition that C sequestration is an important forest function (Nair et al., 2009) along with other tangible benefits from the trees. C storage in the forest includes numerous components including biomass and soil C. Above ground biomass, detritus material, and terrestrial C stocks are forest biomass C whereas below ground C includes both organic and inorganic C (Lal, 2005). Reforestation of abandoned and bare land and management of existing forest and soil can serve as important mechanisms to sequester C (Markewitz, 2006). The C sequestration function of the forests is primarily related to the net primary production of forests. Forest floor and the mineral soil also sequester C (Yanai et al., 2003; Markewitz, 2006). Old growth forests with no timber yield may have high biomass, and thus, stores large amounts of C (Harmon et al., 1990). Plantation forest with regular timber yield often contains relatively low C compared to undisturbed forest (Cannell and Thornley, 2000).

Although forest management activities are less intense than cropland management, they affect the soil C as well. The potential role of forest conservation and management to reduce the GHGs through carbon sequestration is likely to exceed that of agriculture (Nair, 2009). Forest management systems which mimic the regular natural forest disturbance with a continuous canopy cover increase C storage (Cannell and

Thornley, 2000). Forest management activities that might impact the soil C include site preparation, harvesting, soil drainage, fertilization and liming (Hoover et al., 2002). Forest fire reduces aboveground C in the short period where as its early effect on soils are quite variable (Markewitz, 2006). Similarly, fertilization commonly increases both above and belowground C storage in the short period while herbicides responses are generally positive on adding aboveground but negative on belowground C but the long term impact of burning and fertilization on the net C balance in forests is uncertain (Markewitz, 2006).

Out of 0.93 billion ha of land area in the U.S., 33 percent is forest. Out of 302 million ha forest areas in the United States, the southeastern region contains approximately 82 million (ha) of timberlands which has annual productivity higher than 1.41 m^3/ha/yr (Smith et al., 2004). Nearly 61 percent of the softwood and 53 percent of the hardwood timber harvested in the United States comes from the Southern region and production is expected to increase in the future (Haynes, 2002). It produces 18 percent of the global industrial round wood, 25 percent of the global pulpwood. The 15 million ha of southern pine makes up approximately half of the world's industrial forest plantations (Spatari et al., 2005). About 70 percent of 57 million ha regional timberland is in nonindustrial private forest landowners (Smith et al., 2004). Approximately 57.8 billion tons of C is present in forest ecosystems both above and below the ground in the U.S., which is nearly 4 percent of the entire C stored all over the world's forests. The southeast region contains 10 percent of the total forest C in the U.S (Birdsey, 1992).

Southern pine forests with best forest management practices and well established tree improvement programs have produced pulp, woodchip, and saw timber along with

bioenergy and broad range of ecological services. The wide geographic distributions of many pine species show their adaptability to various climate zones and soil types. However, four southern pine species, namely loblolly (*Pinus taeda*), shortleaf (P. *echinata*), longleaf (P. *palustris*), and slash (P. *elliottii*), are the most important due to their broad natural ranges. In addition, only loblolly and slash pine were planted in 15 million ha of timberlands (Peter, 2008).

Silvicultural management of the southern forest plantation has gone through a series of advancements over the last six decades resulting the productivity (Jokela et al., 2004). Coastal plain pine forests in the south are among the most intensively managed (Johnsen et al., 2004) and productive forest in the world (Fox et al., 2004). The southern forest produces more timber than any country in the world (Prestemon and Abt, 2002). A wide range of silvicultural activities has been applied from seed production up to the harvesting of the forest products. Various silviculture activities such as burning, fertilization, and herbicide application affect the C budget of the forest (Knoepp and Swank, 1997; Johnson and Curtis, 2001; Echeverría et al., 2004). Thus, the assessment of the GHG emissions from the forest management activities in order to identify the net C balance of the forest system is important in the context of burning global warming scenario.

Loblolly pine is the most widely planted species for plantation in the south (Samuelson et al., 2004). In plantations, loblolly pine grows fast providing a great potential opportunity to sequester C (Johnsen et al., 2004). However, loblolly pine is usually, on average, maintained for short rotations, so there is less C in the trees in comparison to Spruce-fir and Douglas-fir which are usually maintained for longer

rotation (Birdsey, 1992). It is necessary to assess the environmental impact of forest management activities and explore the possible options for improvement in the forest management (Seppala et al. 1998). In the southeastern United States, the impact assessment of loblolly pine forest management activities will be significant at the regional and national scale. The assessment of net C production from the forest is necessary to quantify the incentive that could be gained from sequestering C in the forest.

Objective

The study aims to assess the life cycle impact of loblolly pine (*P. taeda)* management systems on C sequestration in the southeastern United States. In particular, the study is expected to answer the following questions.

- What are the life environmental impacts from forest activities?
- What is the global warming impact associated with silvicultural practices of the loblolly plantation? Which forest activities produce high the greenhouse gas emissions?
- How much energy is used in the management of the loblolly pine forest considering the inputs throughout the life cycle from seed orchard management to transportation of harvested forest products to sawmill?
- What is the net carbon sequestration from the different management intensities of the loblolly plantation?

CHAPTER 2
LITERATURE REVIEW

Forest Management and Climate Change

Forests are shaped by the climate and the climate is also shaped by the forests. The effects of climate change on forest are numerous. Climate determines what will grow properly in the specific site as changes in the temperature and precipitation regimes will affect the growth of the trees (Malmsheimer et al., 2008). Climate change can affect forests by altering the frequency, intensity, duration and timing of fire, drought, invasive species, insects and pathogen outbreaks, hurricanes, windstorms, ice storms, or landslides (Dale et al., 2001; Lal et al. 2011). There are direct effects of temperature, precipitation, and increasing atmospheric carbon dioxide on tree growth and water use and indirect cumulative effects of the aforementioned climatic parameter on fire severity and pest outbreaks. Moreover, it has the potential to change entire forest systems by shifting distribution and composition (Malmsheimer et al., 2008; Lal et al., 2011).

On the other hand, forests can contribute to climate change protection through carbon sequestration coupled with offering environmental, social, cultural, and economic advantages (Canadell and Raupach, 2008). The terrestrial biosphere which includes forest can slow down the CO_2 increase (IPCC, 2000) and some activities increases the emissions where as some activities decrease the emissions (Schlamadinger et al. 2000). Wild fires are also a major contributor to GHG emissions globally (Flannigan and Van Wagner, 1991, Malmsheimer et al., 2008). GHG emissions can be prevented or reduced by wood substitution, biomass modification, controlling the wildfire behavior, and regulating land-use change (Malmsheimer et al., 2008).The use of

wood instead of fossil fuel intensive products can deal with climate change to some extent. The use of the lumber, wood panels and other forest products can store C for a long time and emit less C in comparison to fossil fuel intensive construction materials like concrete, brick, or vinyl (Malmsheimer et al., 2008). Similarly the use of biomass fuels and bio based products can also reduce oil and gas imports and improves environmental quality (Malmsheimer et al., 2008, Dwivedi et al., 2009).

Forest Management in the Southern United States

Forest resources in the U.S. shows constant improvement in general condition and quality with 33% of the 2.3 billion acres of land area is forest (Smith 2004). Smith et al. (2004) stated that 94% of the southeastern forests equivalent to 82 million hectares are timberland. Deforested and degraded forest land and degraded agricultural land was widespread in the 1950s in the south. The southern pine plantations were less than 2 million acres and a large area of land was abandoned due to widespread deforestation and unproductive land due to disorganized agriculture practices at the end of world war (Fox et al. 2004). The tree planting was extensively increased after the war (USDA Forest Service, 1988). To meet the demand for timber from the rapid expansion of the paper and pulp industry in the 1930s, the pine plantation was augmented in the south (Fox et al., 2004). Also, the south has been a source of timber since colonial times (Williams 1989) and timber harvesting is widespread in the whole southern region but mainly concentrated on the Atlantic and Gulf Coastal Plains (Wear and Greis 2002). Management practices in pine plantation has been drastically improved as plantations produced less than 90 cubic ft^3/ acre/ year during 1950s and 1960s but the plantation in the 1990s produced more than 400 ft^3/acre /year (Fox et al. 2004). Because of the

unprecedented success of the plantation, southern pine plantation is considered as a wood basket in the world (Schultz 1997, Fox et al. 2004)

Southern pine plantation in the U.S. is one of the success stories in the world for forest management (Fox et al. 2007) and the most intensive managed (Johsen et al 2004). Southern forestry is the world's most important supply of industrial wood (Siry et al. 2006). It produced 310 million tons of wood annually (Smith et al. 2004). Eighteen percent of global industrial round wood and 25% of global wood pulp production comes from the southern U.S. (FAO 2004). Southern forests have gone through drastic changes in the ownership and use as well (Allen et al. 2005). With 88% forest owned by private landowners, intensively managed pine plantation growth rate is as much as 7 tons per acre per year (Siry et al. 2006) and plantation has biologically possible rate of 10 tons per acre per year (Allen et al. 2005) . Though loblolly, longleaf, shortleaf, and slash pine are the important species in the south, loblolly and slash pine covers the majority of planted timberland in the southeastern with an approximate area of 15 million hectares (Peter 2005).

The success of pine industry is well supported by research conducted with the cooperative efforts between forest industries, universities, state and federal agencies and disseminated and implemented widely (Peter 2008, Fox et al. 2004). The improvement in the productivity is expected in the future due to refined management regimes and clonal forestry has promising capability to dramatically increase the productivity in southern pine plantation (Fox et al. 2004). There are still lots of challenges to be resolved in order to get the best possible output from plantation in the most economic and environmentally sustainable manner (Allen et al. 2005).

Forest Carbon Sequestration

Between the geological and biological potentiality of C sequestration, geological potentiality has not been demonstrated enough to mitigate CO_2 emissions even though it has higher potential (Hale et al. 2008). The storage of atmospheric into plant tissue is one of the most effective methods to offset CO_2 emissions as biological C sequestration (Sedjo 1989, Sedjo et al. 1997) and forest is considered as a potential source to reduce atmospheric CO_2 by sequestrating C in above- ground stems, leaves, branches and below-ground roots and soil (Sedjo and Sohngen 2000).Forests act as important actor as most efficient natural terrestrial C sink in terms of global C cycle (Malmsheimer et al., 2008). Forest C sequestration is the process of absorbing the atmospheric CO_2 and storing as C in the biomass and soil. During the photosynthesis, plants use sunlight, nutrient, and water to convert into CO_2 which accumulate on leaves, twigs, steams, and roots; and releases oxygen and incorporate the C atoms in the plant cell (Sedjo 2001). Plant releases its stored C to the atmosphere after dying or release into the soil to decompose slowly which eventually enhance the C level in the soil (Gorte 2009). The composition of C sequestration in each part of tree varies upon the regions, forest type, age, quality of site, and land use history (Hale et al. 2008). Soil C presents in humus, decomposers, and roots and dead vegetation parts (Gorte 2007). Forest is the prime terrestrial C sink which stores more than two-thirds of terrestrial source (Dixon et al. 1994; Sedjo et al. 1997). The above ground of trees and soil sequestrate approximately 30% and 60% of the total C and remaining C stores mainly on forest liter and understory (Birdsey 1992).

Unlike agricultural crops, C cycle in forest operates for many centuries or even decades (Sedjo 2001). Young trees can capture faster because of their growth rate

whereas old vegetation stores large amount C. But, C absorption rate of plants changes during the development due to the difference between gross primary production and ecosystem respiration (Domke et al. 2008). Forest can only be considered as C sink when the total photosynthetic rate is higher than ecosystem respiratory rate (Dixon et al. 1994). Your stands act as C source because of having a higher respiratory rate in comparison to photosynthesis whereas middle-aged and old-aged stands normally act as a sink due to higher photosynthetic rate (Domke et al. 2008). C sequestration potential of forest types varies and moist tropical, temperate, and boreal forest approximately contain approximately 110, 70, 180 tons per acre (Gorte 2007).

Forest C sequestration assists in preventing global warming by increasing C storage in forest plants and soil, preserving present tree and soil C, and controlling CO_2 emissions (EPA 2012). Four major forest activities could mitigate C emissions: 1) reforestation to increase the forested area, 2) increasing the C density and C stock in the stand and landscape, 3) replace the fossil-fuel CO_2 emissions by expanding the use of forest products, and 4) avoiding deforestation and degradation (Canadell and Raupach 2008).

Forest Carbon Management in the United States

Forestry is widely recognized as a potential GHG mitigation option (EPA 2005). Forest presently absorbs billions of tons of CO_2 every year which equivalent an economic subsidy worth hundreds of billions of dollars if it has to be done by other ways of C sink (Canadell and Raupach 2008). In the US, atmospheric absorption by the forest exceeds CO_2 emissions from forest land use (Haile et al 2008). Forest and agricultural land comprise a net C sink of 830 million tonnes CO_2 per year in the United States (EPA 2005) which is equivalent to 14.8% of CO_2 emissions and 12.5% of GHG emissions in

the U.S. and out of which forest holds 84% of total sink (Haile et al. 2008). Woodbury et al. (2007) estimated 149-330 Tg C per year is sequestered within the United States and forests, urban trees, and wood products accounts for 65-91% of the total sequestration. Forests including wood products sequestered an average of 162 Tg C per year between 1990 to 2005 in the United States (Woodbury et al. 2007). Similarly, Brown et al. (1996) estimated that between 1995-2050 a large amount of C could potentially be conserved and sequestered by reducing deforestation and degradation (138 million ha) and managing natural forest (217 million ha) land in the tropics and establishing 345 million ha of plantation and agroforestry. These efforts could conserve 11-15 percent of the projected fossil fuel emissions during the same period (Brown et al., 1996).

Forests are an important part of the global C cycle in mainly two ways. Firstly, the terrestrial ecosystem absorbs nearly three billion tons of C every year through net growth which is 30 percent of the C emissions from burning fossil fuels and deforestation. In addition, forest area which is almost 30 percent of the world land area holds more than double the amount of C present in the atmosphere (Canadell and Raupach, 2008). However, the level of C sink mainly depends upon a succession development stage and management intensities and activities in the forest (Phillips et al., 1998). Primeval forest with no timber yield has high biomass , thus, stores large amount of C (Harmon et al., 1990) and plantation forest with regular timber yield, contains relatively low CC compared to undisturbed forest (Cannell and Thornley, 2000). But, increase in forest biomass may not necessarily increase the soil C. Soil C can be increased by appropriate site preparation, adequate soil drainage, species with

high net primary productivity (NPP), applying fertilizers, and adequate fire management (Lal 2005).

There are mainly three types of sound forest management practices to increase C sequestration is conserving the existing C pool through slowing deforestation, increasing C storage by expanding areas of forest, and transferring the forest biomass into biofuel so that use of fossil fuel based products can be reduced (Johnsen et al., 2001).

The C sequestration function of the southern pine is high due to high productivity and industrial infrastructure. C sequestration is not only valuable for regional and national level but also has importance in the global scale. Moreover, C sequestration might be beneficial to the nation in terms of global policy commitments in the future (Johnsen et al., 2001). It will ultimately be useful to effectively implement C based international programs like the Kyoto protocol. It is necessary to assess the dynamics of C fluxes and storage under different management practices in forest ecosystems. However, it is complicated to quantify the C sequestration potentiality of forest with various stocks and fluxes under different management regime ranges. C can not only present in above ground biomass, soil and dead wood but also in manufactured wood products (Masera et al., 2003).

Silvicultural Practices and Environmental Impacts

The southern pines are one of the most intensively and extensively management forest in the world (Fox et al., 2004, Stantrf et al., 2003) and loblolly is most widely planted (Johnsen et al. 2001). Intensity of silvicultural practices for loblolly pine varies depending upon the objective and the investment available (Peter 2008). Site preparation, planting of seedlings, fertilization, thinning, tending operations, and finally

harvesting are the activities required for forest stand establishment and timber harvesting (Jokela et al. 2009, Johnson et al., 2005). The underlying reason for the success of the southern forest management is the application of forest research in tree improvement, nursery management, site preparation, weed control, and fertilization to plantation forestry in the south which increases productivity significantly (Fox et al., 2004).

Forest operations are highly mechanized and need external energy, thus, sources of GHG emissions (Berg and Karjalainen, 2003). Use of the machinery, material, and fuel during silviculture practices causes GHG emissions. Markewitz (2006) concluded that 2.64 Mega gram (Mg) C per hectare (ha) emission over a 25 year rotation in an intensively managed loblolly pine plantation in southeastern United States. The increase of C in the soil and the woody biomass due to forest plantation outweighs the emission due to silviculture activities. The details about the C emissions from each management practices are shown in the Table 2-1.

Management of forest resources has a big impact on the environment (Seppala et al. 1998). Forest fertilization increases the nutrient concentrations in the water body and degrades the water quality (Binkley 1998). Nitrogen is considered as a major pollutant from agriculture in water (Gundersen et al. 2006). Even though the water draining through the forest has nine times less concentration of nitrogen and phosphorus (Omernik 1977), forest road and harvesting operation add sediments; and harvesting and fertilization further increase the concentration of nutrients in the water (Binkley and Brown 1993). Nitrogen leaching may happen even from unfertilized and less intensively managed forest because of the huge amount of Nitrogen from air pollution (Gundersen

et al. 2006). Except fertilization, site preparation, road construction, and forest harvesting may cause to mobilization and leaching of nitrogen (Worrel and Hampson 1997). Timber harvesting can affect the physical, chemical, and biological condition of stream by changing in water temperature, water turbidity, sedimentation and nutrient concentration in the water body (Corbett et al. 1978). Loss of biodiversity is the major environmental problem due to forestry operation (Seppala et al. 1998).

