ABSTRACT

GHARIS, LAURIE WILSON. A Compromise Programming Approach to Effectively Value and Integrate Forest Carbon Sequestration into Climate Change Policy. (Under the direction of Dr. Joseph Roise).

Connections between increasing levels of greenhouse gases and the current rise in the global average temperate have led to greater concerns in developing effective climate change policies. Forests and wood products have been identified as important mechanisms for carbon sequestration and storage. However, policies often do not include the harvested wood products or substitution. Without harvests, forests will reach a point of saturation and more energy intensive products will be utilized.

This dissertation focused on how compromise programming can be employed to simultaneously consider multiple objectives of economic value, forest sequestration, and carbon dioxide emission savings from product storage and substitution to develop the cost of managing a forest for carbon and to effectively integrate forests into climate change policy.

In chapter 1, the relevance of forests in climate change is described. Previously developed regional forest models and current environmental policy options are reviewed, and challenges with current models and policies are discussed. The chapter concludes with the objective of the dissertation.

In chapter 2, a model was developed to investigate optimal stand level management with the three competing objectives of maximizing soil expectation value, carbon storage in the forest, and carbon dioxide emission savings from product storage and substitution. Traditional, stand-level management variables of planting density, thinning timing and density, and rotation length were employed as decision variables. Over time these variables influence the proportion of wood going into pulp, chip-n-saw, and sawtimber where each of

these classes has an expected use (carbon storage) life. The compromise programming solution for the loblolly pine (*Pinus taeda*) example, employing the specified multiple-objective model (with uniform weights and other non-decision parameters such as discount rate, prices, costs, and site index (65)) was $128/acre ($316/hectare) less than if the forest landowner maximized solely for soil expectation value. The choice of a preferred solution, found using alternative sets of weights, is a value statement which is out of the realm of quantitative analysis and into the realm of politics. The methodology provides efficient solutions (Pareto optimality) for decision makers to choose between; it does not make political decisions.

In chapter 3, the two largest carbon dioxide emission sectors in the U.S. are connected to a loblolly pine stand, utilizing the model and the specified objectives and non-decision parameters, through an integrated cap-and-trade and carbon tax policy. Under the policy, the government would agree to buy a certain number of timberland carbon offsets for the amount in foregone profits from managing for multiple objectives (rather than a single economic objective). If the timberland carbon offsets are not bought by the capped electricity generation entities within a certain time period, the government's liability for the carbon offsets would already be covered by a small carbon tax to mobile fuels. This type of climate change policy, if implemented on a large scale, could effectively and efficiently value carbon on different timberlands, decrease emissions by the transportation and the electricity generation sectors, increase carbon sequestration through the forest sector, and provide a potential revenue source for environmental services.

Chapter 4, reiterates how the non-decision parameters in the proposed model affect the cost of carbon, reviews important aspects of effective models and policies for climate change, and provides suggestions for future research.

A Compromise Programming Approach to Effectively Value and Integrate Forest Carbon Sequestration into Climate Change Policy

by
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DEDICATION

To Clint, Sydney, and Pierce

BIOGRAPHY

Laurie Gharis will graduate with her PhD in Forestry and Environmental Resources at North Carolina State University (NCSU) in Raleigh, North Carolina in May 2012. Her research focused on the development of an optimization model for loblolly pine that included economic value, forest carbon, and carbon dioxide emission savings from product storage and substitution. The optimization model was utilized to estimate a cost for growing trees for carbon as opposed to market value. The cost of carbon was integrated into an incentive policy developed by Ms. Gharis to reduce a nation's carbon footprint.

Ms. Gharis was supported by a National Needs Fellowship which was co-sponsored by NCSU's Department of Forestry and Environmental Resources (FER) and the U.S. Department of Agriculture-Cooperative State Research Education Extension Service (USDA-CSREES). Ms. Gharis is a member of the Society for American Foresters. She was the student team leader for an Environmental Protection Agency (EPA) 2010 P3 Phase I grant. She presented at the 14th Symposium for Systems Analysis in Forest Resources in Maitencillo, Chile, the 6th Annual Graduate Student Research Symposium in Raleigh, North Carolina, the Forestry and Environmental Resources Spring 2011 Seminar Series in Raleigh, North Carolina, the 7th Annual National Sustainable Design Expo in Washington, DC, and the 2012 Southern Forest Economics Workers meeting in Charlotte, North Carolina.

Ms. Gharis received her Master's in Public Administration from NCSU in 2002 and her Bachelors of Science in Sociology in 2000 from Texas A&M University in College Station, Texas. Before returning back to school for her PhD, Ms. Gharis worked for the U.S. Air Force providing support in financial and contract management.

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I would like to thank God for giving me this opportunity to study a subject so dear to me and my family for being so supportive and encouraging (especially my mom, dad, sister, and brother-in-law). I want to give a special thank you to my husband who helped me even when he was stationed half way across the world and to my two beautiful children who encouraged me throughout the program with smiles and hugs.

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CHAPTER 1

Why Research Forests and Climate Change?

Heightened concerns of climate change due to increased levels of anthropogenic greenhouse gas concentrations (GHG) have caused a great need for effective and efficient climate change policies. Research has shown that the forest sector can efficiently reduce the levels of carbon dioxide in the atmosphere (van Kooten et al. 1995), and forests are known to provide socio-economical values to many communities in the form of goods, services, and revenue (IPCC 2007a). However, current climate change policies do not properly include forests. The lack of appropriate climate change policies could be due to the absence of forest models that can simultaneously view economic value, forest carbon storage, and product storage and substitution. Without adequate models, policy makers cannot view tradeoffs among forest management objectives in order to develop policies. The focus of this dissertation is to create an appropriate, multiple-objective forest management model and to utilize the model to integrate forests into climate change policy. A suitable economic incentive aimed at increasing carbon sequestration by private landowners could be an efficient and effective avenue for mitigating climate change.

Climate Change

The United Nations Secretary-General recently noted that climate change posed a risk to peace and security around the world (UNFCCC 2011). The Intergovernmental Panel on Climate Change's (IPCC) Fourth Assessment Report stated that there was a likely connection between the current rise in the global average temperature and the rise in anthropogenic GHG concentrations (IPCC 2011). Of all anthropogenic GHGs, carbon dioxide is the most significant. In 2005, the atmospheric concentration of carbon dioxide greatly surpassed the natural range over the last 650,000 years. Since the pre-industrial period, fossil fuel use has been the major cause of increased atmospheric levels of carbon dioxide (IPCC 2007b).

According to the IPCC, eleven of the twelve warmest years in the instrumental record of global surface temperature occurred during the time period of 1995-2006. Climate change is expected to cause environmental changes such as decreased snow cover, increased thaw depth, reductions in sea ice in the Arctic and Antarctic, more extreme tropical cyclones, increases in precipitation in high latitudes, and decreases in precipitations in subtropical regions (IPCC 2007b). GHG emissions can be decreased by increasing carbon sequestration in non-atmospheric pools such as forests and wood products, by decreasing energy usage, and by exchanging fossil fuels for lower GHG emitting, renewable fuels (IPCC 2011, Lippke et al. 2011).

Carbon in Forests

Of the five economic sectors that are considered sources of anthropogenic GHGs in the United Nations Framework Convention on Climate Change (UNFCCC) only Land-Use, Land Use Change, and Forestry (LULUCF) can remove GHGs from the atmosphere. LULUCF can decrease GHG emissions by providing renewable energy, replacing fossil fuel intensive products, and sequestering carbon through improvement of terrestrial carbon stocks (Schlamadinger et al. 2007).   With approximately 10 billion acres (4 billion hectares) of forestland (FAO 2010), forests and forest products can offer significant opportunities for climate change mitigation. Options for forest mitigation are preventing deforestation and degradation, increasing sequestration rates in existing and new forests, substituting wood fuels for fossil fuels, and trading more energy-intensive products for wood products. In addition, these mitigation options can provide benefits such as employment and revenue sources, timber and fiber, and beauty and recreational services (IPCC 2007a).

Many factors can change the amount of carbon a forest stand can store. Species, stand age, and site quality affect the amount of carbon a tree can store (Huang and Kronrad 2006), and planting, site preparation, tree improvement, and fertilization can increase stand level carbon density. Longer forest rotations, fire management, augmentation of wood products that continue storing carbon, and substitution of wood products for fossil fuel intensive products can also increase carbon stocks. Different mitigation activities have unique time sequences, carbon benefits, and costs. Short term gains are largest for emission avoidance activities, whereas sustainable forest management targeted towards maintaining or increasing forest carbon stocks while still generating annual yields of timber, fiber, and/or energy from the forest, will produce the greatest sustained mitigation benefit (IPCC 2007a).

Biological carbon storage in forests is not limitless. The amount of land, the place, and the activities occurring on the land affect carbon storage potential (Schlamadinger et al. 2007). Harvests temporarily reduce forest carbon but help increase the rate of carbon uptake over time (Lippke et al. 2011). Saturation limits of the landscape can be furthered if more long-lived wood products are produced (Schlamadinger et al. 2007). According to the IPCC, much of the wood taken from harvest sites is made into harvested wood products (HWP). HWP are elements of the climate system; they hold GHGs or precursors of GHGs. The amount of time that carbon is held in the HWP is dependent on the type of product and its uses. This time period could be as short as the year of harvest for wood residue that is burned, less than five years to include recycling for different types of paper, or up to 100 years for sawtimber or panels in buildings (IPCC 2006).

Often wood products continue to store carbon after they are disposed. HWP taken to solid waste disposal sites (SWDS) may not degrade for many years. Due to the carbon storage potential of products in use and in the SWDS, the oxidation of HWP might not equal the amount of wood harvested for that specific year. Since the inputs and outputs of HWP are not normally equivalent and HWP can continue to hold carbon for some time, the IPCC has noted that wood product storage needs to be accounted for when giving guidelines for assessing the GHG impact of Agriculture, Forestry, and Land Use (IPCC 2006).

If the annual harvest is fixed at or below the annual forest increment, forest carbon stocks are sustained while society continues to receive a flow of fiber, timber, and energy (IPCC 2007a). Since less fossil fuel is required to manufacture wood products as opposed to non-wood products, biofuels are produced from the wood product chain, and carbon is sequestered in wood building materials, forests can provide carbon sinks and offsets. Positive substitution effects of emission savings from wood products and biofuels being substituted for non-wood products and fossil fuels continues throughout time. Unmanaged forests, however, can lead to carbon dioxide emissions, due to the forest and soil reaching equilibrium, more fossil fuel intensive products being utilized, and greater potential for unnatural wild fires or infestations (Eriksson et al. 2007, Lippke et al. 2011).

Forest Carbon in U.S.

According to the 2010 Forest Resources Assessment, the U.S. along with four other countries account for over 50% of the world’s 10 billion acres (4 billion hectares) of forested land

(FAO 2011). In 2007, almost 66% (514 million acres or 208 hectares) of the nation's forestland was categorized as timberland, and 69% of timberland was owned privately. Timberland is able to produce approximately 20 cubic feet or more per acre (1.4 cubic meters or more per hectare) of industrial wood annually and is able to be legally harvested for timber. 10% of the nation's forests were set aside for non-timber uses such as parks and wilderness areas, and almost 24% were not reserved but were not capable of producing enough timber to be considered timberland. Although low productive forest land is not important for wood production, it provides significant environmental attributes to include watershed protection, wildlife habitat, domestic stock grazing, and forest products for local use (Smith et al. 2009). A policy aimed at increasing carbon sequestration on privately owned timberland will still maintain millions of acres in their normal status as parks, wilderness areas, and low productive forest lands capable of providing significant environmental benefits, but it will also have the potential to make significant contributions to carbon sequestration on the 355 million acres (144 million hectares) of privately owned timberland.

Approximately eight percent of forested land in the U.S. is considered planted forests; the percentage of planted forests has continued to climb by 1.18% each year between 2000 and 2010 (FAO 2011). Trees most frequently planted in the U.S. in descending order are loblolly-shortleaf pine, longleaf-slash pine, Douglas fir, and white-red-jack pine (Smith et al. 2009).

Growth among the forests differs among regions; the South generates more products, whereas the North and Pacific Coast cut a smaller proportion of the new growth while still generating sizable products. On the other hand, the Rocky Mountain region has the largest proportion of total growth turning to deadwood. Due to more of the gross growth harvested into wood products and energy feedstocks, intensively managed forests in the South have the fewest emissions related to natural mortality. Even though a large amount of wood products are taken from temperate forests, the forests maintain their status as carbon sinks (Malmsheimer et al. 2011). However, too many overly mature forests, unnatural wildfires, and/or serious infestations could change this status.

Although consumption of wood products has been relatively stable, domestic timber production has decreased by nearly 3% since 1996. In the South, growing-stock removals were 5% less than 1996 levels. To make up the difference between consumption and production rates, imports were utilized (Smith et al. 2009). Reducing imports could provide extra carbon dioxide emission savings through decreased transportation emissions.