Oneil et al. (2010) had done a life cycle assessment of wood products to assess the economic and environmental impact of forest management activities in inland Northwest and Northeast forest. Johnson et al. (2005) assessed the environmental impacts associated with the life cycle of forest resource activities for the Southeastern and Pacific Northwest region. Life cycle inventory was done of different compounds released from forest operations. It was found that transportation related activities and use of diesel fuel created the highest emissions. White et al. (2005) conducted a life cycle inventory on the round wood production in Northern Wisconsin. They found C budgets in the harvesting process of different forest in the range of 0.1 to 0.18 Mg C per ha. Diesel used in the harvesting operation and transportation is the major contributor in the environmental impacts (Neupanen 2010, Johnson 2005, Michelson 2008, Berg and Lindholm 2003). Acidification occurs due to emissions of sulfur oxides (So_x) and nitrogen oxides (NO_x) from the fuel combustion. NO_x produced during combustion process of fuel is the main reason for eutrophication (Berg and Lindholm 2003).Logging and silviculture activities produce highest levels of certain emissions such as CO_2, So_x, NO_x, and hydrocarbons (Berg and Lindholm 2003).

Life cycle assessment (LCA) has been developed as a tool to assess the environmental impact of products and processes (Richter 1995; Curran 1996) which can also be used to quantify the C emissions from forestry activities. Complete LCA mainly consists of defining the goal and scope of any study, life cycle inventory of the products or process, assigning the inventory data into different impact categories (classification), finding impact category indicators using characterization factors (characterization), normalization of the to the characterized results, weighting of the results, and finally data quality analysis (Pennington et al. 2004). In the forestry sector, it is used to find environmental benefit cost analysis (Ueda et al. 2003), to quantify the energy use and emissions from silvicultural activities (Athanassiadis et al. 2002), and to identify which forest product development state has to be improved to reduce environmental impact (Forsberg 2000).

Table 2-1. The estimated amount of carbon utilized in a hypothetical intensive fiber farming system for Southeastern pine

Time	Forest activities	C use (kg C/ha)
Site preparation	Raking, herbicides application, plowing etc	95
Year 1 to year 20	Machine planting, aerial fertilizer application (3 times) and herbicides application, commercial thinning (2 times)	2068
Year 25	Harvest	465
	Total	2644

CHAPTER 3
METHODS

Environmental Impact Assessment of Forest Activities

A cradle to gate life cycle approach was used to assess the environmental impacts from forest management activities. Literatures were reviewed from published journal articles, US LCI database, Ecoinvent reports and database, Franklin USA 98 database, and equipment manufacturer's manuals etc. Additionally, personal communication with researchers and faculty members was also done to collect the data.

The LCA software SimaPro 7.1 (Pre Consultants 2011) was used to assess the C emission from forest management inputs from seedling planting to transportation to the forest mill. The software which includes different database to carry out impact assessment was used to perform the LCA. The database includes information about natural resources, raw materials, and emissions from products, processes, constructions, operations, maintenance, conversions, transportation, and disposal processes. It allows to model products and system in a systematic and transparent way for life cycle assessment. It can also be used in the C footprint calculation, product design and eco-design, environmental product declaration, environmental impact of products or services, environmental reporting, and determining of key performance indicator (Pre Consultants, 2012). Tool for the Reduction and Assessment of Chemical and other environmental Impacts (TRACI), a midpoint oriented LCIA (Life Cycle Impact Assessment), was used as a life cycle impact assessment method. The TRACI 2 V3.00 available on SimaPro 7.1 was developed by the U.S. Environmental Protection Agency specifically for the US using input parameters consistent with US locations. The characterization factors provided by the TRACI were used to estimate the total

emissions from the outputs of the inventory results. Although assessing global warming impact was a major objective of the study, other environmental impacts were also estimated and discussed.

Life Cycle Assessment

Life cycle assessment is a “cradle-to-grave” approach for identifying, quantifying, and assessing environmental impacts of the whole life of any products, processes, or activities. In this “cradle-to-grave” approach, all the inputs and outputs including energy and material used and released during raw material acquisition, manufacture, use, and maintenance are compiled, evaluated, and interpreted to estimate the cumulative environmental impacts resulting from all the stages of the life. It is also used along with other environmental assessment tools such as risk assessment and environmental impact assessment. Since it gives a broad view of environmental aspects of any products and processes, it can also be used a tool to assess trade-offs between different products or different method of productions.

International Organization of Standardization (ISO) classifies LCA into 4 stages namely, goal definition and scoping, inventory analysis, impact assessment, and interpretation. Goal definition and scoping includes the defining purpose of the study, setting the boundaries of the analysis, describing the intended application and target audience, and establishing the functional unit. Life cycle inventory (LCI) identifies and quantifies energy, water, and material usages and environmental releases based on functional unit and system boundary of the analysis. Similarly, impact assessment stage assesses the results of the LCA in order to understand the potential effects of energy, material, and water usage and the environmental releases during the life cycle.

Interpretation evaluates the results of inventory analysis as well as impact assessment to conclude and present the results.

Goal Definition and Scoping

The main goal of this life cycle analysis is to identify inputs and outputs and emissions from the loblolly pine management activities from orchard management to transportation of the logs to the sawmill to assess the impact of silviculture activities on C sequestration after the end of multiple rotations. In addition, this study quantifies the energy use to produce loblolly pine timber and assesses the environmental impact from resource use and emissions. The result of the study is expected to be useful for forest industries, forest landowners, and researchers.

Functional Unit

The functional unit of the analysis was the one hectare of loblolly pine stand. All the inputs and outputs within one hectare of loblolly pine stand were considered for the analysis. Similarly, the area of land for nursery management and seed orchard was calculated based on the total quantity of seedling required to produce for one hectare plantation and seeds required to produce seedling in the nursery.

System Boundary

System boundary of the analysis includes seed orchard management, nursery management, site preparation activities, planting, weed control, fertilization, thinning and felling, delimbing and loading logs. It also includes transportation of seed from seed orchard to nursery, transportation of seedling from nursery to the planting site, and transportation of logs from the felling site to a nearby sawmill. The inputs of the system include fuels, fertilizers, electricity, herbicides, pesticides, fungicides, propane, and water whereas outputs include timber, and emissions to air, soil and water. Both direct

and embodied energy used throughout the life cycle of the plantation was considered. Direct energy includes electricity, diesel, and gasoline. consumed in the process of operating machineries and transportation. Embodied energy is the amount of energy necessary to produce fertilizers, diesel, materials, propane, herbicides, and pesticides. Two types of intensity of loblolly pine management were considered in the analysis.

- Low intensity with rotation length 22 years without thinning
- High intensity with rotation length 25 years with thinning at age 12 and 18

Low intensity of management was considered with mechanical site preparation, no thinning, and no fertilization for the rotation age of 22 years. High intensity of management was considered with mechanical and chemical site preparation, fertilization, thinning at 12 and 18 years for the rotation age of 25 years. These two management intensities were considered as common loblolly management practices for non-industrial private forest and industrial forest in the southeastern United States following (Johnson et al. 2004, Gonzalez-Benecke et al. 2011). Table 3-1 shows the details about the management prescription for two intensities of loblolly pine management. The schematic diagram of system boundary is presented in the Figure 3-1. Two way transportation from the harvesting site to the sawmill was assumed 193 km. Similarly, two way distances between seed orchard to nursery and nursery to plantation site was assumed to be 160 km. Two-way transportation was considered for the life cycle analysis with the 50% loading factor for the trucks. System boundary considered only the timber as an output of the loblolly management during thinning and final harvesting. Production process of machinery was not included, but production of material, herbicides, and fertilizers were included. Transportation of labor, machinery,

and supplies to working sites were not included and production of machine, the building is also not included in the analysis.

Life Cycle Inventory

Life cycle inventory considers all the process from seed orchard management up to the harvesting of the trees and its transportation to the mills. Thus, the inventory also encompasses transportation of seeds from orchard to nursery, nursery management, and transportation of seedlings from nursery to the plantation site including various management activities during orchard, nursery, and plantation management.

Life Cycle Impact Assessment

EPA has developed TRACI to assist the impact assessment in life cycle assessment where impact categories are selected, then, categorized based on the reviewed methodology. TRACI quantifies the stressors having an effect on global warming, ozone depletion, acidification, eutrophication, smog formation, Eco toxicity, human health cancer, and human health no cancer (Bare 2011). Many of the impact assessment impact within TRACI methods are mainly based on midpoint characterization approach and the impact assessment model shows the strength of the stressors at a common midpoint within the cause-effect chain (Bare et al. 2000). Among the impact assessment phase defined in the LCA methodology (ISO 2006), only classification and characterization were considered for this study. Normalization and evaluation were excluded because they are optional method and they did not give extra information for the given goal and scope of the study. The details about the environmental impact categories are provided on appendix-B.

Interpretation

Interpretation is the last stage of the life cycle assessment which involves identifying the importance of environmental issues. An evaluation is done on these issues and finally suggestions and recommendations are made to improve the life cycle of any products or services to eliminate or reduce these issues.

Plantation Area

The functional unit of the analysis was one hectare of land. Planting density of 1500 trees per hectare was assumed following (Gonzalez-Benecke et al. 2011) as a commonly used plantation density of the industrial plantation and non-industrial private plantation.

Nursery Management

Plantation density of loblolly pine plantation for both intensities was considered as 1500 seedlings per ha. It was considered that 12% seedling is damaged due to transportation and mortality. About 1704 seedlings per hectare were required to produce from the nursery after considering mortality. Then, total area required for seedling production was determined on the basis of seedling density of 28 seedlings per square foot and 12 beds per acre in the nursery. Total number of seedlings required was divided by seedling density to estimate the total nursery area required for the seedling production. Total bedding area required to produce 1704 seedlings was 5.67E-04 hectares. Considering the spacing between the seed bed, 756196 per acre seedlings can be produced and the total nursery was found to be 9.11E-04 hectares to produce 1704 seedlings.

Seed Orchard Management and Seed Processing

It was assumed that 1704 seedling is required after considering 12% mortality during the transportation. Germination percent of loblolly pine was considered as 90% whereas 20% seed damage was assumed during seed collection and transportation. Considering seed damage during transportation and collection and germination percent, total numbers of 2366 seeds were required to produce in the seedling. Productivity of loblolly pine seed orchard was assumed to be 48 trees per acre and average production of 55,000 seeds was assumed from one acre of seed orchard. Thus, about 1.74E-02 hectares is required to produce 2366 seedlings.

Direct and Indirect Energy Use

The total energy included both direct and indirect energy use to produce one hectare of loblolly pine plantation. Direct energy inputs include electricity, diesel, propane, and gasoline used in the process of running various machineries and equipments. Total quantity of direct energy was calculated per functional unit for each equipment.

Indirect energy inputs include the amount of energy necessary to produce machinery and materials per functional unit at each stage. The indirect energy required for producing the component of machinery, fertilizers, and chemicals were used from the literature (Hill et al. 2006). Similarly, total energy necessary to produce a liter of diesel and gasoline was used following Furuholt (1995). The composition of each equipment was calculated by following the values give in Burnham et al. (2006). A scaling factor was used to allocate the embodied energy for each functional unit. The scaling factor was calculated by taking the ratio of hours of machine used per functional unit for the lifetime of the equipment. Finally, total embodied energy to produce each

component was multiplied by scaling factor to get the embodied energy used during the forest management activities. The following formula shows the calculation of embodied energy for each component.

$$\text{Material Use} = W \times \frac{T}{L}$$

Where W is the total weight of the equipment use, T is the total time (hrs) of the use of machinery and equipment, L is the lifetime of each machinery (hrs). After calculating the total material use for each forest activities, total embodied energy of the material is calculated by total material use of any forest activities multiplied by embodied energy required to produce per unit of the material.

Where EE is the embodied energy (MJ) required producing of each component (Kg) of each machinery, direct energy from the various inputs such as diesel, propane, electricity, gasoline was estimated by multiplying the total quantity by their calorific values. Calorific values of diesel, propane, and gasoline were found 38.6, 26.0, and 34.8 MJ per liter respectively. Similarly, the embodied energy of the materials, fuels, fertilizers, and chemicals were calculated. It was found that embodied energy from diesel and gasoline was 2.1 and 4.12 MJ per liter. Similarly, total energy needed to produce nitrogen, phosphorus, and potassium was found to be 51.47, 9.17, and 5.96 MJ per kg whereas embodied energy for herbicide, insecticides, and pesticides were found to be 319, 325, and 475 MJ per kg. It was assumed each piece of machinery consists entirely of steel in order to calculate its embodied energy. It was found that it requires 25 MJ energy to produce 1 kg of steel and additional 50% energy for the assembly. Total embodied energy of materials, chemicals, and fuel used was calculated by multiplying the total quantity by the energy required to produce per unit quantity.

Direct energy was mainly used for plantation activities and transportation of logs to the sawmill in both silvicultural management scenarios. Direct energy was mainly used for diesel combustion during the machinery operation and truck transportation while embodied energy was mainly estimated from diesel use, fertilizer application, herbicide application, and material used during the management and transportation. However, there was no embodied energy for fertilizer and herbicides in low intensity management and only embodied energy was calculated from the materials and diesel use for mechanical site preparation and final harvest of the wood.

Emissions and Environmental Impact Calculation

Emissions in the silvicultural practices result from the different forest management activities. The amount of emissions mainly depends on the intensity and frequency of the silvicutural treatment (Markewitz, 2006). To calculate the total emissions from silviculture activities, total use of various materials and energy inputs were calculated for plantation management, seed orchard, nursery, and corresponding transportation. Total quantity of emissions related to equipment use was calculated within the system boundary. Fuel consumption rate per hour and total number of hours used by a machine per unit functional area were ascertained to calculate the emissions from machinery operation. Rate of application of fertilizers, herbicides, and pesticides, frequency of application, method of application, and amount of application was calculated to quantify the emissions from the chemical treatment. Emissions associated with the productions of diesel, fertilizers and materials were also considered for the analysis. In order to calculate total emissions from machinery, energy, fertilizer, and herbicides, total emissions of various chemicals from each activity was multiplied by their respective characterization factors from TRACI to convert into CO_2 equivalent.

Summing up the total characterized value gives the total CO_2 equivalent emissions from different forest activities and total emissions from the complete life cycle of the loblolly pine management.

Similarly, different impact categories available in TRACI 2 version 3 were considered for the environmental impact assessment of silviculture activities. After adding all the inputs as a process in SimaPro, it gave the inventory results about the total emissions from the process into the air, water, and soil. Then, the inventory results were multiplied by a characterization factor to get the total environmental impacts. TRACI provides environmental impact categories in unit of different chemical equivalent. It includes global warming (kg CO_2 eq[1]), acidification (H+ moles eq), carcinogenics (benzene eq), non carcinogenics (toluene eq), and respiratory effects (kg PM2.5 eq), eutrophication (kg N eq), ozone depletion (kg CFC-11 eq), ecotoxicity (kg 2, 4-D eq), and smog (kg NOx eq). Appendix B provides the detail of individual impact category.

Machinery and Materials Used

Different types of machinery were used for seed orchard management to harvesting of timber. Available literatures were reviewed to collect the data for machinery and materials used for the loblolly pine management. In addition, consultation with researchers and experts was done to collect the information related to machinery and materials for the management. Machinery use for each forest activity was considered for materials calculation. The use rate (hours per hectare) of machines and fuel use rate (liters per hour) was determined following (Dwivedi et al. 2012) and

[1] eq = Equivalent

other available literature and total diesel consumption of each activity was calculated and added to get the total diesel use during the whole management activities. Company catalogue and available literature was followed to find the total weight of the equipments. Nemecek et al. (2007) and Berg and Lindholm (2002) were followed to estimate the lifetime and the utilization rate per year and approximate lifetime of forestry machinery was assumed from the agriculture machinery. Burnham et al. (2006) was followed to divide composition of the each machinery into steel (61.7%), plastic (11.2%), iron (11.1%), aluminum (6.9%), glass (2.9%), rubber (2.4%), and copper (1.9%). Total use of materials for each activity was estimated using the following formula.

$$\text{Materials (Kg)} = \text{Total material present in a machinery (Kg)} \times \frac{\text{Total use hour of machinery (hrs)}}{\text{Lifetime of the machinery (hrs)}}$$

The total lifetime of each machinery was calculated by multiplying the total life by utilization rate of the machine in a year. Individual material use of each machine per functional area was summed to get the total material use for the management activities. Total material use was again divided into different composition using Burnham et al. (2006).

Chemicals, Fuels, and Water Use

Water use was calculated based on its uses in diluting herbicides and irrigation in nursery and seed orchard per functional unit. The machine use rate (hours per hectare) and fuel economy (liters per hour) were determined following Dwivedi et al. (2012) and other available literature and total diesel consumption of each activity was calculated and added to get the total diesel use during the whole management activities. It was found that propane is used in the seed drying process. Gasoline was assumed to be

used for manually burning the forest residues by drip torch. Urea, diammonium phosphate, and potassium chloride were used as proxy chemicals in SimaPro as nitrogen, phosphorus, and potassium. Atrazine and 2, 4-D were used as proxy insecticides and herbicides. Methyl chloride and nitro-compound were considered as a proxy for methyl bromide and chloropicrin. Similarly, fertilizer and insecticide application was estimated by following US LCI database, Fox et al. (2007) Carey (2001), South and Zwolinski (1996) and Markewitz (2006). The application rate per hectare of each chemical was multiplied by the conversion factor to get the application for each functional unit.

Transportation

Two way hauling distance, with-load and without-load, was considered in the transportation. Total fuel consumed in the transportation was calculated by using the following formula.

$$\text{Diesel use per functional unit (L)} = \frac{\text{Total diesel used (L)} \times \text{Weight of transported material (Kg)}}{\text{Total capcaity of semi-trucks (Kg)}} \times \text{Required number of trips}$$

Similarly, the total life of a semi-trailer was assumed as 50, 0000 miles for the calculation of material. Material composition of semi-truck was calculated following Burnham et al. (2006).The quantity of each material used was calculated using the following formula.

$$\text{Materials used} = \frac{\text{Total material presentin semi-truck (Kg)} \times \text{Total weight of transported material (Kg)}}{\text{Total materials that can be transported in the lifetime (Kg)}}$$

Here, total materials that can be transported for the lifetime can be calculated by multiplying the total loading capacity of truck by number of trips during the lifetime of the truck. The number of trips in the lifetime of the truck can be determined by dividing the total life of a semi-truck by the total distance travelled in each trip. Similarly, an average fuel economy of 0.62 liter/miles was assumed for the calculation of diesel use per functional unit.