Over the past four decades, wood removals have varied widely suggesting that forest owners and managers vary supply quickly depending on the level of demand and prices of wood products. Between 1990 and 2005 prices of wood products steadily increased while employment in the primary production of forest goods decreased. After 2005, prices dropped dramatically (FAO 2011), but the majority of forest management costs have not dropped (Barlow et al. 2009). The Southeast and Northeast regions of the U.S. contain the most urbanized areas and showed the largest increases in the amount of urban land between 1990 and 2000 (Smith et al. 2009). Decreases in timber prices, increases in forest management costs, and increases in urbanization could be incentives for converting forestland. On the other hand, government sponsored forest incentives, such as tree planting programs have been considered beneficial at preventing losses of forestland (Smith et al. 2009).

Forest Models

In the past, numerous articles have been written about carbon sequestration in forests. Models have included different types of forests, products, and approaches. A review of regional models was conducted to learn more about authors' objectives, prices of carbon, products included, and results found.

What are the studies' objectives?

The main objectives in these studies were to optimize management practices for carbon sequestration and to maximize net present value with carbon subsidies in place. Hennigar et al. (2008), Kaipainen et al. (2004), Meng et al. (2003), and Peng et al. (2002) modeled how forest management practices affect carbon storage. Cao et al. (2010), Pohjola and Valsta (2007), Huang and Kronrad (2006), Backeus et al. (2005) and van Kooten et al. (1995) developed models for forest management when carbon subsidies and taxes were present.

What is the price of carbon?

Many of the authors employed a carbon subsidy and/or tax to establish an economic value for the stand. Cao et al. (2010) employed rates of \$0, \$14, \$25, \$36, and \$72/tonne of CO_2. Pohjola and Valsta (2007) analyzed costs of \$13 and \$26/tonne of CO_2. Backeus et al. (2005) looked at prices from \$0 to \$179/tonne of CO_2. Huang and Kronrad (2006) set costs at \$3, \$15, and \$30/tonne of CO_2.

How are products treated in the model?

Pohjola and Valsta (2007) and Peng et al. (2002) did not consider product carbon. Huang and Kronrad (2006), Backeus et al. (2005), and Liski et al. (2001) included products in their models. Huang and Kronrad (2006) considered pulpwood and sawtimber produced from harvests as long-lived wood products, which would not be taxed. Backeus et al. (2005) discounted emission rates for sawn timber and pulpwood products, which gave an advantage to longer life products. Liski et al. (2001) analyzed organic carbon in vegetation, soil, and wood products. Hennigar et al. (2008) and Eriksson et al. (2007) included products and substitution in their models. Hennigar et al. (2008) optimized forest carbon, product carbon, and product substitution of wood products (not biofuels), whereas Eriksson et al. (2007) considered products and substitution in their simulation study.

Findings of Reviewed Studies

The reviewed articles all considered carbon sequestration in a stand. However, authors chose different objectives, accounted for forest carbon in varying ways, and restricted models uniquely. Some taxed and/or subsidized carbon, while others did not. Variances between studies led to unique results.

Schmid et al. (2006), Meng et al. (2003), and Peng et al. (2002) did not include product carbon in their models. Schmid et al. (2006) noted that although the managed systems take in less carbon over the simulated years, they may still have the ability to take in carbon after 100 years. Meng et al. (2003) found the optimized managed scenario sequestered less carbon than the natural, non-harvested forest due to harvests occurring at the culmination of the mean annual increment as per the wood supply objective. Peng et al.

(2002) showed that increasing harvest intensity would reduce total ecosystem carbon, soil carbon storage, and nitrogen availability, whereas longer rotations increased levels of total ecosystem carbon stock and nitrogen availability.

Pohjola and Valsta (2007), Huang and Kronrad (2006), Backeus et al. (2005), and van Kooten et al. (1995) looked at carbon subsidies and taxes. In the Pohjola and Valsta (2007) study, average rotation lengths were increased by 9 years for Scots pine and17 years for Norway spruce with a carbon subsidy of $13/tonne of CO_2. Huang and Kronrad (2006) found that stands with site indices of 80 or 90 had a higher rate of mortality than growth at approximately 40 years, which prevented longer rotations from being profitable in terms of storing more carbon. Stands with lower site indices had lower mortality and could continue accumulating biomass (and thus storing carbon) with longer rotations. Their results also demonstrated that with low alternative rates of returns (ARR) (2.5-5%), as the price of carbon rose, the financially optimal rotation length for the production of both timber and carbon continued to be steady or to decline; however, with medium or high ARRs, an increase in the price of carbon resulted in an increase in rotation. In both Huang and Kronrad (2006) and Backeus et al. (2005), low-productive sites were affected more by incorporating carbon benefits than high productive sites. The Backeus et al. (2005) study predicted that no harvests would be conducted at a carbon price of approximately $149/tonne. The results of the van Kooten et al. (1995) study demonstrated that with higher timber prices and discount rates, the optimal rotation age is shorter, but as carbon prices increase, the optimal rotation length increases. However, when carbon in wood is permanently stored, rotations are decreased because tax penalties from harvests are smaller. Van Kooten et al. (1995) noted that the discount rate had the greatest effect in decreasing the rotation length.

Hennigar et al. (2008), Eriksson et al. (2007), Kaipainen et al. (2004), and Liski et al. (2001) included products in their models for managing forests for carbon. The Hennigar et al. (2008) study demonstrated that for many cases, carbon storage in product pools plus on-site forest carbon equaled forest carbon storage with reduced harvests. Eriksson et al. (2007) showed that the decreased input of carbon to the soil due to slash and stump removal was minor compared to the impact of using the slash and stumps to substitute for fossil fuel. Their simulations demonstrated that the largest reduction of net carbon emissions occurred when the forest was fertilized, slash and stumps were collected, wood was employed for construction, and the reference fossil fuel was coal. Their study also found that product use made the largest impact on net carbon emission. Kaipainen et al. (2004) noted that for all of the forests, the carbon stock of biomass had a positive relationship with rotation length. Increasing the rotation length of the studied forests, increased the harvesting possibilities in 3 forests and decreased the harvesting possibilities in 4 forests. Liski et al. (2001) concluded that increased rotation lengths of 30 years led to preferable carbon sequestration for Scots pine and Norway spruce due to fewer fossil fuel emissions from harvests.

Various objectives, species, products, and carbon prices led to different results for the study. However, studies that did not include products showed higher carbon sequestration rates in non-managed forests over the simulated years, while studies that included products varied in results. *Of the reviewed studies, no study optimized management for economic value, forest carbon, and product storage and substitution (to include the substitution of* *fossil fuels). Products and product substitution are important for determining appropriate management practices for maximum carbon sequestration over multiple-rotations, and economic value is important for comparing tradeoffs in order to implement practical policies.*

Environmental Policies

A review of current and past policies is important in determining what policies currently exist, the scope of the policies, and the effectiveness of policies. A review such as this also better demonstrates the *individuality of a policy that utilizes a production approach to calculate a cost for managing for multiple objectives including carbon and to connect carbon sequestration by forests to the two largest emission sectors through a combined cap-and-trade and tax policy*.

Many different types of policies exist; each with different mechanisms to encourage specific behaviors. Most policies can be classified into five groups: mandates, pricing incentives, enabling policies, constraints, and ancillary policies. Mandates, such as renewable fuel standards, are policies that require a certain amount of fuel to be from non-fossil fuel energy sources. This type of policy requires the standard to be met at any cost and does not necessarily lead to a decrease in GHGs. Pricing incentives are policies that change pricing relationships between products. Examples include carbon tax and cap-and-trade programs. A carbon price as found in a carbon tax or cap-and-trade program could be an efficient climate change policy mechanism as it has a positive impact on reducing GHGs, oil use, and government expenditures. Applying the carbon price to all energy sources gives a signal in direct proportion to a fuel's GHG effect. Carbon tax policies could encourage efficiencies in many different industries including agriculture. Enabling policies are those that facilitate production or consumption of a product by acting upon the production, distribution, or utilization chain of the product. This category is comprised of policies that encourage infrastructure development or seek to decrease the costs of input materials. Constraints are policies that set restrictions such as quality or environmental performance on product sourcing and/or production. Ancillary policies are those that are not directly aimed at the production or consumption of the product but can affect or are affected by those that are (Galik et al. 2009a).

Mandates such as the Clean Water Act and the Endangered Species acts have led to offset and mitigation credits to protect particular ecosystems and environmental resources. Offsets are normally employed to counteract emissions from a specific pollutant, whereas mitigation is normally utilized to counteract impact to an entire ecosystem. An example of an offset is one entity paying another entity for a certain reduction in water pollution in order to continue polluting into a specific water source. An example of mitigation is an industry paying an individual to develop a new wetland in order to impact another wetland by building a property. Mitigation credits are bundled credits and are expected to contain all of the critical elements of the affected ecosystem (Cooley and Olander 2011). Mitigation credits can be obtained by restoring wetlands, streams, aquatic resources (Normanly and Vacca 2007), or endangered species habitat. Mitigation credits are measured in units that incorporate the service, such as acres of endangered species habitat (Cooley and Olander 2011).

The most recognized international climate change policy is the Kyoto Protocol. It is an international agreement connected to the UNFCCC, which obliges 37 industrialized countries and the European community to decrease GHG emissions to approximately five percent below 1990 levels during the 2008-2012 timeline. The Protocol places the majority of the burden on developed countries, since 150 years of industrial activity has caused GHG emissions to increase. The Kyoto Protocol offers incentive mechanisms for flexibility in meeting the mandates. The mechanisms are emissions trading through the carbon market, the clean development mechanism, and joint implementation (UNFCCC 2012).

Examples of the mandatory cap-and-trade systems are the European Union Emissions Trading Scheme, New South Wales Greenhouse Gas Reduction, New Zealand Emissions Trading Scheme, Regional Greenhouse Gas Initiative (RGGI), and California's AB 32 Scoping Plan. Forests can be included in cap-and-trade programs as offsets. Forest offsets can include afforestation, reforestation, forest management, forest conservation, and forest preservation (Malmsheimer et al. 2011). Although carbon storage can be increased through wood products, the first commitment period in the Kyoto Protocol excluded wood products (UNFCCC 2003). If wood products are excluded, timber harvests are treated as an immediate release of carbon dioxide into the atmosphere, but in actuality, a harvest moves a portion of the forest carbon to products (Woodbury 2007).

Other incentive policies include tax programs and payments for environmental services. Examples of tax programs are North Carolina's Forestry Present Use Property Tax Program (Megalos et al. 2011) and the national Reforestation Tax Incentive (Straka and Greene 2007). Montagnini and Finney (2011) describe payment for environmental services programs as payments for the services ecosystems provide to society, including carbon sequestration, biodiversity, watershed production, and scenic beauty. Environmental services must be recognized and evaluated, and a payment scheme must be put into place to foster the provision of the services. Landowners who manage their land to provide ecosystem services are normally paid by private entities for services such as water and carbon sequestration and by government entities for such services as biodiversity. According to Montagnini and Finney, payments can be based on the economic cost of lost opportunities, the actual value of environmental services provided minus transaction costs, or the global market price as in the case of carbon sequestration. The payments can also be determined based on environmental targets and the costs to landowners for desired land management. They also emphasized that the net benefits of new systems must outweigh those of the conventional system in order for sustainable land use systems to be permanently adopted by landowners. The largest payment for environmental services program in the U.S. is the Conservation Reserve Program (USDA FSA 2012).

An example of an enabling policy is a feed-in-tariffs (FITs) policy. This policy is employed to accelerate the development of renewable energy. FITS increase market growth by developers through long-term purchase agreements for electricity produced with renewable energy sources. Payments can be set based on technology type, project size, resource quality, and/or project location. Technologies focused on employing waste such as wood or animal waste can be set higher. FIT payments are often based on the cost of renewable energy generation plus a targeted return. The value of the renewable energy generation can include such concerns as climate change mitigation, health impacts, energy security, fixed price incentive, or auction-based mechanisms. Fixed price payments can be independent from the market and remain the same over time or can be dependent on the market with a premium added to the market electricity price (Couture et al. 2010).

There are also non-policy options for resource protection. Some current non-policy programs for climate change are voluntary emissions offset protocols such as the American Carbon Registry (ACR), Climate Action Reserve (CAR), GHG Protocol for Project Accounting and Land Use, Land Use Change, and Forestry Guidance for GHG Project Accounting, and Voluntary Carbon Standard (VCS) (Malmsheimer et al. 2011). Another example of a non-policy option is forest certification. Forest certification can be an instrument for environmental marketing, market access, and market advantage for the forest industry, landowners, and managers. Forest certification provides governments with a soft policy instrument to promote sustainable forest management and sustainable consumption patterns and environmentalists with an instrument to influence forest management (Rametsteiner and Simula 2003).

Objective of Dissertation

Numerous articles have covered carbon sequestration in forests, but *a gap exists* in models that can simultaneously compare economic value, forest sequestration, and product storage and substitution. Authors have input varying carbon prices into their models, but what is the actual cost of managing a stand for carbon? The economically minded forest landowner will not manage for anything less than the actual cost and a government will want cost-efficient carbon offsets.

Although many policies and programs exist for forest carbon sequestration in the U.S., they lack large scale potential. For example, regional cap-and-trade programs differ in definitions for eligibility of offsets, carbon sequestration procedures, baselines, included carbon pools, crediting periods, leakage of carbon, and permanence of carbon offsets (Malmsheimer 2011). Another challenge is that the U.S. did not ratify the Kyoto Protocol and does not currently have a national climate change policy in place. Even the Kyoto Protocol has significant downfalls. For example, wood products were not included in the first commitment period (UNFCCC 2003), even though sustainable forest management targeted towards maintaining or increasing forest carbon stocks while still generating annual yields of timber, fiber, and/or energy from the forest, produces the greatest sustained mitigation benefit (IPCC 2007a, Lippke et al. 2011).

The *lack of economically appropriate policies for forests and climate change* may be due to the absence of operational level models, which could be employed to analyze outcomes of different forest options in climate change policies (Hohne et al. 2007). An operational level model, which optimizes aboveground carbon sequestration and substitution in order to quantify the carbon and economic impacts of different policies, could be very useful to policy makers, especially if the model included product pools and substitution, was scientifically sound, and was relatively simple to understand. If a model could be developed to optimize a unit of a specific site index of timberland rather than a stand of varying size, it would be scalable. If the model could be developed in easily assessable and user-friendly software such as Microsoft Excel, it could be useful to many parties.

The objective of this study is to develop an accurate and usable model to investigate optimal unit level management with the competing objectives of (1) maximizing economic value, (2) forest sequestration, and (3) carbon dioxide emission savings in product storage and substitution. The model will be employed to determine an example cost of managing timberland for carbon so that forests can be effectively integrated into climate change policy. These three objectives were chosen because objective one represents the business as usual (BAU) scenario, objective two represents policies that increase rotations and decrease production (a possible, habitat and soil organic carbon friendly approach), and objective three represents a production approach that takes into account carbon storage in products and carbon offsets. The optimization model will include basic stand level management variables: planting density, thinning timing and density, and rotation length. An optimization model that is region specific, operationally minded, and includes economic value, forest carbon, and product carbon and substitution would provide an accurate and practical quantitative tool for policy makers and forest landowners.

Due to the amount and types of forest land, the U.S. and specifically the Southern U.S. show much promise to sequestering more carbon. Approximately 33% of the U.S. is forested (compared to 50% in the 1600's), and the majority of forest land is classified as timberland. The South harvested the greatest percentage of U.S. growing stock removals in 2001, and the majority of harvested volumes were produced by non-industrial private forest (NIPF) landowners. The volume of wood harvested on NIPF land has increased since 1986 (Smith et al. 2003).

Since loblolly pine is the most common tree planted in the U.S. (FAO 2006), the possible utility of the model will be demonstrated with this species. In the South, 64% of all acres are planted in this softwood species (Smith et al. 2003). It is a productive tree capable of yielding high quality wood products and will provide a practical example of the developed model and proposed policy.

CHAPTER 2

A Compromise Programming Model for Developing the Cost of Managing a Forest for Carbon

Preface

Chapter 2 is a manuscript in review, as of March 26, 2012, for the *Annals of Operation Research*. The manuscript was written by Laurie Gharis, Joseph Roise, and James McCarter. Dr. Roise's contribution to the manuscript was the idea to employ optimization for forest management of carbon and to integrate a growth and yield model into an optimization model. Dr. McCarter's contribution to the manuscript was the idea of employing site indices to simulate soil organic carbon; he also developed the computer program necessary to run simulations on the growth and yield model. Both Dr. Roise and Dr. McCarter also reviewed the article before submission. My contribution to the article was to cultivate a dissertation topic, to conduct all research, to develop all product equations utilizing statistical analysis software, to create an optimization model with multiple objectives, to decide on what objectives to include, to select a solving method, and to write the manuscript.

Abstract

Environmental policy makers need research based decision analysis models that include carbon sequestration and forest products in order to make policies that are both economically viable and effective. Forests and wood products have been identified as important mechanisms for carbon sequestration and storage. Policies often cover carbon sequestration but not product storage and substitution. Furthermore, many researchers have developed and published models on carbon management. However, a gap exists in operational level models

that include product substitution. We develop a model to investigate optimal stand level management with competing objectives of maximizing soil expectation value, carbon storage in the forest, and carbon dioxide emission savings from product storage and substitution. Our purpose is to produce an accurate and useable analytical product for Southeastern U.S. foresters growing loblolly pine (*Pinus taeda*) in the presence of carbon policies. The decision variables are the traditional stand level management variables of planting density, thinning timing and density, and rotation length. Over time these variables influence the proportion of wood going into pulp, chip-n-saw, and sawtimber where each of these classes has an expected use (carbon storage) life. Compromise programming was employed to solve the problem. The compromise programming solution (SI 65) was $128 per acre ($316 per hectare) less than if the forest landowner maximized solely for soil expectation value under the specified multiple-objective model and non-decision parameters; this value was approximately $24/tonne of CO_2 equivalent. This practical knowledge can lead to economically viable policies for foresters and effective carbon sequestration policies for the environment.

Keywords compromise programming; forest management; decision analysis model; policy; unit level analysis; product substitution

Introduction

The United Nations Secretary-General recently called climate change "a very credible threat to peace and security around the world" (UNFCCC 2011). The Intergovernmental Panel on Climate Change's (IPCC) Fourth Assessment Report noted that the current rise in the global average temperature is likely due to a rise in anthropogenic greenhouse gas (GHG) concentrations. In 2010, GHG levels had increased to 39% above preindustrial levels. Since fossil fuel combustion causes the majority of global anthropogenic GHG emissions, energy conservation and efficiency, fossil fuel exchanges, and renewable energy are important avenues for decreasing GHG emissions (IPCC 2011).

With approximately 10 billion acres (4 billion hectares) of forestland holding 289 gigatonnes of carbon in just their biomass (FAO 2010), effectively tracking the carbon flow to and from forests is also imperative for effective climate change policies. Forest can aid in climate change mitigation through four different avenues: decreasing deforestation and degradation, increasing the sequestration rate in existing and new forests, displacing wood fuels for fossil fuels, and substituting wood products for more energy-intensive products. These options for mitigation may also provide additional benefits such as employment and revenue sources, timber and fiber, and beauty and recreational services. Planting, site preparation, and tree improvement are some of the variables that affect stand level carbon stock. Different mitigation activities have unique time sequences, carbon benefits, and costs. Short term gains are largest for emission avoidance activities, whereas sustainable forest management targeted towards maintaining or increasing forest carbon stocks while still generating annual yields of timber, fiber, and/or energy from the forest, will produce the greatest sustained mitigation benefit (IPCC 2007a).

Many studies have investigated carbon sequestration in forests. Certain studies have looked at how forest management practices such as rotation length would affect carbon sequestration (Liski et al. 2001, Kaipainen et al. 2004). Other studies have simulated how increased levels of harvesting would affect carbon sequestration (Peng et al. 2002, Eriksson et al. 2007). Meng et al. (2003) and Hennigar et al. (2008) optimized forest management practices such as: planting, thinning, and rotation length for carbon sequestration. Other authors have analyzed the economic value of the forest when a carbon tax or subsidy was administered (van Kooten et al. 1995, Backeus et al. 2005, Huang and Kronrad 2006, and Pohjola and Valsta 2007). Many different tree species and regions have been included in analyses. Models have encompassed soil (Meng et al. 2003, Hennigar et al. 2008) and products (Backeus et al. 2005, Hennigar et al. 2008, Eriksson et al. 2007, Liski et al. 2001, Huang and Kronrad 2006, Cao et al. 2010, Kaipainen et al. 2004, van Kooten et al. 1995, Woodbury et al. 2007). However, few models have accounted for product substitution. Hennigar et al. (2008) optimized for product substitution but did not include fossil fuel substitution, and Eriksson et al. (2007) included fossil fuel substitution but did not optimize. Many articles have covered carbon sequestration in forests, but a gap exists where optimization models have simultaneously considered economic value, forest carbon sequestration, and carbon dioxide emission savings from product storage and substitution of construction materials and fossil fuels. With climate change causing an emphasis on fossil fuel exchanges, forest biofuels should not be left out of the equation.

Numerous authors have integrated the price of carbon into their models (van Kooten et al. 1995, Pohjola and Valsta 2007, Huang and Kronrad 2006, Cao et al. 2010), but research is lacking on how much it costs the forest landowner to manage a stand for carbon storage rather than how much industry is willing to pay. Establishing the optimal management regime for carbon sequestration and timber production is beneficial for the environment, for society, and for the forest landowner. Governments could utilize subsidies and/or tax based instruments to offset the cost of meeting the required emissions, and forest landowners who sequester carbon in their forests could assist the country in meeting its target (Pohjola and Valsta 2007). The actual cost of managing a stand for carbon sequestration is necessary for this type of policy to be effective. Proper subsidies could prevent forest conversions and could further the environmental services and sustainable products provided by forest landowners.

Optimization or simulation of specific scenarios can be employed for forest carbon sequestration analysis. Although when a specific goal exists for the analysis, an optimization approach permits the researcher to look at many more alternatives than a simulation approach (Backeus et al. 2005). Stand level management decisions such as planting density (Hyytiainen et al. 2005) and thinnings and final fellings affect the growing stock, which in turn impacts carbon sequestration (Pohjola and Valsta 2007) in biomass, soil, and wood products (Eriksson et al. 2007). Different approaches can be employed to integrate multiple objectives in an optimization model. Some of these approaches are to: develop a single objective from multiple objectives, optimize one objective and make the other objectives constraints, or to apply forms of compromise programming such as goal programming (Lee 1996). A weakness for developing a single objective from multiple objectives is that it can be difficult to decide on appropriate and meaningful weights for the objectives. A weakness for applying one objective and making the other objectives constraints is that the researcher cannot assess tradeoffs among all objectives at once. Compromise programming minimizes the gap between the achieved levels of objectives and the best one (Krcmer et al. 2005). The equation scales each objective by the inverse of its range (Gershon 1982), so multiple objectives with different units of measurements can be optimized. In addition, compromise programming can also be employed without having predetermined weights; instead the decision maker's risk attitude can be integrated into the compromise equation (Krcmer et al. 2005).

The objective of this study was to develop a model to investigate optimal stand level management with the three competing objectives of maximizing soil expectation value (SEV), carbon storage in the forest, and carbon dioxide emission savings from product storage and substitution of more fossil fuel intensive products by both biofuels and wood construction products. These three objectives were chosen because objective one represents the BAU scenario, objective two represents policies that increase rotations and decrease production (a possible, habitat and soil organic carbon friendly approach), and objective three represents a production approach that accounts for carbon storage in products and carbon offsets. The multiple-objective optimization model was solved utilizing compromise programming, and the decision maker's risk attitude was integrated. An optimization model that is region specific, operationally minded, and includes economic value, forest carbon, and product carbon and substitution potentials on a scalable level provides a practical, quantitative tool for policy makers considering climate change policies.

We applied the proposed model to the management of one acre (0.4047 hectares) of loblolly pine in the Southern U.S. Due to the amount and types of forest land, the U.S. and specifically the Southern U.S. show much promise to sequestering more carbon. The Southern region of the U.S. (Region 8) is made up of Alabama, Arkansas, Florida, Georgia, Kentucky, Louisiana, Mississippi, North Carolina, Oklahoma, South Carolina, Tennessee, Texas, Virginia, Puerto Rico, and the Virgin Islands. The South provided 63% of U.S. growing stock removals in 2001. The majority of harvested volumes in the U.S. were produced by NIPF landowners (Smith et al. 2003). The loblolly pine tree is found in the majority of Southern U.S. plantations (FAO 2006) and is thus the tree of interest for this investigation. Demonstration of the model for the management of one acre of loblolly pine in the Southern U.S. will be beneficial in developing a scalable, economic incentive aimed at increasing carbon sequestration by private landowners.

Optimization Model

We developed a multiple-objective forest management model to investigate optimal stand level management with three competing objectives in a sustainably managed forest (with no land use changes). The decision management variables were planting density, thinning timing and density, and rotation length.