Growth and Yield of Loblolly Pine Plantation

The growth and yield assessment was done to calculate total volume production at the end of rotation and its corresponding C content. Various studies had done about the growth and yield prediction of the loblolly pine in the southeastern United States (Gonzalez-Benecke et al. 2011, Boarders et al. 1990, Harrison et al. 1996, Matney and Farrar 1992, Sullivan et al. 1972, Clutter 1963). The hybrid growth and yield model developed by Gonzalez-Benecke et al. (2011) was used to calculate total biomass and C in the loblolly pine plantation. The model gives the stem, root, branches, and understory C except C presents in the soil. This model integrated the mostly used growth and yield models of loblolly pine that could be applied to lower coastal plain, upper coastal plain and piedmont regions in the United States. In addition, published allometric and biometric equations are considered in the model in order to develop a new model to simulate *in situ* C pools. Similarly, this model used forest product conversion efficiencies and forest product decay rates to calculate *ex situ* C pools. However, the *ex situ* C pools were not considered in the analysis because only *in situ* C pools is necessary to assess the C sequestration by the plantation for this study. The hybrid model assumed that C storage in soil is not affected by any forest management activities (Gonzalez-Benecke et al. 2011). The study found that average net C stocks

are 35% lower on low productivity sites in comparison to average productivity stands where as high quality site has 38% greater net C stocks than average sites. In addition, thinning has net C positive effect due to deposition of larger amount of *ex situ* C in comparison to smaller reduction on *in situ* C storage and effect of silvicultural management has insignificant effect on net C stock as it contributes only 1.6 % of the gross C stock (Gonzalez-Benecke et al. 2011). The study further added that e*x situ* C storage has huge contribution on net C stock as it accounts nearly 34% of the average net C stock. Extending rotation length higher than biological rotation length increases stand C stock density as 18-year-rotation has 7% lower net C density and 35-year-rotation has 4% more C in comparison to stand at rotation age 22 (Gonzalez-Benecke et al. 2011).

The inputs of the model include number of trees planted per ha, site index (m) at a reference age of 25 years , method of site preparation, method of weed control and fertilization treatment, and time and intensity of thinning and outputs include survival, basal area (m^2ha^{-1}), dominant height (m), quadratic mean diameter (cm), total stem volume (outside and inside bark, m^3ha^{-1}), as well as C contains in the trees, understory vegetation, forest floor and dead trees.

Gonzalez-Benecke et al. (2011) used the following formula to calculate the net C stock:

Net C stock (Mg ha-1)= Total C *in situ* (C stored in loblolly pine trees, understory, forest floor, coarse woody debris, and standing dead trees + Total C *ex situ* (C stored in wood products such as sawn timber, chip-n-saw, and pulp wood) – (Total C from silvicultural activities including transportation of forest products).

However, only total C *in situ* was considered for the analysis. The following formula was used for the analysis in order to calculate the C stock from the loblolly pine plantation as follows:

Total C stocks= Total C *in situ* (C stored in loblolly pine trees, understory, forest floor, coarse woody debris, and standing dead trees).

Initial site index was assumed to be 22 m at the age of 25 years for both planting intensity. Organic matter and forest floor decay rate was considered as 15%. Thinning intensity was assumed to be 33% percent of basal area of the plantation for the high intensity plantation but no thinning prescription was assumed for low intensity plantation. Table 3-1 provides the detail about the planting scenario and the assumption for both intensity of management.

Table 3-1. Management scenario and assumptions use in low and high intensity loblolly pine

Management prescription	Low intensity nonindustrial private landowners	High intensity private land owner/industrial plantation
Site index at 25 years (m)	22	22
Plantation density (Trees per ha)	1500 per ha	1500 per ha
Site preparation	Chopping, Piling, Disking, Bedding, Plantation	Chopping, Pilling, Burning, Disking, Bedding, Herbicide application, planting
Herbaceous weed control	No	Banded treatment at 1 and 2 year
Fertilization(Years)	No	1,5,12,18
First thinning (Years)	No	12
Second thinning (Years)	No	18
Rotation age (Years)	22	25

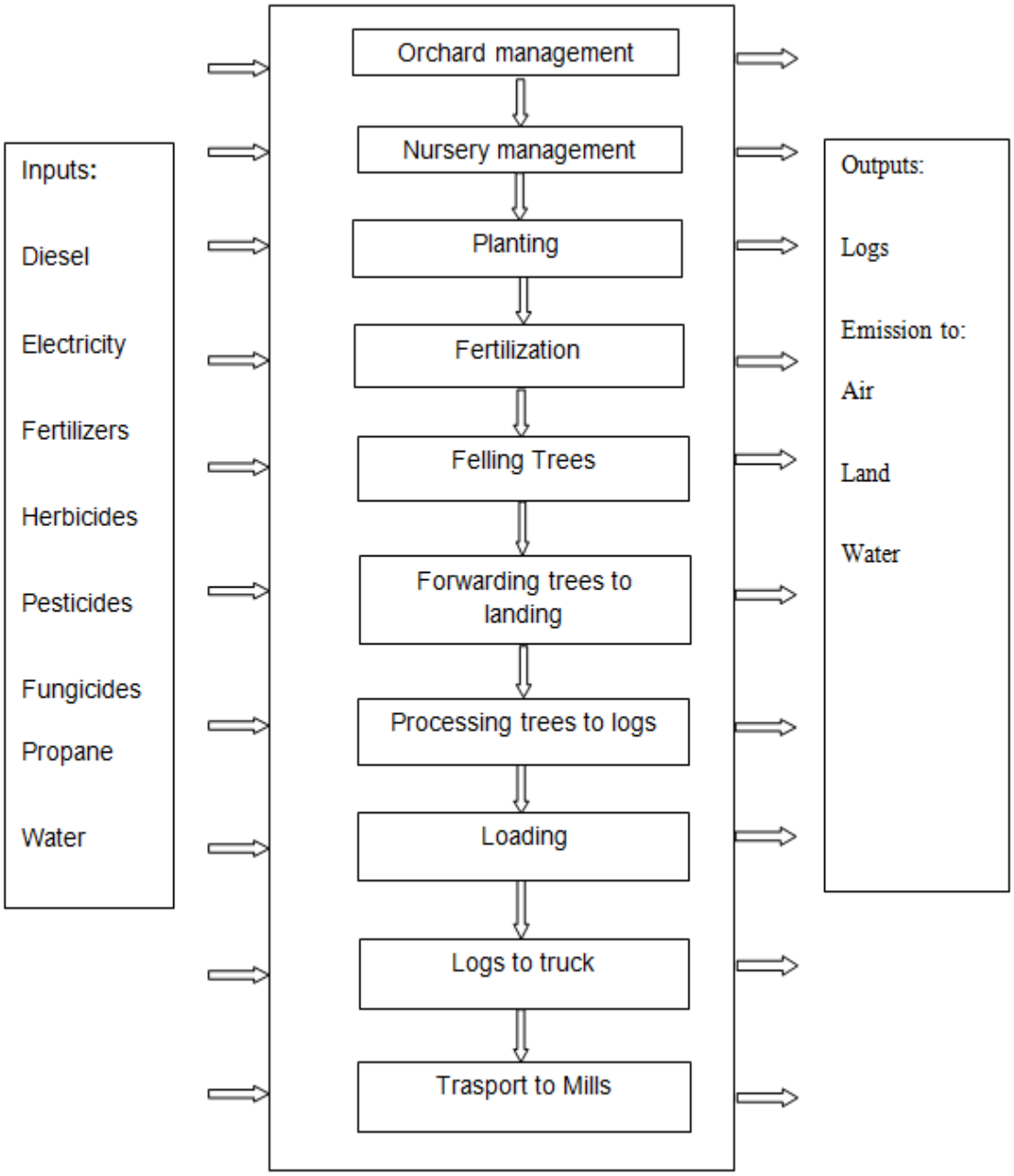

Figure 3-1. System boundary of the analysis

CHAPTER 4
RESULTS AND DISCUSSIONS

Results

Seed Orchard

Fuel use

Diesel is used for operating machineries for different management activities such as fertilizer application, herbicide application etc. Total diesel use for the required nursery area was found to be 8.5 liters.

Equipment use

Total material was found to be 1.14E-01 kg for required area of seed orchard. Composition of materials was found to be 7.06E-02, 1.27E-02, 1.28E-02, 7.89E-03, 3.32E-03, 2.74E-03, and 2.17E-03 kg for steel, iron, plastic, aluminum, glass, rubber, and copper, respectively.

Chemicals and water use

Nitrogen, phosphorus, and potassium are used with the total application rate of 713.5, 215.4, and 323.1 kg per hectare. The total amount of nitrogen, phosphorus, and potassium was found to be 1, 0.29, and 5 kg respectively per functional unit area of the orchard. Herbicides application of Goal and Fusilade, with the rate of 0.6 and 0.2 kg per hectare respectively. Total use of Goal and Fusillade was found to be 1.03E-02 and 1.26E-02 kg per required area of seed orchard respectively. Similarly, pesticide application of Asana and Chlorpyrifos was assumed with the rate of 0.1 and 0.3 kg per hectare. Asana and Chlorpyrifos are applied 1 times with total application of 1.01E-03 and 4.89E-03 kg in the required area respectively. Water is used for mixing herbicides and total water application was found to be 13 liters. Electricity is used for operating

equipment during seed processing. Total electricity for seed processing was found to be 5.21E-03 MJ.

Nursery Management

Fuel use

Diesel is used for operating machineries for different management activities such as site preparation, fertilizer application, herbicide application etc. Total diesel use for the required nursery area was found to be 0.1 liters.

Equipment use

Total material was found to be 9.52E-03 kg for hectare of plantation. Composition of materials used was found to be 5.87E-03, 1.06E-03, 1.07E-03, 6.57E-04, 2.76E-04, 2.29E-04, and 1.81E-04 kg of steel, iron, plastic, aluminum, glass, rubber, and copper respectively.

Chemicals and water use

Nitrogen, phosphorus, and potassium are used with the total application rate of 329, 55,181 kg per ha. The total amount of nitrogen, phosphorus, and potassium was found to be 7.53E-02, 1.26E-02, and 2.57E-02 kg respectively per functional unit area of the nursery. Herbicides application of Goal, Fusilade, and Cobra with the rate of 33.4, 1.4, 1.1 kg per ha respectively. Total use of Goal, Fusillade, and cobra with 8, 1 and 3 times was found to be 7.41E-03, 3.14E-04, and 2.57E-02 kg per required area of nursery respectively. Similarly, pesticide application of Asana and Chlorpyrifos was assumed with the rate of 1.7 and 1.1 per ha. Aasna and Chlorpyrifos are applied 5 and 1 times with total application of 1.67 and 1.11 kg for the required nursery area. Baytleton, Methylebromide, and Chloropicrin fungicides are applied with 3, 1 and 1 times with the application rate of 2, 976, and 175.7 kg per hectare. Baytleton is used

both as a seed treatment as well as foliar spray. Approximately, 4.72E-04 is used as a foliar spray whereas 7.85E-06 kg was applied for seed treatment. Methyl bromide and chloropicrin are applied with the rate of 395 and 71.1 kg per hectare and the total amount was found to be 2.24E-01and 4.03E-02 kg for the required nursery area. Water is used for irrigation and for mixing herbicides for application. Total water used was found to be 904.6 liters during the management of the nursery.

Plantation Management

Fuel use

Diesel is used to operate the machineries from site preparation to harvesting. In the low intensity management, total use of diesel was found to be 562.3 liters for site preparation and harvesting of the trees at the end of the rotation. In the high intensity management, total use of diesel was found to be 1279.5 liters. Also, gasoline is used for drip torch during the manual burning of the forest residues during site preparation. Total use of the gasoline was found to be 1.1 liters.

Equipment use

Various type of equipments such as tractors (Ford 3910 and Ford 7610) with necessary attachment, drip torch feller buncher, skidder, delimber, and loader etc. Total materials used in the plantation included the attachment used for different activities like fertilizer application, planting etc.

In the low intensity plantation, Total material was found to be 3.14E01kg for one hectare of plantation. Composition of materials used was found to be 1.94E01, 3.49, 3.5, 2.2, 9.12E-01, 7.55E01, and 5.97E01 of steel, iron, plastic, aluminum, glass, rubber, and copper. In the high intensity plantation, total material was found to be 5.48E01 kg for one hectare of plantation. Composition of materials used was found to

be 3.38E01, 6, 6.13, 3.8, 1.6, 1.3, and1of steel, iron, plastic, aluminum, glass, rubber, and copper respectively.

Chemicals and water use

Fertilizers and herbicides were assumed to be applied in high intensity management. The chemical inputs in the plantation include nitrogen, phosphorus, and potassium as fertilizers; and velar and glyphosate as herbicides. Nitrogen is applied at the rate of 44.9, 145.8, 224.3, and 224.3 kg/ha at the age of 1, 5, 12, and 18 respectively with the total amount of 639.2 kg/ha. Phosphorus is applied at the rate of 45, 28, 28, and 28 kg/ha at the age of 1, 5, 12, 18 respectively with the total amount 134.6 kg/ha. Potassium is applied at the rate of 56.1 kg/ha at the age 5. Velpar ULW is applied for site preparation with the rate of 6.7 kg/ha and it is also applied as herbicides at the age of 1 with the rate of 2.7kg/ha. In addition, banded application of glyphosate is applied with the rate of 11.1 kg ai/ha at the age of 2. Water used was found to be 561.7 liters per hectare for herbicide mixture.

Materials and Diesel Use in Transportation

Seed orchard to the nursery

The total weight of the seeds per functional unit of the plantation was 0.06 kg. Total material used per functional unit was found to be 6.31E-06, 1.14E-06, 1.15E-06, 7.06E-07, 2.97E-07, 2.45E-07, and 1.94E-07 kg for steel, iron, plastic, aluminum, glass, rubber, and copper, respectively. Total diesel use was found to be 1.20E-04 liters with a round trip distance of 80.5 km with an average fuel economy of 2.6km/liters.

Nursery to plantation site

The total weight of the seedlings per functional unit of the plantation was 61.2 kg. Total material used to transport 61.2 kg of seedling was found to be 6.55E-03, 1.18E-

03, 1.19E-03, 7.32E-04, 3.08E-04, 2.55E-05, and 2.02E-04 kg for steel, iron, plastic, aluminum, glass, rubber, and copper respectively. Total diesel use was found 0.15 liters with a round trip distance of 80.5 km with an average fuel economy of 2.6km/liters.

Low intensity plantation site to sawmill

The total weight of the logs per functional unit of the plantation was 278712.3 kg and semi-truck was assumed for the transportation of timber. Total material used to transport 278712.3 kg of wood was found to be 3.58E01, 6.43, 6.49, 4, 1.68, 1.39, and 1.1 kg of steel, iron, plastic, aluminum, glass, rubber, and copper respectively. Total diesel use was found 682 liters with a round trip distance of 193.2 km with an average fuel economy of 2.6km/liters. The total diesel used was found to be 26327.8 MJ.

High intensity plantation site to sawmill

The total weight of the logs per functional unit of the plantation was 493464 kg and semi- truck was assumed for the transportation of timber. Total material used to transport 493464 kg of wood was found to be 6.33E01, 1.14E01, 1.15E01, 7, 2.9, 2.5, and 1.9kg for steel, iron, plastic, aluminum, glass, rubber, and copper respectively. Total diesel use was found 1207.6 liters with a round trip distance of 193.2 km with an average fuel economy of 2.6km/liters. The total diesel used was found to be 46613.6 MJ.

Energy Use

Both transportation and plantation management had a higher contribution to the total energy used in both management scenarios. Diesel use in forest operation machineries and truck transportation had the major contribution. Total direct energy for low intensity plantation and transportation was found to be 21085 and 26327.7 MJ respectively. Similarly, total energy for high intensity of the plantation and transportation

was found to be 49377.8 and 46613.6 MJ respectively. Energy use for the nursery and seed orchard management was insignificant in both scenarios. Figure 4-1 provides the details about the direct energy use for low and high management scenarios of loblolly pine plantation.

Both transportation and plantation management had a higher contribution to the total embodied energy for both management scenarios. The embodied energy of fertilizers, diesels, materials, herbicides, insecticides, and other inputs were considered for the analysis. Diesel use in forest operation machineries and diesel use for transporting harvested timber had a major contribution in embodied energy. Total embodied energy for low intensity plantation and transportation was found to be 1721 and 9911.6 MJ respectively. Similarly, total embodied energy for high intensity plantation and transportation was found to be 40495.9 and 17548.8 MJ respectively. Embodied energy use for the nursery and seed orchard management was insignificant in both scenarios. Figure 4-2 provides the details about the embodied energy use for low and high management scenarios.

Considering both direct and embodied energy use for the complete management from seed orchard to the transportation to sawmill, low intensity management intensity needed 59454.4 MJ energy in comparison to high intensity plantation with total energy of 154444.7 MJ.

Material Use

Different equipments were used from seed orchard management to final harvesting and transportation of the timber into the mills. Total weight of different type of equipment used is shown in Table 4-1. Total use of the material for the complete management cycle including transportation for low and high intensity management

scenarios was found to be 87.9 and 154.6 kg respectively. The total amount of materials used in plantation and transportation of timber to the sawmill was found to be 30.9 and 56.9 kg for low intensity plantation whereas 53.7 and 100.7 kg for high intensity plantation. Most of the material used (61.7%) was steel (Burnham et al. 2006).