Theoretical Framework

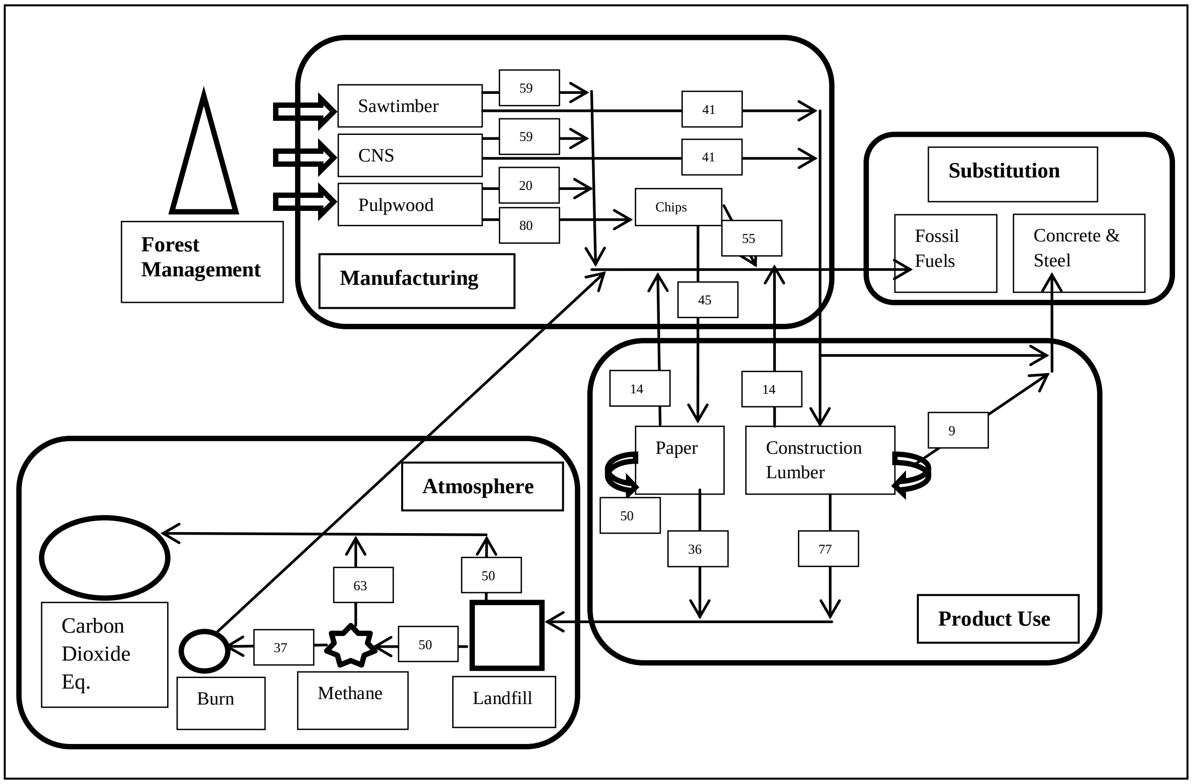

Figure 1. Theoretical Framework. Drawing adapted from Hennigar et al. (2008). A forest stand is managed sustainably and optimally for SEV, carbon storage in the forest, and carbon dioxide emission savings through product storage and substitution of more fossil fuel intensive products by biofuels and wood construction products. A certain percentage of sawtimber, chip-n-saw, and pulpwood is produced. Wood construction products and biofuels are manufactured and substituted for fossil fuel intensive products. Products are landfilled, recycled, or burned for energy after their useful lives. The percentages of products transferred in each stage are shown above.

Developing an Appropriate Growth and Yield Equation

In the model not only is the forest stand managed for carbon sequestration on site but also for long term wood products and for substitution of more fossil fuel intensive products by biofuels and wood construction products. To find the combination of stand management activities that maximizes the three objectives, an appropriate growth and yield equation is needed. The growth and yield equation must take into account the four decision variables.

For our investigation the Hafley and Smith North Carolina State University (NCSU)–Managed Pine Plantation Growth and Yield Simulator – Version 3.2 was integrated into the optimization model (Hafley et al. 1982, Hafley and Buford 1985). This stand level growth model was constructed employing long-term spacing studies and operational plantation data (Buford 1991). The model utilizes Johnson's S_{BB} distribution to model diameter and height. S_{BB} employs the following parameters: smallest height and diameter, largest height and diameter, the modal height and diameter, the standard deviation of height and diameter, and the correlation between height and diameter. A negative binomial probability function is employed to exhibit mortality (Buford and Hafley 1985). The model has been assessed and found acceptable over combinations of site indices of loblolly pine at 45 to 85 feet (approximately 14 to 26 meters) at a base age of 25 years, ages 5 to 50 years, and densities of 100 to 2722 trees per acre (TPA) (247 to 6726 trees per hectare (TPH)) (Hafley et al. 1982). Buford compared the predictions of four growth and yield models (UGA, SE-27, COYIELD, and Hafley and Smith NCSU) to the actual results from a 30 year spacing study and found that overall the Hafley and Smith NCSU model provided the closest results over the range of planting densities in the study (Buford 1991).

To develop growth and yield equations, loblolly pine was grown from bare land utilizing the Hafley and Smith NCSU simulation model. For all trials, the piedmont/upland height/age curve was utilized, fertilizer was not applied, and trees had an initial survival rate of 100%. To obtain the data, the following operable ranges over site indices of 55, 65, and 75 feet at base age 25 were applied. Planting densities were increased from 200 TPA to 1000 TPA in 10 TPA increments (494 TPH to 2471 TPH in 25 TPH increments). Thinnings were run from 8 to 22 years at 1 year increments. Residual basal area (BA) left after the thinning treatment had to be a minimum of 40 square feet per acre (9.18 square meters per hectare) or no removal would occur. Ranges for thinning were considered for residual BA above 40 square foot per acre at 5 square foot increments (9.18 square meters per hectare at 1.15 square meter increments). Rotation lengths were included from 20 years to 50 years at 1 year increments. In addition, harvests (both thinnings and final fellings) had to be five years apart. This combination resulted in 2,630,003 simulations being run. Outputs analyzed were pulpwood, chip-n-saw (CNS), and sawtimber.

Data from the simulation model was input into SAS, and graphs of the growth and yield data were analyzed in order to develop predictive equations for the response surface. Relationships appeared to be quadratic or cubic between the management variables and the wood products for this dataset and timeline. With polynomial relationships, rather than sigmoidal relationships, and no comparisons between treatments, a regression procedure (PROC REG) could be utilized to provide unbiased estimates (Rawlings et al. 1998). Stepwise selection was employed to develop appropriate equations for each product (thinned CNS, thinned pulpwood, final felling sawtimber, final felling CNS, and final felling pulpwood) and each site index. No thinned sawtimber equations were developed, as thinnings rarely produced sawtimber during the specified thinning range. Sawtimber was measured in 1000 board feet (MBF), which is a commercial measure, and CNS and pulpwood were measured in cubic feet. The selected equations for SI 65, which have model p values of less than .0001, can be seen in Table 1 below. Parameter estimates, F values, and probabilities from the statistical analyses can be seen in Appendices A (SI 55), B (SI 65), and C (SI 75).

Table 1
SAS Beta Coefficients for Yield Equations Developed with Hafley and Smith Growth and Yield Model Simulations (SI 65)

Product	Intercept	Start density (TPA)	Start density^2 (TPA)	Thin year	Thin year^2	Thin year^3	Thin residual BA (ft^2/acre)	Thin residual BA^2 (ft^2/acre)	Thin residual BA^3 (ft^2/acre)	Rotation length (year)	Rotation length^2 (year)
Thin-CNS (ft^3)	-560.78	3.1674	-0.00385	-72.095	7.9588	-0.14021	4.4377	-0.14728	0.00054	-	-
Thin-pulp (ft^3)	-587.67	2.3255	-0.00105	-2.4281	5.825	-0.16494	-8.261	0.00493	-	-	-
Final felling-saw (MBF)	-12.618	-0.01452	0.00001	0.10018	-0.00703	-	0.0336	-0.00015	-	0.8399	-0.00329
Final felling-CNS (ft^3)	1941.0	-1.1562	0.0027	-31.890	0.57653	-	2.0505	0.00298	-	-78.970	0.9487
Final felling-pulp (ft^3)	-641.15	4.3186	-0.00451	-197.27	3.3771	-	27.69	-0.05482	-	103.24	-1.6767

Establishing Monetary and Carbon Values

The optimization model must take into account both market value and carbon mass estimates. The model accounted for value as it relates to time and to multiple-rotations with SEV. SEV computes the net present value of a complete forest rotation starting from bare land that is assumed to repeat in perpetuity. The value is useful as an analyst can compare the present value of various management regimes with different rotation lengths (Cubbage et al. 1991).

The dry biomass of the bole of the loblolly pine was calculated by multiplying the green volume in cubic foot by the weight (pounds) of one cubic foot of water and by the dry weight specific gravity of the green volume of loblolly pine (Heath 2008). Forest carbon values were calculated utilizing the specific gravity of mature loblolly pine from the piedmont region of North Carolina (Talbert and Jett 1981). The factors for aboveground and belowground biomass from the total amount of merchantable wood were utilized to obtain the total biomass per acre (GGLS8 2010). Biomass was converted to carbon by multiplying by 0.5 (Hennigar et al. 2008, Dwivedi et al. 2009). A comparison was made of the optimization model's prediction for carbon to Dwivedi et al. (2009). They estimated the maximum carbon sequestration potential of 1 acre (0.4047 hectares) of slash pine (SI 70 at age 25), with 700 TPA (1730 TPH) at year two and a thinning conducted at year 15, as 40,065 kg/acre (99,000 kg/hectare). Our model estimated the maximum carbon sequestration potential of 1 acre (0.4047 hectares) of loblolly pine (SI 70 at age 25), with 700 TPA (1730 TPH) and a thinning conducted at year 15, as 42,845 kg/acre (105,869 kg/hectare). The final standing carbon is within 7% of Dwivedi et al.

Emissions from managing a pine plantation, transporting lumber to the mill, and producing softwood lumber were adapted from Puettmann and Wilson (2005). The estimated cradle-to-gate, cumulative energy allocated to 1 cubic meter of softwood lumber manufactured in the Southeast was 203 MJ/cubic meter for harvest, 3175 MJ/cubic meter for product manufacturing, and 114 MJ/cubic meter for transportation.

To accurately integrate carbon storage potential for long term products into the optimization model, uses of long term products have to be known. Bergman and Bowe (2010) noted that most softwood lumber is used in residential construction, including new construction and repair and remodeling of existing buildings. As can be seen in Figure 1, we assumed that CNS and sawtimber would be utilized to make construction products. To obtain the dry biomass of products per acre, the specific gravity of a mature tree in the piedmont region of North Carolina (Talbert and Jett 1981) with the reference substance of water was multiplied by the amount of CNS and sawtimber per acre. Then a log mass conversion rate of 41% was applied (Milota et al. 2005). For this study, the other 59% went to fuel. To calculate the amount of carbon in products, a conversion rate of .50 was utilized (Hennigar et al. 2008, Dwivedi et al. 2009). For paper products, the model considered that 80% of pulpwood went to chips (Hennigar et al. 2008), and 45% of chips were converted to paper (Briggs 1994). Leftover pulpwood went to fuel.

Half-lives for product usage and disposal were taken from Skog (2008) for products employed in 2010. The percentages of products produced, percentages of products disposed of, and half-lives for usage and disposal can be seen in Table 2 below.

Table 2
Usage and Disposal of Products in Developed Models

Starting product	Finished product	Percentage of finished product made from starting product	Finished product half-life (years)	Percentage landfilled	Percentage burned for energy	Percentage recycled	Landfill decay half-life (years)	Percentage of landfilled product subject to decay
Sawtimber and CNS	Single family house	33%	97.75	77%	14%	9%	29	23%
Sawtimber and CNS	Upkeep and improvement on houses	33%	31.42	77%	14%	9%	29	23%
Sawtimber and CNS	Sawn-wood Other uses	33%	30	77%	14%	9%	29	23%
Pulpwood	Paper	100%	2	36%	14%	50%	14.5	56%

The model gave CO_2 a GHG equivalency of 1 and CH_4 a GHG equivalency of 23 (GGLS8 2010). A first order decay rate and a landfill gas mix of 50% CH_4 and 50% CO_2 were modeled in this study (NCASI 2004). We also considered that 49% of the landfills were equipped with methane capturing systems and 75% of the methane was burnt, in landfills with capturing abilities (Upton et al. 2008). Figure 1 shows the overall percentage (37%) of methane captured for energy.

To assess our model on emissions, comparisons were made with peer-reviewed articles. In our model, the emissions for stand management and harvest, transportation and manufacturing of products, and disposal of products were calculated to be 0.15 tonnes of carbon emitted/tonne of carbon harvested. This estimate is higher than the estimate of 0.08 to 0.09 tonnes of carbon emitted/tonne of carbon harvested calculated by White et al. (2005) for the production of roundwood under government, state, and NIPF land management in Wisconsin.

Product substitution savings were based on the following:

- Wood construction products were considered to have a 31% savings in emissions over concrete products without considering carbon storage (Lippke et al. 2010).
- Biofuels were modeled as having an emission savings of 82.4% (Dwivedi et al. 2011).
- GHG emissions of the fossil reference chain of bioliquids used for cogeneration (electricity and heat) was 82 g CO_2 equivalent (eq.)/MJ (GGLS8 2010).
- GHG emissions of the fossil reference chain of petrol and diesel was 83.8 g CO_2 eq./MJ (GGLS8 2010).
- To calculate the amount of energy produced from wood, one dry ton of wood was set equal to 17,936 MJ (NC Extension Forestry 2011).
- Moisture content was assumed to be 50% for green wood (NC Extension Forestry 2011).

To calculate energy savings from recycled wood, 41% of the recycled wood was converted to long term products (same as virgin materials). Recycled long term products were also considered to require the same amount of energy for manufacturing and transportation as virgin long term products and to have a continued savings of 31% over concrete. Burned waste wood and waste paper were given a 74% default savings, which is the wood waste ethanol savings (Directive 2009). Captured landfill methane was calculated with the same GHG emissions as the default for biogas from municipal organic waste as compressed natural gas (23 g CO_2 eq./MJ) (Directive 2009). Since short-term wood products such as paper do not continue storing carbon for long periods while in use or in landfills and do not result in large savings from substitution (Franklin 2011), only decay emissions (no savings) were input into the model.

Objectives

The specific investigation objectives are to: (1) maximize SEV, (2) maximize carbon storage in the forest, and (3) maximize carbon dioxide emission savings from product storage and substitution of more fossil fuel intensive products by biofuels and wood construction products. The objectives are not congruent and are measured in different units. The model is formulated as a multiple objective nonlinear program. The decision variables are planting density, thinning timing and density, and rotation length.

The financial benefits were measured as the SEV of an acre of land producing timber. Objective $\boldsymbol{S}$ represents maximization of SEV. The discounted net revenues were calculated over an infinite time horizon with rotation age $\boldsymbol{T}$ and a discount rate $\boldsymbol{r}$ and includes (at time $\boldsymbol{t}$, whenever there is a harvest) the stumpage price value returns $\boldsymbol{h_t}$ for sawtimber, CNS, and pulpwood (from thinning and final felling) and regeneration costs $\boldsymbol{r_c}$ (cost of site preparation, planting, and seedlings). $\boldsymbol{h_t}$ is a function of the decision variables, planting density $\boldsymbol{w}$, thin year $\boldsymbol{x}$, residual thinning density $\boldsymbol{y}$, and rotation length $\boldsymbol{T}$, and of the non-decision variable, $\boldsymbol{v_{k,t}}$ price of $\boldsymbol{k}$, sawtimber, CNS, and pulpwood, at time $\boldsymbol{t}$. A 3% real discount rate was employed in the example (Backeus et al. 2005, Pohjola and Valsta 2007, Cao et al. 2010).

$$\boldsymbol{S} = \left[\left(\sum_{t=0}^{T}(h_t)\,(1+r)^{-t} - r_c\right)\frac{1}{1-(1+r)^{-T}}\right] \tag{1}$$

$$\boldsymbol{h_t} = f_1(w, x, y, T, v_{k,t}) \tag{2}$$

Forest carbon (kg of CO_2 eq./acre) was measured as the sequestration of one acre of forestland. Objective ***C*** represents maximization of forest carbon benefits. Carbon benefits are modeled as the difference between carbon in trees at ***t*** = 0 (bare ground, no carbon present) and ending forest carbon stock at ***T*** $\leq$ 50 years. The amount of carbon sequestered depends on the forest's growth ***g***, which is determined utilizing the Hafley and Smith NCSU Growth and Yield model equations.

$$\boldsymbol{C} = \sum_{t=0}^{T}(g) \tag{3}$$

$$\boldsymbol{g} = f_2(w, x, y, T) \tag{4}$$

Product carbon storage (kg of CO_2 eq./acre/year) was measured as products from one acre of forestland utilizing the 100-year method. The 100-year method considers any carbon remaining in wood products in use or in landfills after 100 years as permanently stored (Galik et al. 2009b). Objective ***P*** represents maximization of the annual amount of carbon in products $\boldsymbol{w_p}$ (storage minus emissions) which is permanently stored, carbon dioxide emission savings from product substitution of construction materials $\boldsymbol{s_c}$, and carbon dioxide emission savings from product substitution of fossil fuels $\boldsymbol{s_f}$.

$$\boldsymbol{P} = \sum_{t=0}^{T}(\boldsymbol{w_p} + \boldsymbol{s_c} + \boldsymbol{s_f})/T \tag{5}$$

$$\boldsymbol{w_p} = f_3(w, x, y, T) \tag{6}$$

$$\boldsymbol{s_c} = f_4(w, x, y, T) \tag{7}$$

$$\boldsymbol{s_f} = f_5(w, x, y, T) \tag{8}$$

The feasible set for each objective included constraints on the growth of the loblolly pine due to site productivity, forest management practices through the set of specified ranges, and non-negativity.

Solution Approach

Optimization Solver

An operational model will have a greater potential for utilization, if it can be solved with easily assessable, relatively inexpensive, and user-friendly software. Microsoft solver is one of the most widely released and employed general-purpose optimization modeling systems (Fylstra et al. 1998), which makes it an excellent candidate to solve an operation level model. Thus, it was chosen as the optimization solver.

Compromise Programming

Compromise programming was applied to minimize the gap between the achieved levels of SEV ***S***, carbon storage in the forest ***C***, and carbon dioxide emission savings from product storage and substitution ***P*** and the best values of each objective. The compromise equation scaled each objective by the inverse of its range, which allowed us to analyze the different objectives together. The objective of this study was to find the combination of stand management activities that maximized the objectives. A feasible land management strategy $\in$ *Feasible Set* is defined in terms of a multiple objective programming model criteria:

$$\boldsymbol{f_q},\ q \in Q = \{\mathbf{S, C, P}\} \qquad (9)$$

Where:

$$\boldsymbol{f_S} = S \qquad (10)$$

$$\boldsymbol{f_c} = C \qquad (11)$$

$$\boldsymbol{f_p} = P. \tag{12}$$

The ideal point L_p is calculated as follows:

$$\boldsymbol{L_p(x)} = \left\{\sum_{i=1}^{n} a_i^p \left|\frac{f_i^* - f_i(x)}{f_i^* - f_{i,w}}\right|^p\right\}^{\frac{1}{p}} \tag{13}$$

Where: $\boldsymbol{n}$ is the number of objectives, $\boldsymbol{a_i}$ is the weight; $\boldsymbol{f_i^*}$ is the best value of the $\boldsymbol{i^{th}}$ criterion; $\boldsymbol{f_{i,w}}$ is the least optimal criterion, and $\boldsymbol{f_i(x)}$ is the result of implementing decision $\boldsymbol{x}$ with respect to the $\boldsymbol{i^{th}}$criterion (Gershon 1982). There are three objectives in this analysis. The distance parameter $\boldsymbol{p}$ can be between 1 and infinity; it takes into account the decision maker's risk attitude and prevents the need for predetermined weights. If $\boldsymbol{p}$ equals 1 the decision maker is considered risk neutral, and the solution is considered the compromise min sum or compromise average program. If $\boldsymbol{p}$ equals infinity, the decision maker is considered to have a high risk aversion (Krcmer 2005). For this model, a $\boldsymbol{p}$ value of 100 was employed to simulate a decision maker with relatively high risk aversion, and each objective was weighted equally. Positive and negative deviations were considered equally to calculate the smallest overall absolute deviation from the target structure.

The model was first solved for each objective separately (benchmark runs) with the model set at SI 65. All constraints that define the feasible set were in place, and an additional constraint was added to make harvests produce at least 6 cords of wood to prevent uneconomical harvests. Then the values of the remaining criteria were computed at each objective's optimal solution. The results can be seen in Table 3 below.

Table 3
Values Obtained from the Developed Model (SI 65) by Optimizing each Objective Separately

Model objective	SEV ($/acre)	Forest carbon (kg of CO_2 eq./acre)	Emission savings from product storage & substitution (kg of CO_2 eq./acre/year)
Maximize SEV ($/acre)	$1224 ($3024/hectare)	199713 (493484 kg of CO_2 eq./hectare)	1797 (4440 kg of CO_2 eq./hectare/year)
Maximize carbon in forest (kg of CO_2 eq./acre)	$923 ($2281/hectare)	346043 (855061 kg of CO_2 eq./hectare)	1824 (4507 kg of CO_2 eq./hectare/year)
Maximize carbon in products and product substitution (kg of CO_2 eq./acre/year)	$902 ($2229/hectare)	214644 (530378 kg of CO_2 eq./hectare)	2016 (4981 kg of CO_2 eq./hectare/year)

Planting density, residual thinning density, and the thin year were increased, while the rotation age was decreased when managing for carbon dioxide emission savings from product storage and substitution as opposed to SEV. Maximizing for forest carbon produced very similar management practices as maximizing for carbon dioxide emission savings from product carbon and substitution except that the rotation was extended. Table 4 shows the management regimes for each benchmark scenario, where only one objective is maximized.

Table 4
Management Regimes for each Benchmark Scenario (SI 65)

Scenario	Planting density (TPA)	Residual Thinning Density (BA in square feet/acre)	Thin Year	Rotation (years)
Max SEV	381 (941 TPH)	65 (15 square meters/hectare)	20	37
Max Ending Forest	575 (1421 TPH)	131 (30 square meters/hectare)	22	50
Max Product and Substitution	575 (1421 TPH)	130 (30 square meters/hectare)	22	28

Graphs with the results of constrained planting densities, residual thinning densities, thinning years, and rotation lengths for each of the objectives are shown in figures 2-5 below. The results are for SI 65. Models were solved without minimum harvest constraints, and polynomial trend lines were added for each of the objectives.

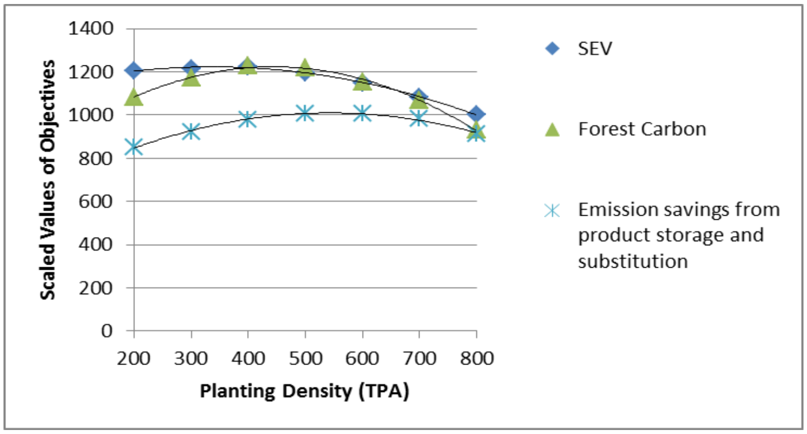

Figure 2. The Developed Model Results for Planting Density. The values of two of the objectives have been scaled so that all three objectives fit on one graph. Forest carbon sequestration (kg of CO_2 eq./acre) was divided by 300, and annual carbon dioxide emission savings from product storage and substitution (kg of CO_2 eq./acre/year) was divided by 2. SEV ($/acre) was not scaled.

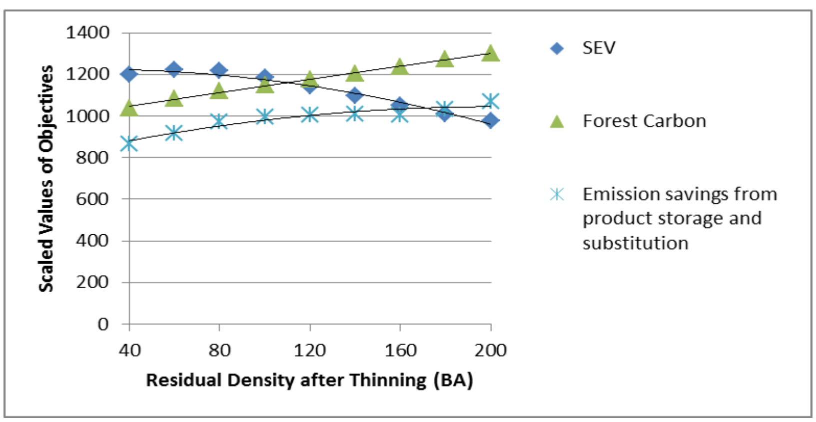

Figure 3. The Developed Model Results for Residual Thinning Density. The values of two of the objectives have been scaled so that all three objectives fit on one graph. Forest carbon sequestration (kg of CO_2 eq./acre) was divided by 300, and annual carbon dioxide emission savings from product storage and substitution (kg of CO_2 eq./acre/year) was divided by 2. SEV ($/acre) was not scaled.