In low intensity plantations, composition of used materials used was found to be 7.46E01, 1.34E01, 1.36E01, 8.35, 3.51, 2.9, and 2.3 kg of steel, iron, plastic, aluminum, glass, rubber, and copper respectively. In high intensity plantations, composition of used materials was found to be 9.72E01, 1.75E01, 1.76E01, 1.09E01, 4.57, 3.78, and 2.99 kg of steel, iron, plastic, aluminum, glass, rubber, and copper respectively. Table 4-2 provides the detail about the total materials used and their composition during the different stages of the life cycle of low and high intensity plantation.

Environmental Impact

In the high intensity plantation, fertilizers, diesel used in forest operations equipment, and transportation were the factors with higher environmental impact. Fertilizers had the highest impact on carcinogenics, non carcinogenics, eutrophication, ozone depletions, and ecotoxicity impact categories. Figure 4-3 and Figure 4-4 provides the details about the environmental impact by sources in the high and low intensity of management.

Transportation, diesel used in forest operations equipment, and fertilizers were major sources of environmental impact in the low intensity management scenario. Transportation was the major contributor to global warming, acidification, carcinogenics, non carcinogenics, respiratory effects, eutrophication, and smog formation. Fertilize was the major sources of ecotoxicity whereas fumigant had a major impact on ozone depletion. The detail about the environmental impact by sources for low intensity

management is shown in Figure 4-4. The total environmental impact on each of the stages of the life cycle of low and high intensity loblolly pine management is shown in Table 4-4 and Table 4-3 respectively.

Global Warming Impact and Carbon Cost of Forest Management Activities

For high intensity of management scenario, sources of C emissions were mainly diesel use in the forest operation machinery, transportation and fertilizers. C emissions for site preparation, herbicides application, fertilization, thinning, and final harvesting was found to be 0.23, 0.05, 0.74, o.47, and 0.23 Mg ha^{-1} respectively. C emissions from seed orchard and nursery management were 9.29E-03 and 1.17E-03 Mg ha^{-1} respectively. Total C emissions from high intensity management were found to be 1.79 Mg ha^{-1}. Transportation from seed orchard to nursery and nursery to plantation area had negligible impact. Transportation from the harvesting site to saw mill for high intensity plantation produced 1.94 Mg ha^{-1} C. Considering the transportation throughout the life cycle between seed orchard to transportation to saw mill, total C emission from high intensity management was found to be 3.73Mg ha^{-1}. Table 4-5 provides the detail about global warming index of each activity and C emissions from each of the forest management operations in the high intensity management plantation. Table 4-7 provides the detail about the global warming impact and corresponding C emissions of transportation during the life cycle of the pine plantation

Most important source of C emissions for low intensity plantation was diesel fueled equipments during site preparation and final harvesting. Total C for site preparation and final harvesting was found to be 0.26 and 0.23 Mg ha^{-1} with total C of 0.51 Mg ha^{-1} for complete plantation management from seed orchard to final harvesting. Transportation from seed orchard to nursery and nursery to plantation area had

negligible value. Transportation from the harvesting site to saw mill for low intensity plantation produced 1.1 Mg ha^{-1} C. The detail about the global warming impact of forest management activities and corresponding C emissions in the low intensity management is shown in Table 4-6. Total C produced for the complete system boundary i.e. from seed orchard management to transportation of harvesting timber was found to be 1.61 Mg ha-1. Table 4-7 provides the detail about the global warming index and corresponding C emissions of transportation during the life cycle of the pine plantation.

Stem Volume and Carbon Yield from the Loblolly Pine Plantation

Total stand volume (over bark) from the low intensity management stand was found to be 328.4 m^3 per ha from 1035 trees at the end of the rotation. In order to consider the C present in a dead tree and forest floor, an average of 5 rotations was considered for each of the scenarios. Total vegetation C and C present in forest floor and dead trees were calculated separately. *In situ* C includes the understory C along with C present in loblolly pine, forest floor, and dead trees. Similarly, the total C content on vegetation and forest floor and dead trees was found to be 89.3 and 26.2 Mg ha^{-1} respectively with total *in situ* C of 116.4 Mg ha^{-1} at the end of 22 years. The annual *in situ* C production from the low intensity management scenario was 5 Mg ha^{-1}. Figure 4-6 provides the details about volume production and Figure 4-7 provides the details about the C present in vegetation, C in floor and dead trees, and total C throughout the rotation

Two thinning were assumed for the high intensity management scenario at the age of 12 and 18. In each thinning 33 percent of tree basal area was assumed to be removed. Total stem volume (over bark) removed at the first and second thinning was about 64.9 and 95.4 m3 ha-1, respectively, and total stem volume (over bark) extracted

at final harvest was found to be 421.1 m^3 per ha from 510 surviving trees. The total C content of living vegetation and forest floor and dead trees was found to be 109.26 and 33.8 Mg ha^{-1} respectively with total *in situ* C of 143.9 Mg ha^{-1} at the end of 25 years. The carbon removed during the thinning at age 12 and 18 was found to be 8.2 and 15.7 $Mgha^{-1}$. The annual *in situ* C production from the high intensity management scenario was 5.8 Mg ha^{-1}. Figure 4-8 provides the details about volume production and Figure 4-9 provides the details about the C present in vegetation, C in floor and dead trees, and total C throughout the rotation.

Discussion

It was found that diesel use in forest operation equipments, fertilizers, and transportation are the major sources of environmental impact. Most of the environmental impact was due to the transportation between harvesting site to mill in low intensity management. However, silvicultural management activities had a higher impact on respiratory, ozone depletion, and ecotoxicity. Fertilizer application had the highest percentage effect on most of the environmental impact categories in high intensity management except global warming, acidification, and smog. Fertilizers are a major source of impact on carcinogenic, non carcinogenic, eutrophication, ecotoxicity, ozone depletions, and respiratory effect. But, effect of fertilizer on the low intensity management is less compare to high intensity management. In the low intensity management, most of the environmental effects were due to transportation and diesel use during forest harvesting and site preparation stage. Even though transportation and diesel use in machinery had higher effect, the contribution of fertilizers increases when the management shifted to higher intensity management scenarios. Johnson et al. (2005) also found the same conclusions on a similar study done for the life cycle impact

assessment of forest activities. Other studies (Neupane et al. 2010, Kendall and Chang 2009, Garcia et al. 2009, Dwivedi 2012) concluded that the use of fertilizer has significant impacts on the environment

Nitrogen has a higher impact on environmental categories than phosphorus and potassium. Nitrogen has the highest impact on global warming impact, non carcinogenic, carcinogenics, respiratory effect, ecotoxicity, and smog formation whereas phosphorus had the highest impact on carcinogens and eutrophication effects. Nitrogen has a strong influence on environmental impact (Heller et al. 2002, Dwivedi et al. 2012).

The use of the fertilizer in the high intensity plantation is responsible for considerable emissions of N_2O. The total CO_2 equivalent emissions from fertilizer application were found to be 41.7% of the total CO_2 equivalent emissions. This can be reduced by using better techniques such as mixing as a nitrification inhibitor with the fertilizer which helps in controlling the release of N_2O (Freney 1997). In the low intensity management, diesel use on transportation and forest operation had the highest impact on most of the impact categories except ecotoxicity, ozone depletion, and non carcinogenics.

There should be better application rate of fertilizer in forest management to reduce its adverse effect on human health and effect on soil and water (Dwivedi 2011). Goyne et al. (2008) suggested efficient use of fertilizers to mitigate environmental nitrogen contamination. Nitrogen use efficiency can be improved by adopting fertilizer, soil, water and crop management practices which will enhance nitrogen uptake, minimize nitrogen losses, and optimize indigenous soil nitrogen supply. Availability of phosphorus is reduced by reaction with calcium and magnesium in high pH soils and iron and

aluminum in low pH soils and fertilizer use efficiency may be enhanced by products that reduce these phosphorus reactions (Grant and Wu 2008).

Diesel use during transportation, and silvicultural practices were major sources of environmental impact. The total global warming impact of diesel use for transportation and forestry operation was found to be more than 80% for high intensity management and almost 100% in the case of low intensity management. This result is consistent with other LCA studies for forest activities (Johnson et al. 2005, Machelson 2008, Neupane 2010, Berg and Lindholm 2003).

Using Ecoinvent and Franklin database and TRACI characterization factors, it was found that about 28 and 14.2 Kg CO_2 equivalent of GHGs were emitted into the atmospheres for each m^3 of timber in high and low intensity management respectively. The emissions were increased to 58.7 and 44.9 kg CO_2 equivalent per m^3 when considering the transportation to the mill in high and low intensity management respectively. It implied that a large part of GHG emissions was mainly released during transportation. Total emissions of transportation from seed orchard to nursery and from nursery to plantation site were minimal due to the weight of the seeds and seedling required to produce plants for 1 hectare plantation. The C cost from the silvicultural activities was found to be 2.03 and 1.55 $kgm^{-3}ha^{-1}$ for high and low intensity management scenarios. While considering transportation, C cost for high and low intensity management scenarios was found to be 4.9 and 6.43 $kgm^{-3}ha^{-1}$. Transportation and required diesel fuel used for operating tractor and harvesting machinery have the highest emissions (Aldentun 2001, Johnson et al. 2005). Neupaen (2011) and Berg and Lindholm (2005) also found that transportation accounts the highest GHGs emissions.

Michelsen et al. (2008) found that logging, transporting by a forwarder, and truck transportation have highest impact on emissions. The LCA study of pulp production from eucalyptus had found the diesel consumption as main source of environmental impact (Garcia et al. 2009). Logging and silviculture generate the highest level of emissions either related to fuel related (CO_2, So_x) or engine related (hydrocarbons, NO_x) (Berg and Lindholm, 2003).

Transportation contributed with 52.2% and 69.2% of the total GHGs emissions on the high and low intensity management scenarios, respectively. However, the distance between harvesting site to the mill (Johnson 2005, Neupane 2011, Michelsen et al. 2008) , loading factor, and loading size of timber affect the total environmental impact of transportation (Michelsen et al. 2008). The emissions due to the use of diesel can be reduced by using forest harvesting and operating equipments with better fuel efficiencies (Dwevidi 2011) or use of renewable fuels, improvement in engine design and better adjustment of engines to forest operations (Berg and Lindholm 2003). Also, transportation truck's fuel economy could be made efficient to reduce the emissions during the transportation.

It was found that energy use of high intensity plantation was about 271.9 MJ per m^3 and 158.2 MJ per m^3 with and without considering transportation, respectively. Energy use of low intensity management scenario was found to be 181.1 MJ per m^3 and 69.4 MJ per m3 with and without considering transportation, respectively. Considering the direct energy only, total energy used for the plantation and transportation was found to be about 144.3 and 168.9 MJ per m^3 for low and high intensity management scenarios, respectively. Energy use for silvicultural activities and transportation from the

harvesting site to the mill was 38% and 61% of low intensity and 58% and 42% of high intensity respectively. Berg and Lindholm (2003) study found that energy use of 150-200 MJ per m3 in the different Swedish forest comprises all operations including seedling production, silviculture, logging, and secondary transport to forest industries. Even though their study includes transportation of labor, machinery and supplies to the forest, it doesn't include most of the embodied energy including energy use for production of pesticides and production of machinery.

The correct application of machine operation by using larger harvesters for harvesting larger trees as larger harvesters consume more energy than a smaller harvester (Berg and Lindholm 2003) . Smaller machines can be used for thinning smaller trees. Another factor can also help in increasing the loading factor of trucks which eventually reduce the emissions and energy use during transportation. Commonly, return trips of trucks are unloaded which means loading factor of 50%. In order to get higher loading factor, the use of better route planning could be an effective option (Berg and Lindholm 2003).

Total C cost due to silviculture activities was found to be 1.24% and 0.43% of the *in situ* C produced during the respective rotation age of high and low intensity management. Sonne (2006) stated that there are 4.7% CO_2 equivalent GHG emissions of average C storage for Pacific Northwest coastal Douglas-fir plantation for 40 years. Similarly, this study found that the percent of emissions vary between 2.5% for 60 -yr rotation ages and 6.8% for 30-year rotation ages. While considering transportation, C cost was found to be 2.5% and 1.38% of the total *in situ* C in the high and low intensity management respectively. Markewitz (2006) estimated 2.6 Mg C ha^{-1} emissions from

silviculture activities for an intensive fiber farming operation of southern pine on a 25 year rotation from plantation to harvesting. However, forest harvesting machine rates are 3 times higher than this study but Markewitz (2006) found the low C use due to fertilization. Gonzalez-Benecke et al. (2011) stated that C cost due to silvicultural and harvest activities is about 1.6% of the total stand C stock in the loblolly pine. Similarly, C emissions due to silvicultural activities on the stand and transportation of log to the mill is about 2.2 to 2.3% of the gross C stock in the slash pine (Gonzalez-Benecke et al.2010).Dwivedi et al. (2012) found 1.76 Mg ha^{-1} C use from site preparation to harvesting of slash pine stand which is similar to the C cost for high intensity management to this study. Thinning operation had excluded in his study and emissions of nitrous oxide were calculated separately following (Bouwman 1996). In contrast, GWI calculation was completely based on characterization factor provided by TRACI on this research. The comparison of C cost of silvicultural activities from different studies is shown in the Figure 4-5.

Increasing the fuel efficiency of equipments used in the silvicultural activities and transportation could be the effective solution to reduce the GHGs emissions. Also, using the size and power capacity of the harvester with the tree size to be harvested decreases the fuel use consumption. Establishment of saw mill near to the bigger plantation size could reduce the emissions due to the transportation. Proper route planning during the transportation could increase the loading factor which eventually reduces the diesel consumption per m^3 timber during the transportation. Also use of the biofuel and other renewable source of energy during transportation, silvicultural

practices, and production of fertilizers, pesticides, and herbicides could reduce the total emissions.

Table 4-1. Total weight (kg) of equipment used

	Total weight
Feller buncher	12315.0
Skidder	16895.0
Delimber/load	14850.0
Ford 3910	2020.0
Ford 7610	2692.0
Tree shaker	2692.0
Dryer	350.0
Dewiner	270.0
Cleaner	1870.0
Size sorter	300.0
Weight sorter	300.0
Semi- truck trailer	13000.0
Drip Torch	2.4

Table 4-2. Material use (kg) of each of forest management activities in 1 hectare loblolly pine plantation

	Steel	Iron	Plastic	Aluminum	Glass	Rubber	Copper	Total
Seed orchard	7.06E-02	1.27E-02	1.28E-02	7.89E-03	3.32E-03	2.74E-03	2.17E-03	1.12E-01
TR[2]_orchard to nursery	6.31E-06	1.14E-06	1.15E-06	7.06E-07	2.97E-07	2.45E-07	1.94E-07	1.00E-05
Nursery	5.87E-03	1.06E-03	1.07E-03	6.57E-04	2.76E-04	2.29E-04	1.81E-04	9.34E-03
TR_nursery to plantation	6.55E-03	1.18E-03	1.19E-03	7.32E-04	3.08E-04	2.55E-04	2.02E-04	1.04E-02
Low intensity plantation	1.94E+01	3.49E+00	3.52E+00	2.17E+00	9.12E-01	7.55E-01	5.97E-01	3.08E+01
TR_plantation to mill	3.58E+01	6.43E+00	6.49E+00	4.00E+00	1.68E+00	1.39E+00	1.10E+00	5.69E+01
High intensity plantation	3.38E+01	6.08E+00	6.13E+00	3.78E+00	1.59E+00	1.31E+00	1.04E+00	5.37E+01
TR_plantation to mill	6.33E+01	1.14E+01	1.15E+01	7.08E+00	2.98E+00	2.46E+00	1.95E+00	1.01E+02
Total for low intensity	7.46E+01	1.34E+01	1.36E+01	8.35E+00	3.51E+00	2.90E+00	2.30E+00	1.19E+02
Total for high intensity	9.72E+01	1.75E+01	1.76E+01	1.09E+01	4.57E+00	3.78E+00	2.99E+00	1.55E+02

[2] TR= Transportation

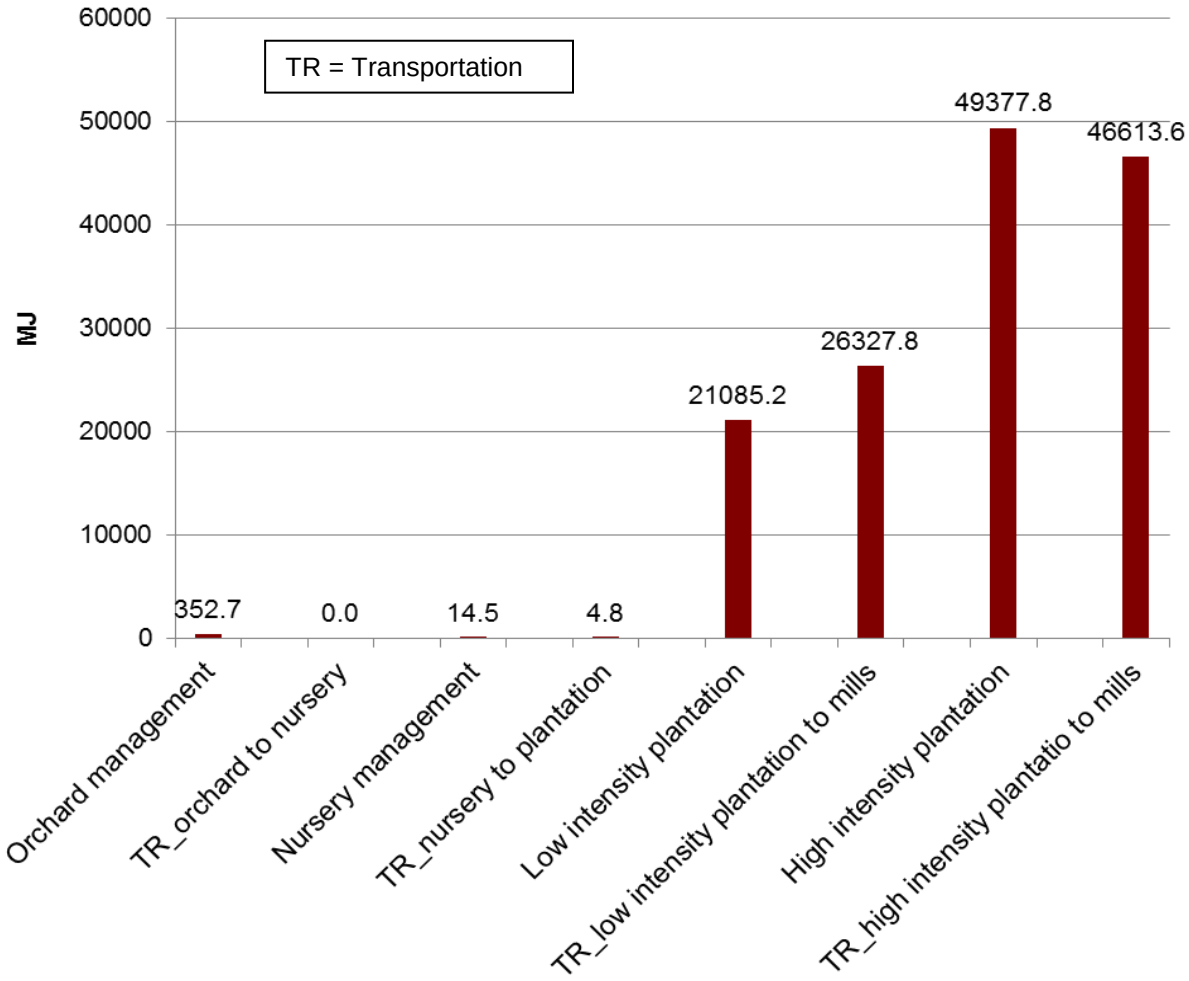

Figure 4-1. Direct energy use in 1 hectare low and high intensity management of loblolly pine plantation

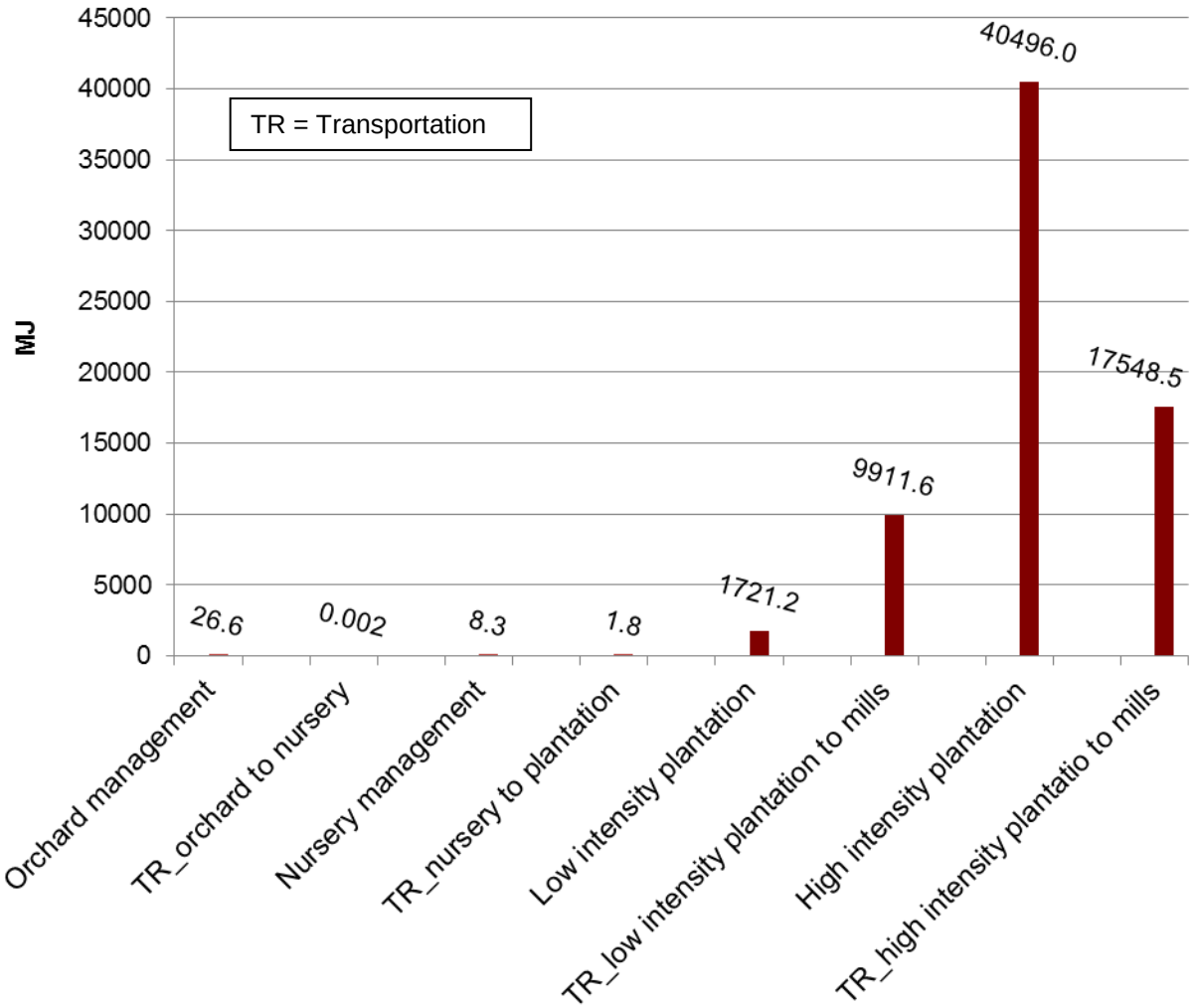

Figure 4-2. Indirect energy use in 1 hectare low and high intensity management of loblolly pine plantation

Table 4-3. Environmental impacts of life cycle of 1 hectare high intensity loblolly pine plantation

Impact Factors	Equivalent	Seed Orchard	TR[3] to Nursery	Nursery	TR to Plantation	Plantation	TR to Mill	Total
Global Warming Index	kg CO_2 eq	3.41E+01	1.26E-02	4.30E+00	2.09E+00	6.52E+03	7.16E+03	1.38E+04
	Relative contribution[4]	0.25	0.00	0.03	0.02	47.51	52.19	100.00
Acidification	H+ moles eq	2.48E+01	7.77E-03	2.25E+00	1.29E+00	4.39E+03	1.25E+04	1.70E+04
	Relative contribution	0.15	0.00	0.01	0.01	25.88	73.95	100.00
Carcinogenics	benzene eq	3.39E-02	3.42E-07	3.36E-03	5.68E-05	1.41E+01	5.53E-01	1.47E+01
	Relative contribution	0.23	0.00	0.02	0.00	95.98	3.77	100.00
Non Carcenogenics	toluene eq	2.63E+02	1.67E-03	2.18E+01	2.77E-01	1.17E+05	2.69E+03	1.20E+05
	Relative contribution	0.22	0.00	0.02	0.00	97.51	2.25	100.00
Respiratory effects	kg PM2.5 eq	3.23E-02	6.46E-06	9.68E-02	1.07E-03	8.58E+00	1.04E+01	1.91E+01
	Relative contribution	0.17	0.00	0.51	0.01	44.79	54.53	100.00
Eutrophication	kg N eq	1.05E-01	6.93E-06	4.50E-03	1.15E-03	4.10E+01	1.12E+01	5.23E+01
	Relative contribution	0.20	0.00	0.01	0.00	78.39	21.39	100.00
Ozone Depletion	kg CFC-11 eq	6.41E-07	6.74E-12	2.79E-06	1.12E-09	3.54E-04	1.09E-05	3.68E-04
	Relative contribution	0.17	0.00	0.76	0.00	96.11	2.96	100.00
Ecotoxicity	kg 2,4-D eq	4.52E+00	7.77E-06	7.20E-01	1.29E-03	1.98E+03	1.26E+01	2.00E+03
	Relative contribution	0.23	0.00	0.04	0.00	99.11	0.63	100.00
Smog	kg NOx eq	5.16E-01	1.58E-04	4.92E-02	2.62E-02	7.95E+01	2.55E+02	3.35E+02
	Relative contribution	0.15	0.00	0.01	0.01	23.74	76.08	100.00

[3] TR= Transportation

[4] Relative contribution = Percentage contribution of each of the management steps in each impact categories

Table 4-4. Environmental impacts of life cycle of 1 hectare low intensity loblolly pine plantation

Impact Factors	Equivalent	Seed Orchard	TR[5] to Nursery	Nursery	TR to Plantation	Plantation	TR to Mill	Total
Global Warming Index	kg CO_2 eq	3.41E+01	1.26E-02	4.30E+00	2.09E+00	6.52E+03	7.16E+03	1.38E+04
	Relative contribution[6]	0.58	0.00	0.07	0.04	29.81	86.55	100.00
Acidification	H+ moles eq	2.48E+01	7.77E-03	2.25E+00	1.29E+00	4.39E+03	1.25E+04	1.70E+04
	Relative contribution	0.29	0.00	0.03	0.01	17.25	82.42	100.00
Carcinogenics	benzene eq	3.39E-02	3.42E-07	3.36E-03	5.68E-05	1.41E+01	5.53E-01	1.47E+01
	Relative contribution	8.50	0.00	0.84	0.01	12.33	78.31	100.00
Non Carcenogenics	toluene eq	2.63E+02	1.67E-03	2.18E+01	2.77E-01	1.17E+05	2.69E+03	1.20E+05
	Relative contribution	12.89	0.00	1.07	0.01	11.45	74.57	100.00
Respiratory effects	kg PM2.5 eq	3.23E-02	6.46E-06	9.68E-02	1.07E-03	8.58E+00	1.04E+01	1.91E+01
	Relative contribution	0.44	0.00	1.31	0.01	18.14	80.10	100.00
Eutrophication	kg N eq	1.05E-01	6.93E-06	4.50E-03	1.15E-03	4.10E+01	1.12E+01	5.23E+01
	Relative contribution	1.34	0.00	0.06	0.01	18.18	80.41	100.00
Ozone Depletion	kg CFC-11 eq	6.41E-07	6.74E-12	2.79E-06	1.12E-09	3.54E-04	1.09E-05	3.68E-04
	Relative contribution	6.09	0.00	26.56	0.01	8.88	58.45	100.00
Ecotoxicity	kg 2,4-D eq	4.52E+00	7.77E-06	7.20E-01	1.29E-03	1.98E+03	1.26E+01	2.00E+03
	Relative contribution	33.67	0.00	5.36	0.01	8.20	52.77	100.00
Smog	kg NOx eq	5.16E-01	1.58E-04	4.92E-02	2.62E-02	7.95E+01	2.55E+02	3.35E+02
	Relative contribution	0.29	0.00	0.03	0.01	18.65	81.02	100.00

[5] TR= Transportation

[6] Relative contribution = Percentage contribution of each of the management steps in each impact category

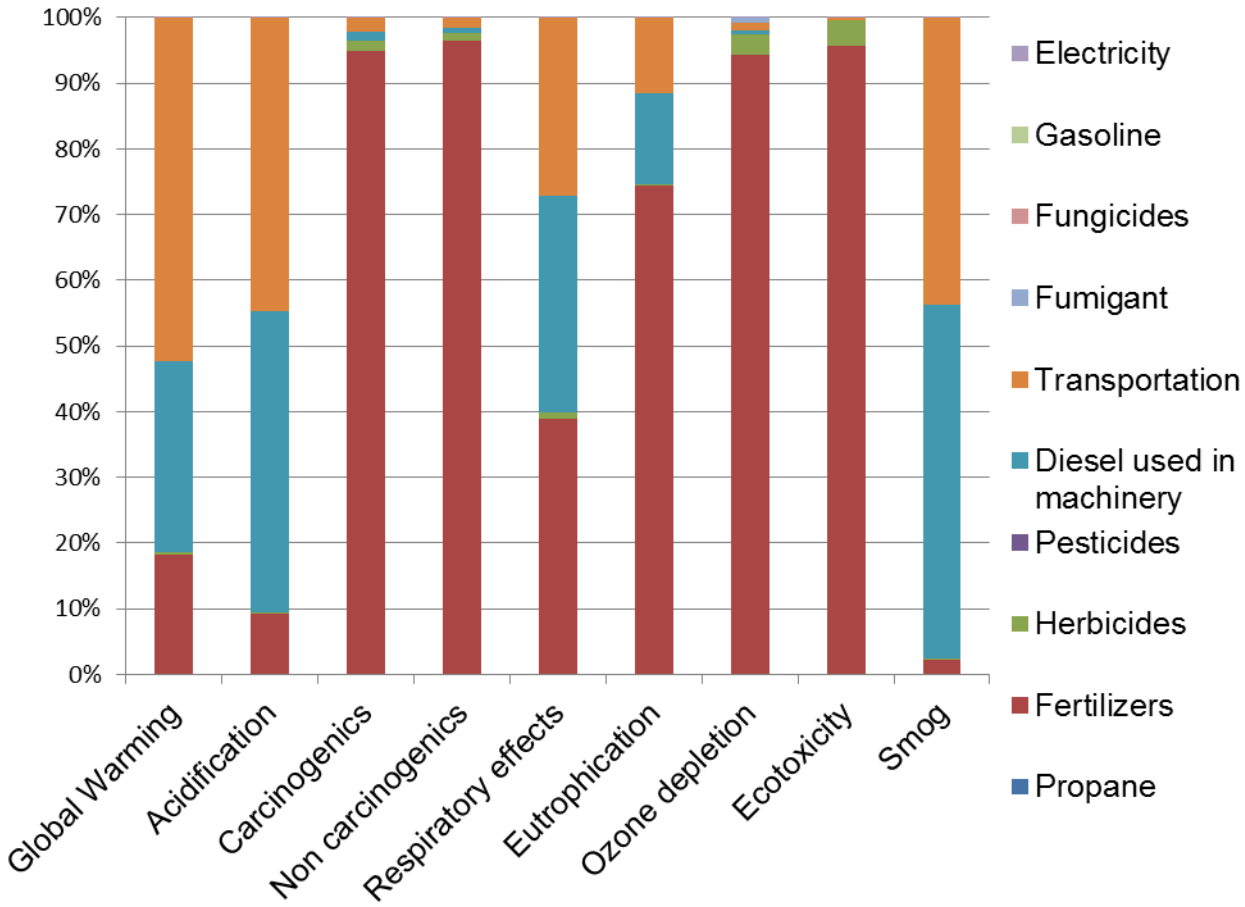

Figure 4-3. Environmental impacts by sources in the life cycle of 1 ha high intensity loblolly pine plantation

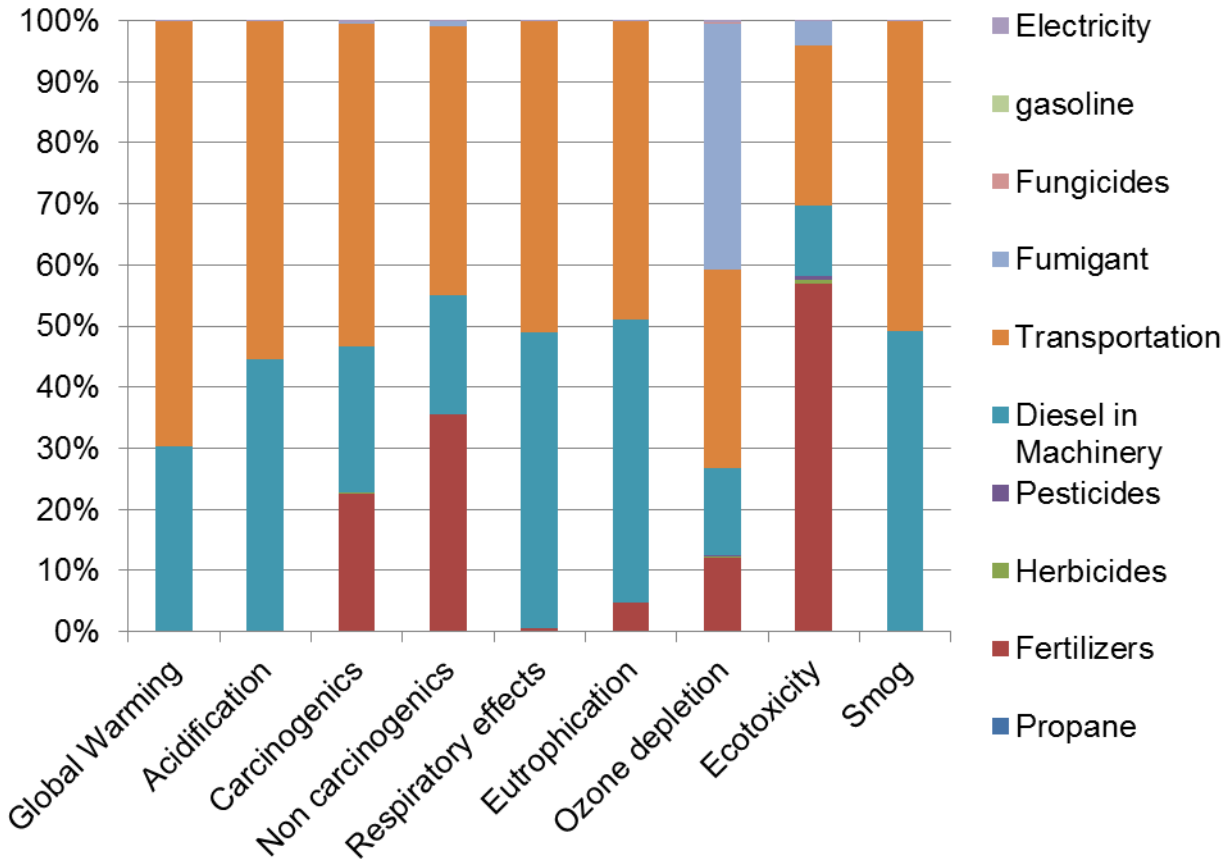

Figure 4-4. Environmental impacts by sources for the life cycle of 1 ha low intensity loblolly pine plantation