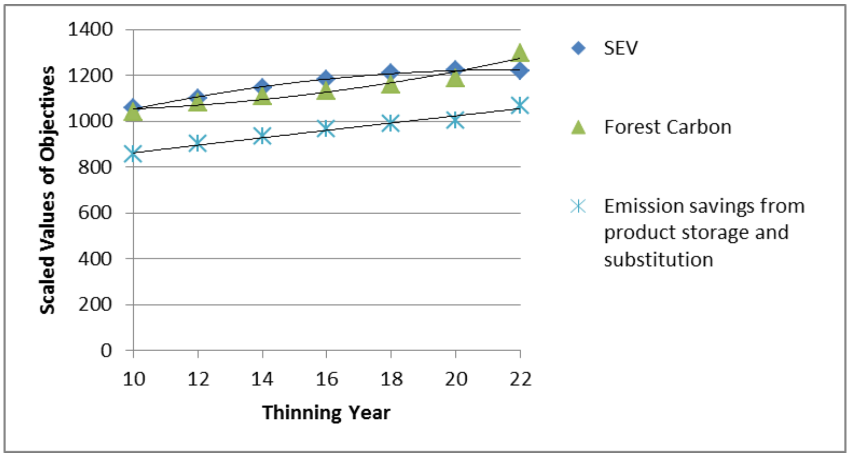

Figure 4. The Developed Model Results for Thinning Year. The values of two of the objectives have been scaled so that all three objectives fit on one graph. Forest carbon sequestration (kg of CO_2 eq./acre) was divided by 300, and annual carbon dioxide emission savings from product storage and substitution (kg of CO_2 eq./acre/year) was divided by 2. SEV ($/acre) was not scaled.

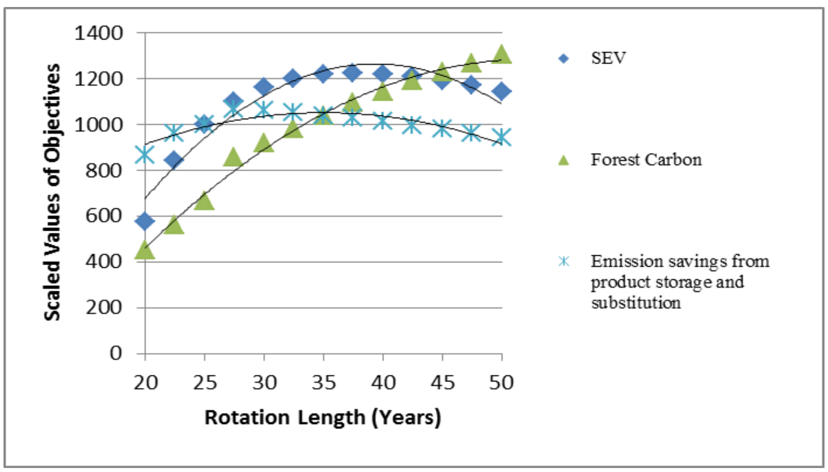

Figure 5. The Developed Model Results for Rotation Length. The values of two of the objectives have been scaled so that all three objectives fit on one graph. Forest carbon sequestration (kg of CO_2 eq./acre) was divided by 300, and annual carbon dioxide emission savings from product storage and substitution (kg of CO_2 eq./acre/year) was divided by 2. SEV ($/acre) was not scaled.

The optimal rotation for each of the single objectives solutions were also analyzed and compared to rotations at the mean annual increment. Optimizing management only for SEV or for maximum carbon dioxide savings from product carbon and substitution produced harvests at the peak mean annual increment, but optimizing management only for ending forest carbon yielded a harvest 22 years after the peak mean annual increment.

Application Results and Discussion

After solving for the optimal solutions for each objective, compromise programming was employed to solve for $\boldsymbol{p}$ = 100. For this problem, an additional constraint was added to make all changing variables integers. The integer constraint prevented half of a tree from being planted or harvested.

Optimizing management for multiple objectives of SEV, ending forest carbon, and carbon dioxide emission savings from product carbon and substitution extended the harvest beyond the peak mean annual increment. The compromise programming solution improved SEV by \$194/acre (\$479/hectare) over maximizing only carbon dioxide emission savings from product storage and substitution. It improved forest carbon by 86,789 kg of CO_2 eq./acre (214,453 kg of CO_2 eq./hectare) over maximizing only SEV. It improved carbon dioxide emission savings in product storage and substitution by 137 kg of CO_2 eq./acre (339 kg of CO_2 eq./hectare) over maximizing only SEV. The compromise programming solution was \$128 per acre (\$316 per hectare) less than if the forest landowner maximized solely for SEV. Over the 39 year rotation period, the compromise solution produced an extra savings of 5.343 tonnes of CO_2 eq./acre (13.2 tonnes of CO_2/hectare) compared to the SEV solution; average cost per tonne of CO_2 eq. was \$24. The results of the multiple-objective solution compared to the single objective solutions can be seen in Table 5 below.

Table 5
Difference between the Model (SI 65) Results for Compromise Solution and Maximizing each Objective Separately

Model objective	SEV ($/acre)	Forest carbon (kg of CO_2 eq./acre)	Emission savings from product storage & substitution (kg of CO_2 eq./acre/year)
Compromise Solution	$1096 ($2708/hectare)	286502 (707937 kg of CO_2 eq./hectare)	1934 (4779 kg of CO_2 eq./hectare/year)
Maximize each objective separately (Best solutions)	$1224 ($3024/hectare)	346043 (855061 kg of CO_2 eq./hectare)	2016 (4981 kg of CO_2 eq./hectare/year)
Maximize each objective separately (Worst solutions)	$902 ($2229/hectare)	199713 (493484 kg of CO_2 eq./hectare)	1797 (4440 kg of CO_2 eq./hectare/year)
Improvement over worst solution with compromise programming	$194 ($479/hectare)	86789 (214453 kg of CO_2 eq./hectare)	137 (339 kg of CO_2 eq./hectare/year)

For verification of the optimization model's growth and yield predictions, the optimal result from the compromise model was compared to the established Hafley and Smith NCSU Growth and Yield model. The growth and yield model predicted 2538 cubic feet/acre (178 cubic meters/hectare) in construction material from the thinning and final felling, while the optimization model predicted 2669 cubic feet/acre (187 cubic meters/hectare); the results were within 5% of each other. The total pulpwood prediction (thinning and final felling) for Hafley and Smith NCSU Growth and Yield model was 2280 cubic feet/acre (160 cubic meters/hectare) versus 2100 cubic feet/acre (147 cubic meters/hectare) for the optimization model; the results were within 9% of each other. Overall, Hafley & Smith NCSU predicted a total of 4818 cubic feet/acre (337 cubic meters/hectare) whereas the optimization model predicted 4769 cubic feet/acre (334 cubic meters/hectare); the results were within 1% of each other. In addition the model results were compared to Smith et al. (2006) for the average amount of carbon stored in products. Smith et al. estimated that 4504 cubic feet/acre (315 cubic meters/hectare) could be harvested with a 25 year rotation of loblolly pine on high intensity sites with high intensity management, and 16.6 tonnes of carbon/acre (41 tonnes of carbon/hectare) would go to products in use. Our model produced a lower estimate; 4313 cubic feet/acre (302 cubic meters/hectare) could be harvested with a 25 year rotation of loblolly pine (SI 75), and 11.9 tonnes of carbon/acre (29.4 tonnes of carbon/hectare) would go to products in use; the results are within 25% of each other.

Although the cost of managing loblolly pine for multiple objectives including carbon was calculated to be $24/tonne of CO_2 eq., this is not necessarily what a government would utilize as the cost of managing a forest for carbon. It was the cost calculated for the equally weighted, specified model objectives and non-decision parameters (examples include: site index, discount rate, costs, and prices). To demonstrate the importance of the non-decision variables, alternative discount rates were employed for the SI 65 loblolly pine example. Keeping all other specified model objectives and non-decision parameters the same, the model was resolved with new discount rates. A graph of the costs per tonne of carbon dioxide eq. with different discount rates is shown in figure 6 below. As can be seen in the graph, higher discount rates have lower costs of carbon in this example.

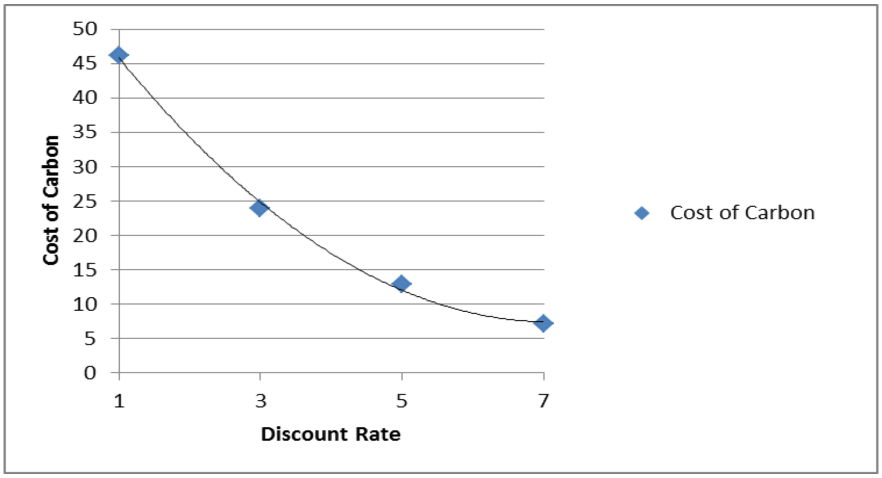

Figure 6. The Effect of Discount Rate on the Cost of Multiple-Management for Carbon.

This optimization model does not include soil organic carbon specifically in the calculations. Some researchers in the past have assumed no change in soil organic carbon if no changes in land use occurred (Krcmer et al. 2005, Woodbury et al. 2007). This model considered only sustainable forest management and no land use changes. However, certain studies have shown that intensive management decreases the soil organic carbon (Peng et al. 2002, Sarkhot et al. 2007, Jimenez et al. 2008). Without the right level of soil organic carbon, the land might not be able to produce plants long-term (Sanchez et al. 2003). To incorporate this concern into the model, growth and yield equations were analyzed for three different site indices (55, 65, 75) at a base age of 25.

For this example, an increase in site index allowed an increase in planting density, a decrease in thinning year, and an increase in the residual basal area; however, rotation ages stayed very similar for the different site indices. These calculations demonstrate that if intensive forest management decreases the soil organic carbon and site index values, it would decrease carbon sequestration and SEV. For this example, a site index decrease of 10 feet (3.048 meters) led to an approximate decrease of $550-$730/acre in SEV ($1,359-

$1,804/hectare), of 87,000-117,000 kilograms of CO_2 eq./acre (214,974-289,103 kilograms of CO_2 eq./hectare) in ending forest carbon, and of 590-640 kilograms of CO_2 eq./acre/year (1,458-1,581 kilograms of CO_2 eq./hectare/year) of emission savings from product storage and substitution. Table 6 shows the compromise solution for each of the site indices.

Table 6

Compromise Solutions for Models with Different Site Indices

Model	SEV ($/acre)	Forest carbon (kg of CO_2 eq./acre)	Emission Savings from product carbon & substitution (kg of CO_2 eq./acre/year)	Planting density (TPA)	Thin year	Residual Thinning Density (BA in square feet/acre)	Rotation (years)
SI 55	$549 ($1357/ hectare)	199750 (493575 kg of CO_2 eq./hectare)	1340 (3311 kg of CO_2 eq./hectare/year)	424 (1048 TPH)	22	89 (20.4 square meters/hectare)	40
SI 65	$1096 ($2708/ hectare)	286502 (707937 kg of CO_2 eq./hectare)	1934 (4779 kg of CO_2 eq./hectare)	476 (1176 TPH)	21	120 (27.6 square meters/hectare)	39
SI 75	$1821 ($4500/ hectare)	403518 (997079 kg of CO_2 eq./hectare)	2578 (6370 kg of CO_2 eq./hectare)	487 (1203 TPH)	17	124 (28.5 square meters/hectare)	41

In addition, the cost per tonne of CO_2 eq. was calculated for SI 55 and SI 75. The cost per tonne of CO_2 eq. for SI 55 was $7.48 per tonne of CO_2 eq.; an additional 10.16 tonnes of CO_2 eq. in emission savings from product storage and substitution was produced over the rotation for $76. The cost for SI 75 was $147.87 per tonne of CO_2 eq.; an additional 1.312 tonnes of CO_2 eq. in emission savings from product storage and substitution was produced over the rotation for $148. Since very few additional CO_2 eq. were saved in the compromise solution for SI 75, the cost per tonne of CO_2 eq. was very high compared to SI 55 and SI 65.

Conclusions

Although recently several authors have written about carbon sequestration in southern tree species (Nepal et al. 2012, Sohngen and Brown 2008, Smith et al. 2006), it can be hard to compare studies due to differences in objectives, products included, and non-decision variables. Furthermore, very few studies take into account substitution of products and fuels. Recent work by Nepal et al. (2012) and Sohngen and Brown (2008) focused on increasing product storage through extended rotations. Extending the rotation brings more carbon for the single rotation but does not necessarily bring more carbon for multiple-rotations, unless the rotation length is based on the maximum annual rate of carbon storage.