Table 4-5. Global warming Index and carbon emissions from high intensity plantation

	Global warming index (Kg CO_2 eq) in 1 ha	Carbon (Mg ha^{-1})	Carbon cost Kg m^{-3} ha^{-1}
Seed orchard	34.43	0.01	0.01
Nursery	4.35	0.00	0.00
Plantation			
Site Preparation			
Chopping	88.40	0.02	0.03
Piling	476.39	0.13	0.15
Burning	62.61	0.02	0.02
Disking	116.66	0.03	0.04
Bedding	116.66	0.03	0.04
Planting	184.16	0.05	0.06
Herbicides	174.36	0.05	0.05
Fertilization			
Nitrogen	2213.64	0.60	0.68
Phosphorus	453.57	0.12	0.14
Potassium	87.41	0.02	0.03
First thinning			
Felling	235.39	0.06	0.07
Skidding	314.85	0.09	0.10
Delimbing/loading	311.99	0.08	0.10
Second thinning			
Felling	235.39	0.06	0.07
Skidding	314.85	0.09	0.10
Delimbing/loading	311.99	0.08	0.10
Final harvesting			
Felling	235.39	0.06	0.07
Skidding	314.85	0.09	0.10
Delimbing/loading	311.99	0.08	0.10
Total	6599.25	1.79	2.03

Table 4-6. Global warming index and carbon emissions from low intensity plantation

	Global warming index (Kg CO_2 eq) in 1 ha	Carbon (Mg ha^{-1})	Carbon cost Kg m^{-3} ha^{-1}
Seed orchard	34.43	0.01	0.03
Nursery	4.35	0.001	0.00
Plantation			
Site Preparation			
Chopping	88.40	0.02	0.07
Piling	476.39	0.13	0.39
Disking	116.66	0.03	0.10
Bedding	116.66	0.03	0.10
Planting	184.16	0.05	0.15
Final harvest			
Felling	235.39	0.06	0.19
Skidding	314.85	0.09	0.26
Delimbing/loading	311.99	0.08	0.26
Total	1883.25	0.51	1.55

Table 4-7. Global warming Index and carbon emissions during transportation

Transportation	Global warming index (Kg CO_2 eq) in 1 ha	Carbon (Mg ha^{-1})	Carbon cost Kg m^{-3} ha^{-1}
Orchard to nursery	0.02	0.00	0.00
Nursery to plantation	2.12	0.00	0.00
Low intensity plantation to mill	4067.79	1.10	3.35
High intensity plantation to mill	7202.52	1.94	3.35

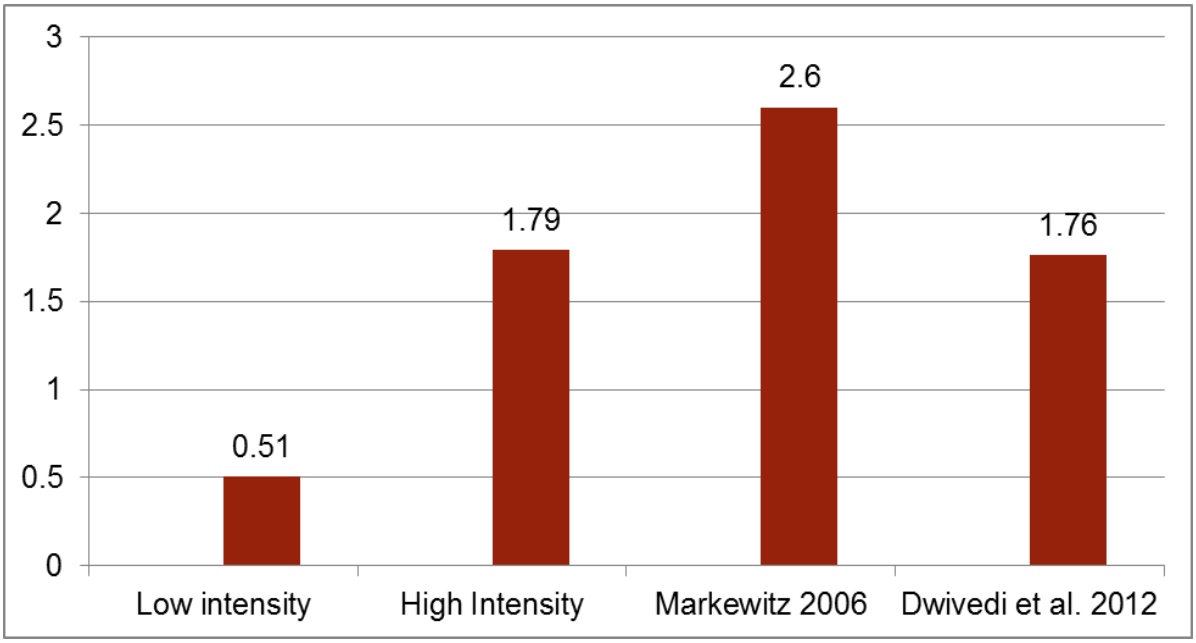

Figure 4-5. Comparison of C cost of silvicultural activities in different study

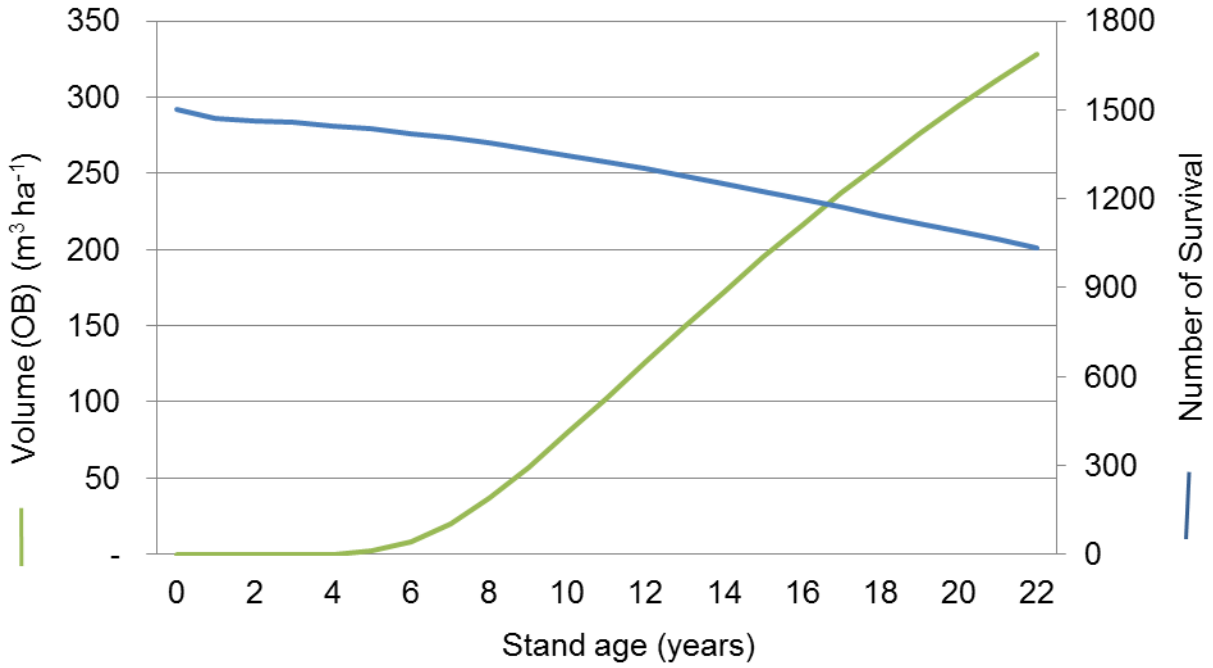

Figure 4-6. Trees per ha and stand volume for loblolly pine plantation under low intensity management for 22 years

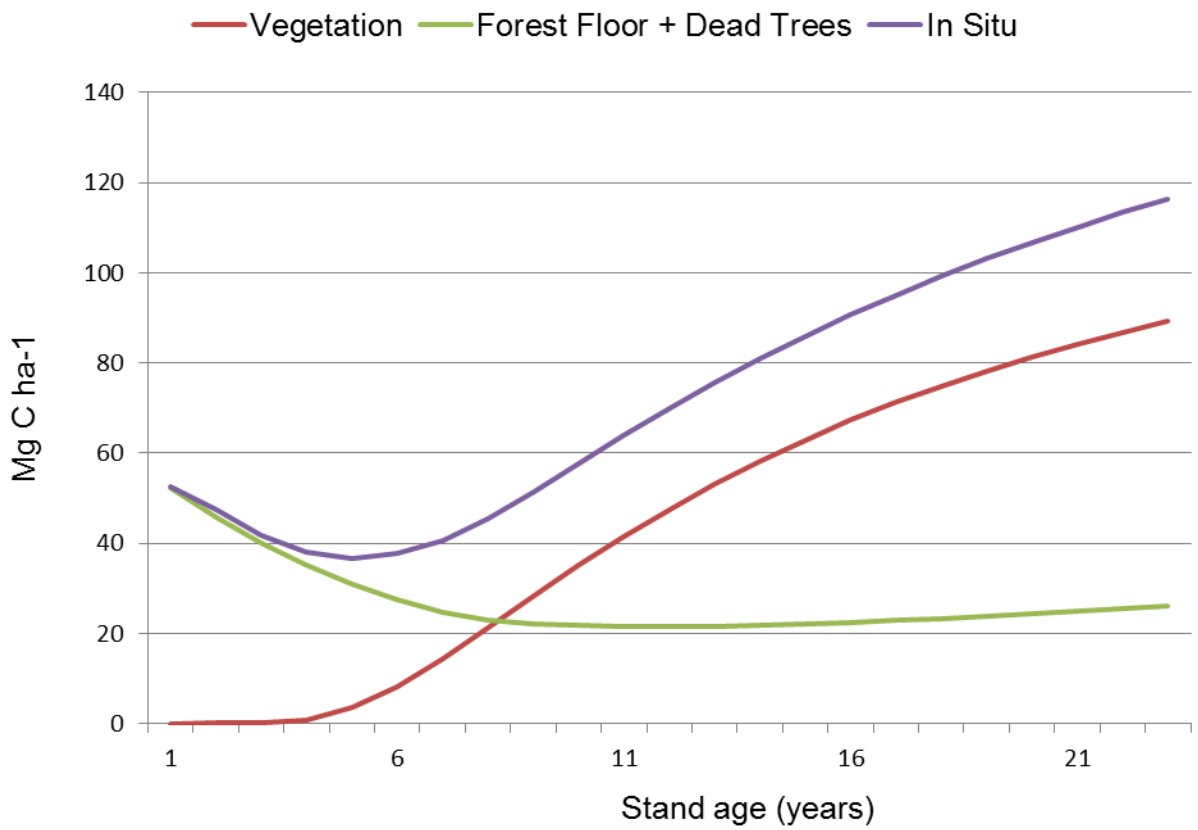

Figure 4-7. Carbon stock for loblolly pine plantation under low intensity management for 22 years

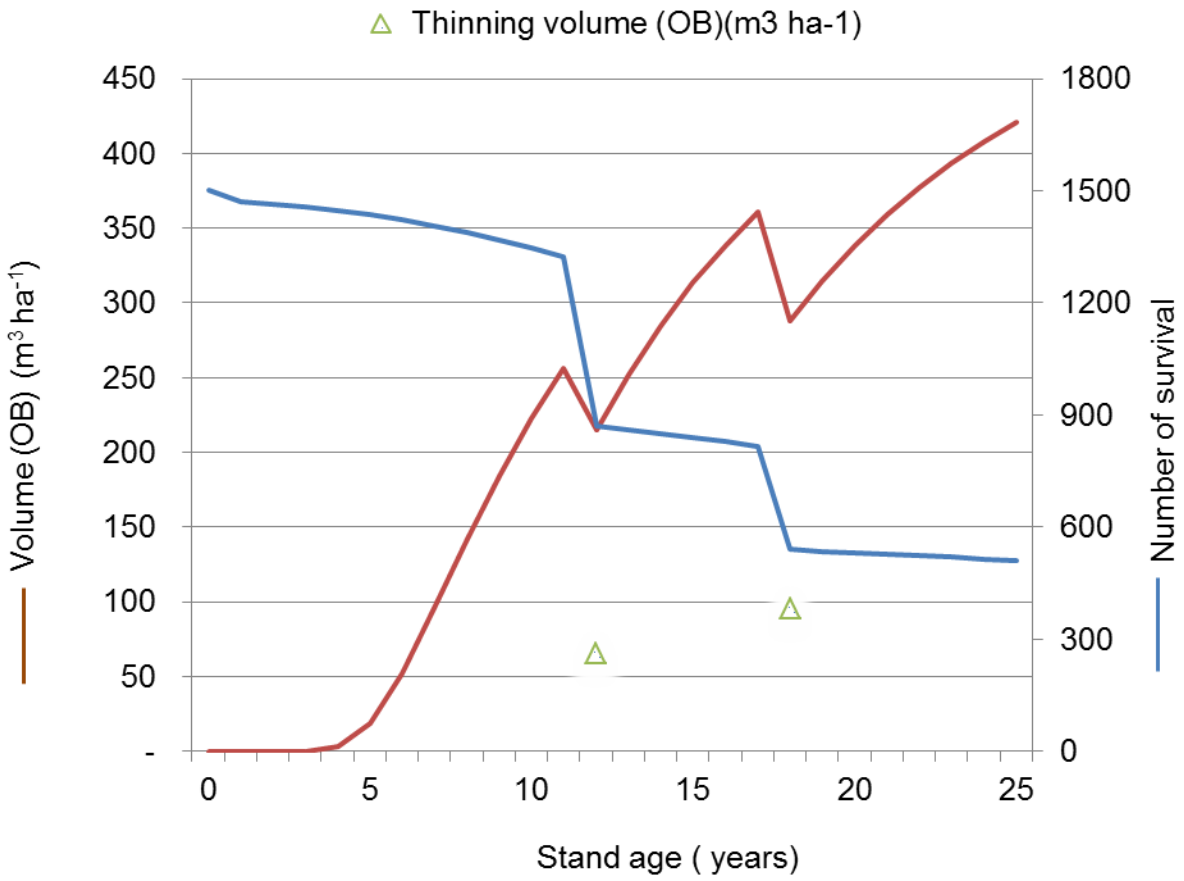

Figure 4-8. Trees per ha and stand volume for loblolly pine plantation under high intensity management for 25 years

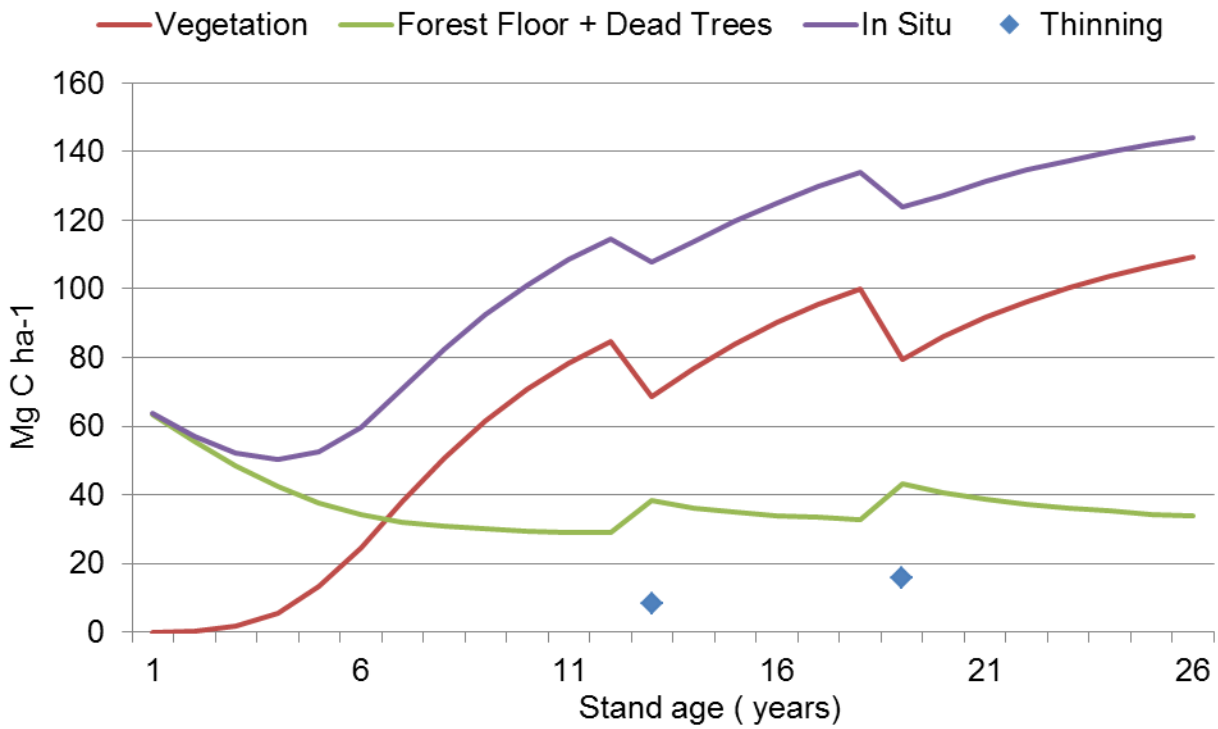

Figure 4-9. Carbon stock for loblolly pine plantation under high intensity management for 25 years

CHAPTER 5
SUMMARY AND CONCLUSION

This study analyzed the life cycle impact on *in situ* C sequestration of low and high intensity loblolly pine management in the southern United States. It used cradle to gate LCA approach to assess the environmental impact of loblolly management from seed orchard management to transportation of timber to the mill. A hybrid carbon balance model was used to calculate the total stem volume (OB) production and total in situ C production from the two scenarios of loblolly pine management. Ecoinvent and Franklin database available in SimaPro 7.1 LCA software were used and TRACI was used to characterize the inventory results into the impact category. Even though few studies has been done on LCA on forest activities in the United States, this study has importance among researcher because it specifically assesses the C emissions and environmental impact of loblolly pine, the most important planted species in the southern united states and one of the most widely planted species in forest plantation. It was found that C emission from silvicultural practices is minimal in comparison to in situ C production during the rotation age.

Diesel use in transportation and silvicultural practices consumed the highest amount of direct and indirect energy both intensity of management. Energy use from seed orchard and nursery management was insignificant. Energy use per m3 volume of timber for high intensity management was 2.3 times higher than low intensity management. Using the correct application of bigger harvesters for larger trees and smaller for thinning in the small trees could be an appropriate method to reduce energy use. An adjustment in the loading factor by using better route planning is another option

as it will reduce the energy use in the transportation. Most of the materials consumed were steel as equipments were assumed to be mainly composed of steel.

Fertilizers and diesel use in silviculture practice and transportation had highest environmental impact. Fertilizers had significant impact on carcinogenics, non carcinogenics, eutrophication, ozone depletion, and ecotoxicity impact categories. It was found that the fertilizer's contribution increases when the management shifts from lower to higher intensity of management. Among the three macro nutrient used, nitrogen has the highest impact on the highest number of environmental categories. Fertilizers contribute 41.7% of GHGs emission from silvicultural activities. The effect of nitrogen can be reduced by mixing as a nitrification inhibitor with fertilizer which helps in controlling the release of N2O. Forest management practices with the better application rate and efficient use of fertilizers to reduce the fertilizers' effect on the environment.

Major sources of GHG emissions are mainly diesel use in silvicultural activities and transportation to the mill. Seed orchard nursery management had minimal emissions. C cost for high intensity management was three times higher than low intensity management. Silvicultural activities had low impact on net C balance in the loblolly pine management. The total C cost due to silviculture activities was found to be 1.2% and 0.4% of the total in situ in high and low intensity management. When transportation from the harvesting site to the mill was taken into consideration, the contribution was found to be 2.5% and 1.38% of high and low intensity management

Increasing the fuel efficiency of equipments used in the silvicultural activities and transportation and using the size and power capacity of the harvesters with the tree size to be harvested decreases the fuel use consumption in the forest management

activities. If volume is only the objectives of management, low intensity of management should be done as it significantly reduces the CO2 emissions coupled with maintaining the production relatively same. Proper route planning during the transportation could increase the loading factor which eventually reduce the per m3 diesel consumption during the transportation. Also, use of the biofuel and other renewable source of energy during transportation, silvicultural practices, and production of fertilizers, pesticides, and herbicides could reduce the total emissions.

Conclusions

Loblolly pine, the most important forest species in the southern United States (Baker and Balmer 1983), management could be vital as forest in southeast and south central stores 13% and could have potential to capture $C0_2$ equivalent of 23% of the regional GHG emissions (Han et al. 2007). The study found that silviculture has low impact on net C balance in the loblolly pine management. However, C cost for highest intensity management has three times higher than low intensity management. Total volume for low and high intensity do not differ significantly for the same rotation age, thus, carbon emissions from transportation between low and high intensity does not have difference. If the volume production is the objective of forest management with less environmental impacts, low intensity management should be done to get lower CO2 emission from.

Diesel use in transportation and harvesting machinery has highest GHG emissions. Fertilization also has significant environmental effect. As fertilization also has contributed to CO2 emissions, the rate of application should be properly applied based on the expected quality and quantity of product. Efficient use of harvesting

machinery and truck to reduce the diesel consumption could reduce the diesel consumption and emissions due to forest management.

Limitation of the Study

Obtaining the data from multiple type of source adds uncertainty to the data's accuracy. Even though Franklin database is based on US, Ecoinvent database was used which is mainly based on European condition due to unavailability of the database that completely represents US. Some of the data were approximated which might have an effect on the final results of the analysis. The system boundary doesn't include process based LCA of various equipments used in the various forest activities. Even though loss of biodiversity is one of the major environmental impacts by forest operations, impact on biodiversity hasn't been assessed in this study. It should have included to get the holistic idea of forest management impact on biodiversity. The study didn't include the soil C for the total *in situ* C assessment. Soil C should have been included as it constitutes the larger amount of C within the forest.

This study only analyzed the life cycle of loblolly pine management from seed orchard to transportation of harvested logs to the saw mills. The completely cradle to grave life cycle of the woods including the waste wood treatment in landfills could give the real picture of net C balance of the management of the loblolly pine. It would be better to include the production process of forest products their use and the decomposition in the landfill in order to find out the net C balance of loblolly pine management. Studying LCA analysis of natural forest management could be fruitful to compare between the C cost and net C balance between intensive management and natural forest management.

APPENDIX A
LOBLOLLY PINE MANAGEMENT STEPS IN SOUTHERN UNITED STATES

Seed Orchard Management and Seed Collection

Different forest management activities are necessary in the seed orchard before the seed collection. Sub-soiling to the depths of 30 to 90 cm is necessary to reduce compaction by continuous use of machines and to enhance tree vigor. Subsoiling in the established stand should be done on one or two sides of the trees and precaution should be taken as it might damage the root of the seed tree. Subsoiling should be preceded by a rolling cutter to cut the rooms to prevent the surface roots from tearing away. Mowing is a common treatment in the seed orchard which helps in developing the healthy sod and increasing the benefits of fertilizers and water. Disking is also helpful to maintain the understory and to promote the rapid orchard growth. Disking should follow along the contour in the contour in order to reduce erosion. Fertilization application of nitrogen, phosphorous, potassium is done with the use of diesel tractor. Diesel tractor is also used for the application of herbicides and pesticides. Goal and Fusilade are the commonly used herbicides in the pine orchard whereas Asana and chlorpyrifos are used as pesticides. Necessary equipment is attached to the diesel tractor for the application of herbicides and pesticides.

Seed fall starts in October but mainly releases in November and early December. Time of collection and seed storage period affect yield and germination. The number of seeds releases from the cone increase with longer collection time and delayed in seed collection. Seed year is generally between 3 to 6 years however seed production varies with physiographic region, climatic condition, and stand condition. Seed is produced at the rate of 80,000 per acre from the good seed crop. Mechanical shaker attached with

diesel tractor is used to shake the loose cones in order to collect the seeds. After that, the seeds go through various processes before seeding it in the nursery.

Seeds are extracted from cones in forced draft kilns with temperature of 35°C to 40.5^{o}C as soon as cones open to release the seeds. To overcome the dormancy of the seed, stratification is done by putting seeds inside the burlap bags and layered in drums with sphagnum moss. After extracting seeds from cones, they are dewinged, cleaned, and dried (Barnett and Varela, 2003). Wings are removed by brushing and tumbling by mechanical dewingers. Empty seeds are removed before putting it into the store by using mechanical cleaning equipment or soaking into the water is an alternative method to seed sorting. As the seed size has important effects on germination even than seedling development sizing of the seeds is done to get the uniform rate of seed germination. Size and weight sorting should be done because smaller seeds have a slower rate of germination in comparison to larger seeds. The seeds are stored either in a burlap bag or crate storage with open conditions. It is recommended to store the seeds below 10% moisture and at subfreezing temperature (Barnett and McLemore 1970).

Transportation from Seed Orchard to Nursery

It was assumed that diesel fueled refrigerated semi-box trailer is used to transport seeds from seed orchard to the nursery for seedling production. The average two ways haul distance between plantation sites and saw mill was considered as 100 Miles (161 Kilometers).

Nursery Management

Seeds can be stored for a long time at subfreezing temperature with a high germination rate. Seeds can be stored between -17 to -21 ^{o}C up to 20 years. The seeds

should be removed from freezer at least 60 to 90 days before the average date of the last spring freeze. Then, it is soaked in water in a zip the jut bags and drain completely without completely making dry for 2-3 hours. Again, the seeds are put in the cooler at -7 ^{o}C for 7 days. In nursery, seeds are passed through stratification in which seeds are pretreated to simulate winter condition which is necessary for germination. Stratification by moist chilling at 1 to 5°C is essential to break seed dormancy stage.

Seedling in the south is generally done in the spring. Nursery bed is fumigated with methyl bromide and chloropicrin to control soil-borne pathogenic fungi, insects, nematodes, and weeds. Removing the contamination of fungus improves seed germination and seedling establishment in the nursery. However, loblolly pine has a lower level of fungi contamination in comparison to other pine species. Seedbed formation is the last steps before sowing seeds and. Vacuum seeder is used for seed sowing. Chopped or partially rotten pine needles, sawdust, bark is spread over the seed bed to prevent the displacement of seeds from wind, rain or irrigated water.

Mowing and plowing are done before the planting by a diesel powered tractor with additional equipment. Similarly, fertilization with N, P, K; bed shaping, and herbicide application is done by using diesel tractor with necessary equipment attachment. Commonly used herbicides are Goal, Fusillade, and Cobra whereas Asana and chlorpyrifos are used as insecticides. Bayleton fungicides are used for seed treatment as well as a foliar spray whereas methyl bromide and chloropicrin are also used as fungicides.

Transportation of Seedling from Nursery to Plantation Site

Transportation of seedling from nursery to planting sites in a refrigerated can with temperatures maintained between 1 ^{o}C to 7 ^{o}C. The average two ways haul distance between nursery and plantation was considered as 100 Miles (161 Kilometers).

Plantation Management

Mainly, chopping, pilling, burning, disking, bedding, herbicide application, and fertilizer application were identified as site preparation and management activities. During thinning and final harvesting, felling, skidding, delimbing, and loading to trucks were necessary management activities.

Site Preparation

The site should be prepared before the seedling establishment. The objectives of the site preparation are clearing the debris from the site, reducing the vegetation competition, and preparing the soil favorable for planting. Site preparation includes both mechanical and chemical treatments. Site preparation starts with chopping and piling of the logging debris and residual trees by using followed by burning. Burning is done with mechanical equipment attached to the diesel tractor as well as manual by a drip torch which is followed by disking and bedding. Disking is required to control competition while bedding increases the palantability as well as improves the soil tilth in the bed. Finally machine planting is done with the use of necessary equipment attached to diesel tractor.

Fertilization and Herbicides

Generally N, P, and K are applied for the loblolly pine plantation whereas boron (B), copper (Cu), and manganese (Mn) micronutrients are also used if necessary in problematic sites. There macro nutrients are applied during the rotation starting from the

year of plantation. In addition, fertilization is applied between 4 to 6 years, between 12 to 15 years after the first thinning, between 18 to 20 years after second thinning. Herbicide application is done using Velpar ULW and glyphosate. Velpar is used for site preparation as well as in the first year while glyphosate is applied during the first year of the plantation.

Thinning

The first thinning generally takes place between the years 12 to 15 with additional thinning after 5 to 8 year interval. Thinning includes cutting of targeted trees, dragging to the loading area, removing the branches, and loading to the trucks with the use of feller buncher, wheeled skidder, delimber, and loader respectively.

Final Harvesting

Forest harvesting normally includes five major steps: felling the standing, removing non merchantable limbs and tops and cutting trees into logs, skidding of the logs or trees from harvesting sites to the loading area, loading to the trucks and transportation to the nearby saw mill. Each activity requires larger feller buncher, skidder, delimber, and loader.

Transportation of Wood from Plantation to Saw Mill

Forest logs or timbers are transported from the harvesting site in a diesel fueled semi-truck to the saw mill. The average two-way haul distance between plantation sites and saw mill was considered as 120 Miles (193 Kilometers).

APPENDIX B
LIFE CYCLE ENVIRONMENTAL IMPACT CATEGORY

Global Warming Potential

It is the increase in the temperature of the earth's surface and atmosphere due to both natural and human induced causes. Mainly, it is due to increase concentration of GHGs in the atmosphere such as carbon dioxide, water vapor, methane, nitrous oxide, and ozone from human activities. Combustion of fossil fuel along with other industrial emission is considered as a major source of global warming, which is regarded as a major reason to change climate in these days. Global warming potential (GWP) is used by TRACI to calculate the potency of GHGs relative to CO_2 (IPCC 1996). The GWP is expressed in terms of CO_2 for the time of 100 years as recommended by the IPCC. It is expressed in global warming index which is calculated as:

$$\text{Global Warming Index} = \sum_{i} ei \times GWPi$$

Where, e_i is the emission in kilograms of the i substance and GWP_i is the global warming potential of the substance i.

Acidification

It is the process of increasing the concentration of hydrogen ion (H +) due to the addition of acids or other substances which increase the acidity in the environment Various chemical reactions due to natural processes in the soil and biological activities cause the increment in the soil acidity. Acid rain, fog, dust, and smoke are common causes of acidification deposition in air and water which are being transported from long distance. In fractures, lakes, streams, and rivers including all the living beings are damaged due to acidification. The acidification factors are expressed in H^+ mole

equivalent deposition per kilogram of emission. Factors for acidification are available for each step as characterization factors have different value based on the expected differences in total deposition in the difference location (Bare et al. 2003).

Eutrophication

Eutrophication is the process of increasing nutrients such as nitrates and phosphates in the aquatic ecosystem which results the increment of biological productivity and quantity of algae and weeds. Excessive use of nitrogen and phosphorus is the common cause of eutrophication in the United States (Bare et al 2003). Nitrogen mainly damages the coastal ecosystem whereas excessive use of phosphorus affects freshwater lakes and streams. In addition, foul odor or taste, death or poisoning of fish; and production of toxic chemicals to humans, marine mammals, and livestock. The characterization factors are the products of nutrient factor and transport factor which estimate the eutrophication potential for air or water per kilogram of chemicals released, relative to 1 kg nitrogen released to surface freshwater.

Ozone Depletion

Ozone depletion is the reduction of the protective ozone within the stratosphere due to the emissions of ozone- depleting substances. Chlorofluorocarbons (CFCs) and other contributory substances used as refrigerants, foal blowing agents, solvents, and halons are major ozone depleting substances. Ozone layer in the atmosphere prevents from skin cancer, and cataract which is due to the effect of harmful ultraviolet rays passing through the atmosphere. A steady decline in volume of ozone and creation of the ozone hole is the two phenomena that cause the threat to the earth. The ozone depletion potential is used to calculate the relative importance of CFSs, hydrochloroflucarbons (HFCs), and halons which contributes to the depletion of ozone.

Chemicals are characterized relative to CFC-11 in order to calculate ozone depletion potential of a chemical. Ozone depletion Index, final sum of ozone depletion potential shows the contribution of any chemical to ozone depletion.

$$\text{Ozone Depletion Index} = \sum_{i} ei \times ODPi$$

Where e_i is the emission in kilograms of substance i ODP_i is the ozone depletion potential of substance i.

Human Health Respirator Effects

Chronic and acute respiratory symptoms are related to ambient concentrations of particulate matter which are measured as total suspended particulates. In this impact category, different human health effects that are related to exposures to ambient particulates are aggregated (Bare et al. 2003).

Human Health Cancer and Non-cancer Effect

The relative toxicological concern of an emission in the context of human health is calculated based on human toxicity potentials (HTP) based on the inherent toxicity of a compound and its potential dose, which is a calculated index that reflects the potential harm of a unit of chemical released into the environment (Hertwich et al. 2000). In addition to respirator effects, TRACI has categorized human health impact into cancer and non-cancer human health impact which measure the potential of chemical released during the process into the environment to cause human cancer and non-cancer effects (Bare et al. 2003). HTP is used to weight emissions and aggregate in terms of a reference compound and total emissions can be evaluated in terms of benzene equivalents for carcinogenic impact and toluene equivalents for non-carcinogenic impact (Hertwich et al. 2002).

Smog Formation

Nitrogen Oxides (NO_x) and volatile organic compounds (VOCs) in the atmosphere form a complex network of photochemical reactions induced by ultraviolet light. The final products of this reaction such as ozone, proxy-acetyle nitrate (PAN), per-Oxy-benzoyl nitrate (PBN) are harmful to biotic community and it degrades the materials as well. In TRACI, characterization factors evaluate the smog formation impact category in terms of release of NO_x. The characterization for VOC_s and No_x includes the relative influence of individual VOCs on smog formation, and relative influence of Nox concentrations versus an average VOC mixture of smog formation.

Eco-toxicity

Eco-toxicity is expressed in ecological toxicity potential (ETP) which is expressed as the potential ecological harm of a unit quantity of chemical released into the environment. ETP establishes a rank of measure of potential ecosystem of harm for a large set of toxic industrial and agriculture chemicals. ETP is designed to capture the direct impacts of chemical emissions from industrial systems on the health of plant and animal species (Bare et al. 2003). It quantifies the combination of source of concentration and toxicity and includes two components namely, generic concentration to source ration for pollutant emissions and an impact to concentration. Generally, 2, 4-Dichlorophenoxyacetic acid is used as a reference substance to calculate ETP for characterization.

LIST OF REFERENCES

Aldentun, Y., 2002. Life cycle inventory of forest seedling production from seed to regeneration site. J. Clean. Prod.10, 47-55.

Allen, H.L., Fox, T.R., Campbell, R.G., 2005. What is ahead for intensive pine plantation silviculture in the South? South. J. Appl. For.29, 62-69

Athanassiadis, D., Lidestav, G., Nordfjell, T., 2002. Energy use and emissions due to the manufacture of a forwarder. Resour. Conserv. Recy. 34, 149-160.

Baker, J.B., Balmer, W.E., 1983. Loblolly pine. Silvicultural systems for the major forest types of the United States.Agric.Handb445, 148-152.

Bare, J., 2011. TRACI 2.0: the tool for the reduction and assessment of chemical and other environmental impacts 2.0. Clean Technologies and Environmental Policy13, 687-696.

Bare, J., Norris, G., Pennington, D., and McKone, T. 2003. The Tool for the Reduction and Assessment of Chemical and other Environmental Impacts. Journal of Industrial Ecology.6(3-4): 49-78.

Bare, J.C., Hofstetter, P., Pennington, D.W., de Haes, H.A.U., 2000. Midpoints versus endpoints: The sacrifices and benefits. The International Journal of Life Cycle Assessment5, 319-326.