Our developed model accounted for multiple-rotations of loblolly pine rather than for a single rotation as some previous studies have done. If our study had maximized emission savings for product storage and substitution for a single rotation rather than for multiple-rotations (SI 65), the rotation length would have been increased from 39 years to 46 years. Emission savings for the entire rotation is larger for a 46 year rotation (as opposed to the 39 year rotation) when comparing single rotations but is not larger over multiple-rotations. For example, the 39 year rotation length saved 1.934 tonnes of CO_2 eq./acre/year (4.779 tonnes of CO_2 eq./hectare/year) in product storage and substitution whereas the 46 year rotation saved 1.796 tonnes of CO_2 eq./acre/year (4.438 tonnes of CO_2 eq./hectare/year). Over 100 years, an additional 414 million tonnes of CO_2 eq. would be saved, if the 30 million planted acres (12.14 million hectares) of loblolly pine in the U.S. (Smith et al. 2009) were optimized for multiple-rotation multiple-objective management rather than single rotation multiple-objective management.

Our multiple-rotation multiple-objective model estimated a cost of \$24/tonne of CO_2 eq. for an increased optimal rotation of 2 years in the loblolly pine example. Sohngen and Brown (2008) estimated that 15 million tonnes of CO_2 could be sequestered for less than \$7/tonne CO_2 and up to 209 million tonnes of CO_2 could be sequestered for \$55/tonne of CO_2. Nepal et al. (2012) estimated that forest landowners would need a carbon price of \$50/tonne CO_2 equivalent to increase the rotation age by 5 years.

It is important to note that the non-decision variables such as weights, discount rates, site index, costs, and prices do affect the cost of carbon. The weight parameter changes the relative importance of each objective according to decision maker; it is necessary because different decision makers will have varying viewpoints concerning what is important (Prodanovic and Simonovic 2003). Similar to Krcmar et al. (2005) equal weights were employed in the compromise programming solution for our loblolly pine example. The choice of a preferred solution, found using alternative sets of weights, is a value statement which is out of the realm of quantitative analysis and into the realm of politics. The methodology utilized provides efficient solutions (Pareto optimality) for decision makers to choose between, it does not make political decisions.

The model developed in this study included operational level management variables, which makes it useful for providing guidance at the ground level, and it can be utilized to investigate competing forest management objectives including product storage and substitution. Even though the model was developed for Southeastern U.S. foresters growing loblolly pine, equations can be changed easily to different tree species and more active management regimes. Many different stakeholders will be involved in climate change policies, and for a policy to be passed, it will be important for the model to able to demonstrate the tradeoffs between multiple objectives for each forest type. Although costs will vary among forest types, site indices, and regions, to encourage carbon sequestration in forests at a large scale, a policy will have to include a payment of at least the amount in foregone profits. A science based decision analysis model that can allow environmental policy makers to compare tradeoffs will be very beneficial in ensuring the development of economically viable policies for forest landowners and effective carbon sequestration policies for the environment.

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CHAPTER 3

Decision Analysis Models to Effectively Integrate Forests into Climate Change Policies

Preface

Chapter 3 is a manuscript that will be submitted to Forest Policy and Economics. The manuscript was written by Laurie Gharis, Joseph Roise, and Fred Cubbage. Dr. Roise's and Dr. Cubbage's contributions to the manuscript are expert advice on the utilization of optimization models for policy development, rough draft revisions to the manuscript, and final approval of the manuscript. My contribution to the article was to conduct all research, to develop a policy framework, to provide an example application of the policy, and to write the manuscript.

Abstract

Decision analysis models can help decision makers integrate carbon sequestration and carbon dioxide emissions to develop successful climate change policies. We demonstrate how the collective good of forest carbon sequestration can be valued by utilizing a previously developed compromise programming model to investigate optimal stand level management for *Pinus taeda* with the competing objectives of maximum economic value, forest carbon sequestration, and carbon dioxide emission savings from product storage and substitution. The optimal solution for loblolly pine, under the specified objectives and non-decision parameters, decreased soil expectation value by \$128/acre (\$316/hectare) and increased carbon dioxide emission savings by 5.343 tonnes of CO_2 eq./acre/rotation (13.2 tonnes of CO_2 eq./hectare/rotation) as compared to managing the stand solely for economic value. We show how the government could connect

forest carbon sequestration with the two largest carbon dioxide emission sectors through an integrated cap-and-trade and carbon tax policy. Under the policy, a government would agree to buy a certain percentage of timberland carbon offsets for the amount in foregone profits from managing for multiple objectives (rather than a single economic objective), if the offsets were not first bought by the capped electricity generation entities. For the loblolly pine example with the specified objectives and non-decision parameters, the cost of carbon was $24/tonne of CO_2 equivalents. At this cost, a carbon tax of approximately $0.01/gallon of fuel would allow the government to buy 78 million tonnes of CO_2 equivalents of offsets. This type of climate change policy, if implemented on a large scale, could effectively and efficiently value carbon on different timberlands, decrease emissions by the transportation and the electricity generation sectors, and increase carbon sequestration through the forest sector.

Keywords climate change, environmental policies, decision analysis model, economic valuation, forest management, collective good

Introduction

The United Nations Secretary-General recently described climate change as a serious risk to global peace and security (UNFCCC 2011). By 2010, greenhouse gas (GHG) levels had climbed 39% above preindustrial levels. The Intergovernmental Panel on Climate Change's (IPCC) fourth assessment report stated that anthropogenic GHGs were likely linked to the current rise in the global average temperature (IPCC 2011). With increasing evidence of climate change, an effective climate change policy must be developed.

Many suggested climate change policies focus on decreasing fossil fuel combustion as it produces the most anthropogenic GHG emissions (IPCC 2011). However, opportunities also exist to mitigate climate change by increasing carbon sinks and carbon offsets (Lippke et al. 2011). Of the five economic sectors that are considered sources of anthropogenic GHGs by the UNFCCC, only LULUCF category can also remove GHGs from the atmosphere. With approximately 10 billion acres (4 billion hectares) of forest land sequestering 289 gigatonnes of carbon in biomass alone (FAO 2010), carbon flux in forests should be an integral section in climate change policies. Forests can store carbon, replace fossil fuel intensive products, and provide renewable energy (Schlamadinger et al. 2007).

Effective climate change policies must resist focusing solely on forest carbon, as forest carbon sequestration is ecologically limited by site productivity, species and natural disturbance (Hennigar et al. 2008). Instead policies should take into account that harvesting wood products can prevent the saturation of forest carbon stocks by providing product substitution and storage (Lippke et al. 2011). Forest carbon stocks can be sustained while society continues to receive a flow of fiber, timber, and energy, if the annual harvest is fixed at or below the annual forest increment (IPCC 2007a). The benefit of carbon emission savings from wood products being substituted for non-wood products continues throughout time. However, if forests are allowed to reach the point of saturation, carbon is emitted throughout time by the forest reaching equilibrium and by more fossil fuel intensive products being utilized rather than wood products (Eriksson et al. 2007).

According to the 2010 Forest Resources Assessment, Russia, Brazil, Canada, and the U.S. account for more than 50% of the world's forested land. Approximately 62 million acres (25 million hectares) or 8% of forested land in the U.S. is considered planted forests; the percentage of planted forests increased 1.18% each year between 2000 and 2010 (FAO 2011). In 2007, almost 66% (514 million acres or 208 million hectares) of the nation's forest land was categorized as timberland, and 69% of this land was owned privately (Smith et al. 2009).

Over the past four decades, wood removals have fluctuated widely suggesting that forest owners and managers vary supply quickly depending on the level of demand and prices of wood products. Due to the economic and housing crises in the U.S., industrial round wood removals have decreased by approximately 30%. After 2005, wood prices also dropped significantly (FAO 2011), but the costs of most common forest management practices have not dropped (Barlow et al. 2009). Decreasing wood prices and increasing forest management costs provide a positive incentive for converting forest lands. Integrating a forest carbon policy into a climate change policy could make forests more profitable and reduce the incentive for forest conversions. With a high percentage of the world's forested land, the majority of forested land owned privately, and increasing percentages of planted forests, the U.S. provides an ideal place to employ this type of climate change policy.

The objective of this paper is to provide a methodology and an example of how forested land can be effectively and efficiently integrated into climate change policy in the U.S. The second section of the paper will discuss tenets of successful environmental policies. The third section will review environmental policies and programs in the U.S. and demonstrate how carbon sequestration might be improved in some of the programs. The fourth section will describe the proposed carbon policy. The fifth section will provide a conclusion and suggestions for future research.

Tenets of Successful Environmental Policies

Rationale for Carbon Sequestration

A policy for carbon sequestration must presume that the market does not work effectively, but that the market can be modified so that it will work effectively. Both carbon sequestration and carbon dioxide emissions affect climate change and could be considered in policy analyses. Carbon sequestration is considered a collective good. This type of good is described as non-rival, jointly consumable, and not excludable. It can be challenging or impossible to limit or to charge for this type of good in a pure market (Cubbage et al. 2007). Carbon dioxide emissions are externalities and current markets fail to treat them appropriately; people do not pay for the social consequences of the carbon dioxide emissions stemming from their purchases.

Without realistic prices of carbon, economic decisions concerning consumption, investment, and innovation will not be appropriate (Nordhaus 2009). If externalities generate serious problems, then government intervention might be required. Forest regulatory and incentive programs have been created most often due to externalities (Cubbage et al. 2007). People receive benefits from the regulation of ecosystem processes, such as climate and water flow (Thompson et al. 2011). To better ensure a stable climate in the future an effective climate change policy is necessary to regulate the collective good and to prevent externalities originating from carbon dioxide emissions.

Successful Environmental Policies

Much research has been conducted on what makes environmental policies successful. Efficient policies balance trade-offs between the strictness of a target and the number of options players can employ to meet the goal; they decrease the cost of reaching targets and thereby make meeting the strict requirements less expensive (Portney and Stavins 2000); they are quantifiable, practical, and transparent (Gosnell et al. 2011). Good policies keep costs low while still maintaining accuracy and precision (Pearson et al. 2008).

Effective climate change policies include emissions and offsets in carbon accounting (Malmsheimer et al. 2011); they take into account product carbon and substitution effects (Lippke et al. 2010). Successful policies incorporate permanence, leakage, and uncertainty (Murray and Baker 2011). They don't lead to new emissions elsewhere (Cooley and Monast 2011) or increase food scarcity (Murray and Baker 2011). Environmental policies can be enhanced by including economic valuation of environmental systems because it allows policy makers to allocate limited public resources rationally between conflicting economic, social, and environmental policy goals (Thompson et al. 2011). Effective climate change policies focus on encouraging and maintaining good land stewards (Gosnell et al. 2011). Lack of a carbon sequestration value, different stakeholders, and many policy goals are just a few reasons why a successful climate change policy could be challenging to design, but as with other policies, if effectiveness and efficiency are balanced, transparency is provided, and care is taken to incorporate integral elements, an effective policy can be developed.

Environmental Policies and Markets

Many different types of environmental policies exist; each with unique mechanisms to encourage specific behaviors. This section will describe some of the current environmental policies and markets, including current carbon sequestration policies, and it will provide examples of how carbon sequestration can be enhanced in current programs. The section will provide a context to suggest how carbon policies for forests could work.

Examples of Environmental Policies and Markets

Laws such as the Clean Water Act and the Endangered Species Acts have led to offset and mitigation credits to protect particular ecosystems and environmental resources (Cooley and Olander 2011). Hundreds of millions of dollars are contributed annually to the domestic product due to mitigation credits emerging from just the Clean Water Act (EPA 2009). Three examples of programs originating from these mandates are wetland mitigation (Normanly and Vacca 2007), Fort Hood's Recovery Credit System for the Golden Cheeked Warbler (GCWA) (Cloud 2009), and the Healthy Forests Reserve Program (HFRP) (USDA NRCS 2011).

Cap-and-trade programs have received a substantial amount of attention by researchers and politicians. This type of program can include carbon sequestration activities of forests as offsets. Industries that over pollute can buy offsets from participating landowners. Forest landowners can participate by decreasing their emissions and/or increasing sequestration of their lands through afforestation, reforestation, preventing conversions, and/or changing forest management practices (Pearson et al. 2008). Many different protocols exist or have existed in the U.S. Examples include the Chicago Climate

Exchange, California Climate Action Reserve, The Climate Registry, California's AB 32 Scoping Plan, and the Regional Greenhouse Gas Initiative. Studies conducted on cap-and-trade protocols have shown that carbon prices and carbon sequestration amounts can vary tremendously between protocols due to different baselines and eligible pools of carbon (Galik et al. 2009b and Pearson et al. 2008). Furthermore, costs for participating can be expensive due to implementation costs, measurement requirements, and regulatory oversight (Pearson et al. 2008), and the integrity of offset projects can be difficult to ensure due to concepts of baselines, additionality, permanence, and leakage (Cooley and Monast 2011).

Another possible approach for bringing together private and public values in land management is through payment for environmental services (PES). Many different examples of PES can be seen in the U.S. One of the oldest examples of PES is the U.S. Department of Agriculture (USDA) Conservation Reserve Program (CRP). Over 30 million acres (12 million hectares) are registered as CRP land, and \$1.8 billion is paid out annually by the program (USDA FSA 2012). Other examples of PES are the USDA's Farm Service Agency (FSA) Longleaf Pine Program (USDA FSA 2006), the Denver Water/U.S. Forest Service's proactive fire management and resource protection program (Denver Water 2010), and the Willamette Market (Primozich and Vickerman 2007). PES examples show how a market can be developed for a previously "free" good and how buyers and sellers can be connected to make investments in good land stewardship, which benefit landowners and society (Goldstein et al. 2011).