Barnett, J., Varela, S., 2003. Producing high-quality slash pine seeds. Riley LE, Dumroese RK, Landis TL, technical coordinators.Proceedings of the national forest and conservation nursery associations—2002.Ogden (UT): USDA Forest Service, Rocky Mountain Re-search Station.Proceedings RMRS-P-28.p 52-56.

Barnett, J., McLemore, B., 1970. Storing southern pine seeds. J. For.68, 24-27.

Battle, M., Bender, M., Tans, P., White, J., Ellis, J., Conway, T., Francey, R., 2000. Global carbon sinks and their variability inferred from atmospheric O2 and δ13C. Science 287, 2467.

Berg, S., Karjalainen, T., 2003. Comparison of greenhouse gas emissions from forest operations in Finland and Sweden. Forestry76, 271.

Binkley, D., Brown, T.C., 1993. FOREST PRACTICES AS NONPOINT SOURCES OF POLLUTION IN NORTH AMERICA1. JAWRA Journal of the American Water Resources Association29, 729-740.

Birdsey, R.A., 1992. Carbon storage and accumulation in United States forest ecosystems. Notes.

Blasing, T., Smith, K., 2006. Recent greenhouse gas concentrations. Updated July.

Borders, B.E., Harrison, W.M., Adams, D.E., Bailey, R.L., Pienaar, L.V., 1990. Yield prediction and growth projection for site-prepared loblolly pine plantations in the Carolinas, Georgia, Florida, and Alabama. Univ.of Georgia PMRC Tech.Rep2,.

Bouwman, A., 1996. Direct emission of nitrous oxide from agricultural soils. Nutr. Cycling Agroecosyst.46, 53-70.

Brown, S., Sathaye, J., Cannell, M., Kauppi, P., 1996. Mitigation of carbon emissions to the atmosphere by forest management.

Burnham, A., Wang, M., and Wu, Y. 2006. Development and applications of GREET 2.7—the transportation vehicle-cycle model. Argonne National Laboratory,Chicago, IL.

Canadell, J.G., Raupach, M.R., 2008. Managing forests for climate change mitigation. Science320, 1456.

Cannell, M., Thornley, J., 2000. Modelling the components of plant respiration: some guiding principles. Annals of Botany85, 45.

Carey, B. 2001. Important pesticides and their uses for the production of southern pine seedlings. Summary for the auburn nursery cooperative survey 2001. Southern forest nursery management cooperative. Technical note 02-01.

Clutter, J.L., 1963. Compatible growth and yield models for loblolly pine. For. Sci.9, 354-371.

Corbett, E.S., Lynch, J.A., Sopper, W.E., 1978. Timber harvesting practices and water quality in the eastern United States. J. For.76, 484-488.

Cox, P.M., Betts, R.A., Jones, C.D., Spall, S.A., Totterdell, I.J., 2000. Acceleration of global warming due to carbon-cycle feedbacks in a coupled climate model. Nature408, 184-187.

Curran, M.A., 1996. Environmental Life-Cycle Assessment. McGraw-Hill, NY

Dale, V.H., Joyce, L.A., McNulty, S., Neilson, R.P., Ayres, M.P., Flannigan, M.D., Hanson, P.J., Irland, L.C., Lugo, A.E., Peterson, C.J., 2001. Climate change and forest disturbances. Bioscience51, 723-734.

Domke, G.M., Ek, A.R., Becker, D.R., Espeleta, J.F., D'Amato, A.W., Reich, P.B., Suh, S., Kilgore, M.A., Current, D.A., Hoganson, H.M., 2008. Assessment of carbon flows associated with forest management and biomass procurement for the Laskin Biomass Facility. University of Minnesota, St Paul, MN.

Dwivedi, P., Bailis, R., Stainback, A., Carter, D.R., 2012. Impact of payments for carbon sequestered in wood products and avoided carbon emissions on the profitability of NIPF landowners in the US South. Ecol. Econ.

Dwivedi, P., Alavalapati, J.R.R., Lal, P., 2009. Cellulosic ethanol production in the United States: Conversion technologies, current production status, economics, and emerging developments. Energy for Sustainable Development13, 174-182.

Dwivedi, P., Nesbit, T.S., Lindner, A.S., Alavalapati, J.R.R., 2008.Life cycle and cost beneifit analyses of ethanol production from slash pine (Pinus Elliottii) plantations.SOFEWS 193.

Echeverría, M.E.M., Morris, D., Hendrick, L.A., Ronald, L., 2004. Soil organic matter fractions under managed pine plantations of the southeastern USA. Soil Sci. Soc. Am. J.68, 950.

Elliott GP, Baker WL 2004. Quaking aspen (Populustremuloides Michx.) at treeline: a century of change in the San Juan Mountains, Colorado, USA. J Biogeogr 31:733-745

Forsberg, G., 2000. Biomass energy transport analysis of bioenergy transport chains using life cycle inventory method. Biomass Bioenergy 19 (1), 17-30.

Fox, T.R., Jokela, E.J., Allen, H.L., 2004. The evolution of pine plantation silviculture in the southern United States. Notes.

Freney, J., 1997. Emission of nitrous oxide from soils used for agriculture. Nutr. Cycling Agroecosyst. 49, 1-6.

Freppaz, D., Minciardi, R., Robba, M., Rovatti, M., Sacile, R., Taramasso, A., 2004. Optimizing forest biomass exploitation for energy supply at a regional level. Biomass Bioenergy 26, 15-25.

Gan J 2004 Risk and damage of southern pine beetle outbreaks under global climate change. For Ecol Manage 191(1–3):61-71.

Gonzalez-Benecke, C., Martin T., Jokela E., De La Torre R., 2011. A flexible hybrid model of life cycle carbon balance forloblolly pine (Pinus taeda L.) management systems. Forests 2(3):749-776.

Gonzalez-Benecke, C.A., Martin, T.A., Cropper Jr, W.P., Bracho, R., 2010. Forest management effects on in situ and ex situ slash pine forest carbon balance. For. Ecol. Manage.260, 795-805.

González-García, S., Hospido, A., Moreira, M.T., Romero, J., Feijoo, G., 2009. Environmental impact assessment of total chlorine free pulp from Eucalyptus globulus in Spain. J. Clean. Prod.17, 1010-1016.

Gorte, R.W., 2009. Carbon Sequestration in Forests. DIANE Publishing, .

Gundersen, P., Schmidt, I.K., Raulund-Rasmussen, K., 2006. Leaching of nitrate from temperate forests effects of air pollution and forest management. Env. Rev.14, 1-57.

Han, F.X., Plodinec, M.J., Su, Y., Monts, D.L., Li, Z., 2007. Terrestrial carbon pools in southeast and south-central United States. Clim. Change84, 191-202.

Harmon, M.E., Ferrell, W.K., Franklin, J.F., 1990. Effects on carbon storage of conversion of old-growth forests to young forests. Science 247, 699.

Harmon, M.E., Ferrell, W.K., Franklin, J.F., 1990. Effects on carbon storage of conversion of old-growth forests to young forests. Science 247, 699.

Harrison, W., Borders, B., 1996. Yield prediction and growth projection for site-prepared loblolly pine plantations in the Carolinas, Georgia, Alabama and Florida. Plantation Manage.Res.Coop.Tech.Report1,.

Haynes, R.W., 2002. Forest management in the 21st century: changing numbers, changing context. J. For.100, 38-43.

Heller, M.C., Keoleian, G.A., Volk, T.A., 2003. Life cycle assessment of a willow bioenergy cropping system. Biomass Bioenergy25, 147-165.

Hertwich, E.G., Mateles, S.F., Pease, W.S., McKone, T.E., 2001. Human toxicity potentials for life-cycle assessment and toxics release inventory risk screening. Environmental Toxicology and Chemistry20, 928-939.

Houghton, J.T., 1996. Climate Change 1995: The Science of Climate Change. Cambridge Univ Pr, .

Hoover, C., Magrini, K., Evans, R., 2002. Soil carbon content and character in an old-growth forest in northwestern Pennsylvania: a case study introducing pyrolysis molecular beam mass spectrometry (py-MBMS). Environmental Pollution116, S269-S275.

Houghton, J.T., 1996. Climate Change 1995: The Science of Climate Change. Cambridge Univ Pr, .

Johnsen, K., Teskey, B., Samuelson, L., Butnor, J., Sampson, D., Sanchez, F., Maier, C., McKeand, S., 2004. Carbon Sequestration in loblolly pine plantations: Methods, limitations, and research needs for estimating storage pools. Notes.

Johnsen, K.H., Wear, D., Oren, R., Teskey, R.O., Sanchez, F., Will, R., Butnor, J., Markewitz, D., Richter, D., Rials, T., 2001. Meeting global policy commitments: carbon sequestration and southern pine forests. J. For.99, 14-21.

Johnson, D.W., Curtis, P.S., 2001. Effects of forest management on soil C and N storage: meta analysis. For. Ecol. Manage.140, 227-238.

Johnson, L.R., Lippke, B., Marshall, J.D., Comnick, J., 2005. Life-cycle impacts of forest resource activities in the Pacific Northwest and Southeast United States. Wood Fiber Sci.37, 30-46.

Jokela, E.J., Dougherty, P.M., Martin, T.A., 2004. Production dynamics of intensively managed loblolly pine stands in the southern United States: a synthesis of seven long-term experiments. For. Ecol. Manage.192, 117-130.

Karl TR, Melillo JM, Peterson TC (eds) 2009. Global climate change impacts in the United States. Cambridge University Press, Cambridge

Knoepp, J.D., Swank, W.T., 1997. Forest management effects on surface soil carbon and nitrogen. Forest61,.

Ladha, J.K., Pathak, H., J Krupnik, T., Six, J., van Kessel, C., 2005. Efficiency of fertilizer nitrogen in cereal production: retrospects and prospects. Adv. Agron.87, 85-156.

Lal, P., Alavalapati, J.R.R., Mercer, E.D., Socio-economic impacts of climate change on rural United States. Mitigation Adapt. Strat. Global Change 1-26.

Lal, R., 2005. Forest soils and carbon sequestration. For. Ecol. Manage.220, 242-258.

Lippke, B., Marshall, J.D., Comnick, J., Contributors, T.F., 2010. FOREST RESOURCES-PACIFIC NORTHWEST AND SOUTHEAST.

Liski, J., Pussinen, A., Pingoud, K., Makipaa, R., Karjalainen, T., 2001. Which rotation length is favourable to carbon sequestration? Canadian Journal of Forest Research31, 2004-2013.

Matney, T.G., Farrar, R.M., 1992. A thinned/unthinned loblolly pine growth and yield simulator for planted cutover site-prepared land in the Mid-Gulf South. South. J. Appl. For.16, 70-75.

Malmsheimer, R.W., Heffernan, P., Brink, S., Crandall, D., Deneke, F., Galik, C., Gee, E., Helms, J.A., McClure, N., Mortimer, M., 2008. Forest management solutions for mitigating climate change in the United States. J. For.106, 115-118.

Markewitz, D., 2006. Fossil fuel carbon emissions from silviculture: Impacts on net carbon sequestration in forests. For. Ecol. Manage.236, 153-161.

Masera, O.R., Garza-Caligaris, J., Kanninen, M., Karjalainen, T., Liski, J., Nabuurs, G., Pussinen, A., De Jong, B., Mohren, G., 2003. Modeling carbon sequestration in afforestation, agroforestry and forest management projects: the CO2FIX V. 2 approach. Ecol. Model.164, 177-199.

McCarthy, J.J., 2001. Climate Change 2001: Impacts, Adaptation, and Vulnerability: Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge Univ Pr, .

Michelsen, O., Solli, C., Strømman, A.H., 2008. Environmental impact and added value in forestry operations in Norway. J. Ind. Ecol.12, 69-81.

Motavalli, P. P., Goyne, K. W., and Udawatta, R. P. 2008. Environmental impacts of enhanced-efficiency nitrogen fertilizers. Online. Crop Management doi:10.1094/CM-2008-0730-02-RV.

Nair, P.K.R., Kumar, B.M., Nair, V.D., 2009. Agroforestry as a strategy for carbon sequestration. Journal of Plant Nutrition and Soil Science172, 10-23.

Neupane, B., Halog, A., Dhungel, S., 2011. Attributional life cycle assessment of woodchips for bioethanol production. J. Clean. Prod.19, 733-741.

Oneil, E.E., Johnson, L.R., Lippke, B.R., McCarter, J.B., McDill, M.E., Roth, P.A., Finley, J.C., 2010. Life-cycle impacts of inland northwest and northeast/north central forest resources. Wood Fiber Sci.42, 29-51.

Pennington, D.W., Potting J., Finnveden, G., Lindeijer, E., Jolliet, O., Rydberg, T., Rebitzer, G, 2004. Life cycle assessment part 2: Current impact assessment practice. Environmental International Vol. 30 Issue 5, 721-739.

Peter, G.F., 2008. Southern Pines: A Resource for Bioenergy. Genetic Improvement of Bioenergy Crops 421-449.

Phillips, O.L., Malhi, Y., Higuchi, N., Laurance, W.F., Núnez, P.V., Vásquez, R.M., Laurance, S.G., Ferreira, L.V., Stern, M., Brown, S., 1998. Changes in the carbon balance of tropical forests: evidence from long-term plots. Science282, 439.

PR'e Consultants 2011. SimaPro software available at http://www.pre-sustainability.com/content/simapro-lca-software accessed on July 15 2011.

Prestemon, J.P., Abt, R.C., 2002. TIMBR-1: Timber products supply and demand. Southern Forest Resource Assessment. 625.

Richter, K., 1995. Life cycle analysis of wood products. LIFE-CYCLE ANALYSIS 69.

Samuelson, L.J., Johnsen, K., Stokes, T., 2004. Production, allocation, and stemwood growth efficiency of Pinus taeda L. stands in response to 6 years of intensive management. For. Ecol. Manage.192, 59-70.

Scott MJ, Huang YJ (2007) Effects of climate change on energy use in the United States. In: Wilbanks TJ, Bhatt V, Bilello DE et al (eds) Effects of climate change on energy production and use in the United States. Synthesis and Assessment Product 4.5. U.S. Climate Change Science Program, Washington, pp 8–44

Schultz, R.P., 1997. Loblolly pine: the ecology and culture of loblolly pine (Pinus taeda L.). Agriculture Handbook (Washington).

Sedjo, R., Sohngen, B., 2000. Forestry Sequestration of CO2 and markets for timber. Resources for the Future 00-35.

Sedjo, R.A., 1989. Forests to offset the greenhouse effect. Journal of Forestry;(USA)87,.

Sedjo, R.A., 2001. Forest carbon sequestration: some issues for forest investments. Resources for the Future Discussion Paper 01-34.

Sedjo, R.A., Sampson, R.N., Wisniewski, J., 1997. Economics of Carbon Sequestration in Forestry. CRC, .

Seppälä, J., Melanen, M., Jouttijärvi, T., Kauppi, L., Leikola, N., 1998. Forest industry and the environment: a life cycle assessment study from Finland. Resour. Conserv. Recycling23, 87-105.

Siry, J.P., Greene, W.D., Harris, T., Izlar, R.L., Hamsley, A.K., Eason, K., Tye, T., Baldwin, S.S., Hyldahl, C., 2006. Wood Supply Chain Efficiency and Fiber Cost: What Can We Do Better? For. Prod. J.56, 4.

Sonne, E., 2006. Greenhouse gas emissions from forestry operations. J. Environ. Qual.35, 1439-1450.

Smith P, Martino D, Cai Z et al 2007. Agriculture. In: Metz B, Davidson OR, Bosch PR et al (eds) Climate Change 2007: mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge

Smith, W.B., Miles, P.D., Vissage, J.S., Pugh, S.A., 2004. Forest Resources of the United States, 2002. North Central Forest Experiment Station, Forest Service, US Dept. of Agriculture, .

Spatari, S., Zhang, Y., MacLean, H.L., 2005. Life cycle assessment of switchgrass-and corn stover-derived ethanol-fueled automobiles. Environ. Sci. Technol.39, 9750-9758.

South, D.B., Zwolinksi, J.B., 1996. Chemicals used in southern forest nurseries. South. J. Appl. For.20, 127-135.

Sullivan, A.D., Clutter, J.L., 1972. A simultaneous growth and yield model for loblolly pine. For. Sci.18, 76-86.

Stanturf, J.A., Kellison, R.C., Broerman, F., Jones, S.B., 2003. Productivity of southern pine plantations: where are we and how did we get here? J. For.101, 26-31.

Sullivan, A.D., Clutter, J.L., 1972. A simultaneous growth and yield model for loblolly pine. For. Sci.18, 76-86.

Ueda, H., Miyauchi, T., Tsujimura, T., 2003. Application of lifecycle assessment to Shinkansen vehicles and cross ties in Japan. J. Rail Rapid Transit 217, 271-278

USDA Forest Service., 1988. The South's fourth forest: alternatives for the future. .

Wakeley, P.C., 1954. Planting the southern pines. Agric.Monogr18,.

Wear, D.N., Greis, J.G., 2002. Southern forest resource assessment: summary of findings. J. For.100, 6-14.

White, M.K., Gower, S.T., Ahl, D.E., 2005. Life cycle inventories of roundwood production in northern Wisconsin: Inputs into an industrial forest carbon budget. For. Ecol. Manage.219, 13-28.

Williams, M., 1989. Americans and their Forests. Cambridge University Press, .

Woodbury, P.B., Smith, J.E., Heath, L.S., 2007. Carbon sequestration in the US forest sector from 1990 to 2010. For. Ecol. Manage.241, 14-27

Worrell, R., Hampson, A., 1997. The influence of some forest operations on the sustainable management of forest soils—a review. Forestry70, 61-85.

Yanai, R.D., Currie, W.S., Goodale, C.L., 2003. Soil carbon dynamics after forest harvest: an ecosystem paradigm reconsidered. Ecosystems6, 197-212.

BIOGRAPHICAL SKETCH

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