Tax incentives have also been employed to maintain or to increase forests. Two examples of tax incentives are North Carolina's Forestry Present Use Property Tax Program

(Megalos et al. 2011) and the Reforestation Tax Incentive (IRS 2011). Incentives such as these should not be overlooked. Since 1953, increased urbanization has led to declines of 5% in forest land in the North and South regions; however, government sponsored tree planting programs have been credited for preventing greater declines from being realized (Smith et al. 2009).

Although most approaches to protect or to increase environmental services have been policy approaches, other options do exist. Forest certification is an example of developing a new market for environmental goods without government policies. Certification requires management planning for multiple objectives and monitoring of results. It encourages science-based forest management (Thompson et al. 2011) and gives an independent review to forest landowners of their management practices through third-party audits (Rametsteiner and Simula 2003). Certification options for U.S. forest landowners include the American Tree Farm System (ATFS), the Forest Stewardship Council (FSC), and the Sustainable Forestry Initiative (Moore 2007).

Difficulties in Developing Current Programs into Effective Climate Change Policy

Many of the discussed programs include some measure of carbon sequestration or could include carbon sequestration. However, the programs often include competing objectives without a model for comparing trade-offs and/or do not take into account the carbon storage and substitution abilities of harvested wood products. Table 7 provides examples of changes that could be tested for enhanced carbon sequestration by current programs.

Table 7
Possible Examples of How Current Policies and Mechanisms Could Be Changed to Increase Carbon Sequestration

Mechanism	**Change**
CRP	Permit undiscounted, annual revenues for forest harvests, as long as forests are managed sustainably
HFRP	Employ multiple-objective programming to find a better solution for the competing goals of habitat, diversity, and carbon sequestration
California's AB 32 Scoping Plan	Integrate substitution of wood products for fossil fuel intensive products into program
RGGI	Include forest management, wood products, and product substitution in program
Forest certification	Employ multiple-objective programming to demonstrate trade-offs between economic, environmental, and social issues

Although many of the current programs provide avenues for carbon sequestration, few have large scale potential for reducing national carbon dioxide emissions. For example, the CRP is currently the largest private lands carbon sequestration program in the U.S. (USDA FSA 2012) but penalizes harvests (Mapemba et al. 2007), which can prevent forest carbon saturation (Eriksson et al. 2007). The HFRP has a carbon sequestration objective but also has two other competing objectives of diversity and habitat (USDA NRCS 2011) and no model to show tradeoffs. Furthermore, forest landowners who certify their forests do not receive higher prices for their certified timber (Rametsteiner and Simula 2003), and although the regional programs, California's AB 32 Scoping Plan and Regional Greenhouse Gas Initiative, connect some forest sequestration with carbon dioxide emissions, they do not include important substitution potential or provide accurately priced carbon storage incentives. An accurately priced, national incentive is necessary to make a large scale difference in U.S. forest carbon sequestration.

Multi-Objective Programming Policy Contributions

The Model

Gharis et al. (2012) developed a model to investigate optimal stand level management with the competing objectives of maximizing soil expectation value, forest carbon sequestration, and carbon dioxide emission savings from product storage and substitution. The model was built to provide an accurate and useable analytical product for Southeastern U.S. foresters growing loblolly pine (*Pinus taeda*) in the presence of carbon policies. At 30 million acres (12 million hectares), loblolly-shortleaf pine makes up the greatest portion of planted forests (Smith et al. 2009) and provides an excellent opportunity for increasing carbon sequestration. Traditional stand level management variables of planting density, thinning timing and density, and rotation length were utilized in the model. Over time these variables influence the proportion of wood going into pulp, chip-n-saw, and sawtimber where each of these classes has an expected use (carbon storage) life. Compromise programming was employed to solve the multiple-objective problem by minimizing the gap between the achieved levels of objectives and the best objectives (Krcmer et al. 2005). The soil expectation value (SEV) of the compromise solution (with equally weighted objectives and specified non-decision parameters including a SI 65 and real discount rate of 3%) was $1096 per acre ($2708 hectare). The optimal management regime provided an additional 5.343 tonnes CO_2 eq./acre/rotation (13.2 tonnes CO_2 eq./hectare/rotation) in emission savings from product storage and substitution but decreased the SEV by $128/acre ($316/hectare), which amounted to a carbon cost of approximately $24 per tonne of CO_2 eq. (Gharis et al. 2012). This value is similar to the range of carbon values found by Nepal et al. (2012), Sohngen and Brown

(2008), and Australia's proposed fixed carbon price (ASX 2012). However, it is more than values found on the Chicago Climate Exchange for generic credits before it closed (Gosnell et al. 2011) and recent values found on the European Union Emissions Trading System (BBC 2011).

In addition to taking into account additionality over a BAU baseline, the model can incorporate leakage and permanence. The probability of leakage can be decreased by the model's production approach. Contrary to the production approach, mitigation efforts that focus on decreasing production or taking lands out of production have the potential to encourage the use of other lands to make up for losses in production, which can cause leakages (Murray and Baker 2011). Furthermore, permanence can be added to the model by mandating a reserve pool (Malmsheimer et al. 2011). Similar to other programs, the reserve pool could be set at 10% (Cloud 2009). The model could be practical and effective, but how can it be used in a successful climate change policy?

An Application

A simple way to use this model in climate change policy would be through a pay-for-performance mechanism. The government could offer to buy a specific number of certified forest carbon dioxide eq. offsets at a fixed price (the foregone profits of managing for multiple objectives), if the offsets were not first bought by private industry within a five year fixed period. Landowners wanting to participate in the program would first have to certify their forests through a U.S. certification program (ATFS, FSC, or SFI). Certification would provide an upfront cost giving the forest landowner a better incentive to produce the offsets

(Pizer 2011). In addition, it would better ensure that ecological, economic, and social standards were met and sustainable forest management was maintained.

Studies have found that policies in terms of deployment objectives are most effective when the payments cover the project cost plus a profit (Couture et al. 2010). Forest landowners would bid in a reverse auction similar to Fort Hood's GCWA program (Goldstein et al. 2011) but their bids would be solely profit. Landowners with accepted bids would receive a payment to cover the cost of managing their timberlands optimally for the three objectives plus the agreed upon profit. The government could limit offsets to a certain percentage of each type of timberland. This type of approach limits the liability of the government by limiting the number of guarantees (Pizer 2011) but also allows offsets from all types of timberland to be purchased. A program aimed at increasing carbon sequestration on privately owned timberland will still maintain millions of acres in their normal status as parks, wilderness areas, and low productive forest lands capable of providing significant environmental benefits but will also have the potential to make significant contributions to carbon sequestration on privately owned timberland.

To decrease the likelihood of participants not following the optimal management practices, at least 10% of landowners would be randomly selected for in-field verification by the managing government agency along with timberlands in excess of 30,000 acres (12,141 hectares) for each auction period. This practice is similar to CCX's past Rangeland Soil Carbon Offset program (Gosnell et al. 2011). During in-field verification, owners would also be checked for under and over-performing timberlands. To address the difference between predicted and actual timberland results, a protocol would be developed and could include such options as offering an extra percentage in terms of over-performance, a deduction percentage in terms of underperformance, or an increase or a decrease in the reserve pool in accordance to the actual productivity of the timberlands (while still maintaining the mandatory reserve pool). In addition, to decrease chances of early termination of contracts, landowners would be required to pay back any money that they received from the government, for early termination of contract. This practice is similar to Fort Hood's GCWA program (Cloud 2009). The reverse auction could be conducted for the different timberland categories every five years. Five year intervals would allow the models to take into account changes in management practices and timber prices and would allow the best priced timberlands to produce an economically efficient collective good.

Theoretically, markets can be economically efficient and effective at allocating forest resources (Cubbage et al. 2007), and carbon taxes or cap-and-trade programs can be very efficient climate change policy mechanisms (Galik et al. 2009a). Therefore the proposed policy is a combined cap-and-trade and carbon tax. Both the cap-and-trade and the carbon tax will help decrease emissions and will offer an income generating opportunity to pay for carbon sequestration. The two largest GHG emission categories in the U.S. are the electricity generation sector (32.4% of all U.S. GHG emissions) and the transportation sector (25.9% of total U.S. GHG emissions) (EPA 2011a). Thus the policy will connect the two main emitters with forest carbon sequestration. The policy provides a more politically acceptable approach by capping and allowing trading (Portney and Stavins 2000) in the electricity generation sector but taxes the transportation sector, which would be more difficult to cap.

Between 1990 and 2009, U.S. electricity generation emissions were estimated to have increased by 18% (EPA 2011a). The proposed policy would transitionally cap the electricity generation sector by a small percentage each year for the next 10 years until levels are 5% below 1990 levels, similar to the Kyoto Protocol. The electricity generation sector could decrease emissions or pay for offsets from other electricity generation facilities or participating forest landowners. If the electricity generation sector buys offsets from the forestry sector, then the government no longer has the obligation to buy them.

If the electricity generation sector does not buy the offsets, the offsets would already be covered by a small, additional tax to petroleum products. The tax would include the amount of money necessary to pay for carbon sequestration services by forest landowners and to administer the program. Between 1990 and 2009, emissions were estimated to have increased by almost 16% in the U.S. transportation sector; petroleum products produced almost all of the end use energy for this sector (EPA 2011a). A tax on petroleum products would provide a rather simple and effective avenue to decrease carbon dioxide emissions and to increase revenue. Figure 7 gives a depiction of the proposed policy.

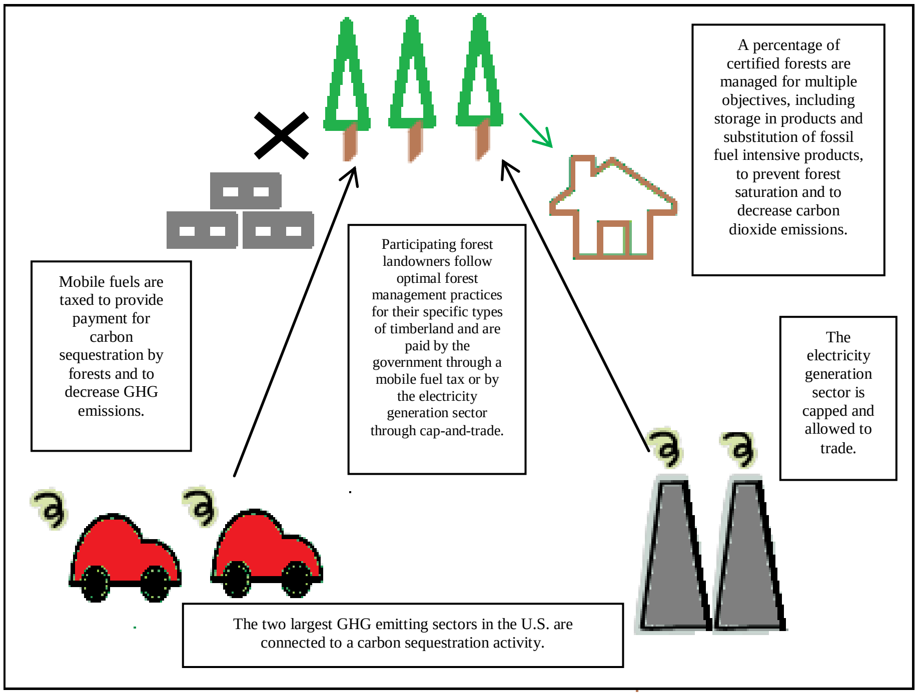

Figure 7. Depiction of the Proposed Climate Change Policy. This policy connects the two largest GHG emitting categories in the U.S. with a large carbon sequestration category. Participating forest landowners manage their certified timberland according to the optimal management plan for SEV, forest carbon, and carbon dioxide emission savings from product storage and substitution. The electricity generation sector is capped and allowed to trade, and mobile fuels are taxed to decrease carbon dioxide emissions and to pay for carbon sequestration by timberlands.

This policy would provide a revenue source to reward good land stewards for increasing forest sequestration, an incentive in the form of a cap to decrease GHG emissions from the electricity generation sector, and an incentive in the form of a tax to decrease GHG emissions from mobile sources. Furthermore, the policy takes into account harvested wood products and product substitution, which can prevent the saturation of forest carbon stocks (IPCC 2007a).

Example

An example of how the proposed policy would work is as follows. The compromise solution for loblolly pine demonstrates that carbon sequestration can be improved over the BAU scenario at a cost of $24/tonne of CO_2 eq. for the specified model and non-decision parameters. There are approximately 30 million acres (12 million hectares) of planted loblolly pine in the U.S. According to the model (Gharis et al. 2012), this amount of planted loblolly pine could prevent an extra 158 million tonnes of CO_2 eq. from going into the atmosphere. The government would auction half of this amount in a reverse auction to obtain the best priced offsets. Loblolly pine timberland owners wishing to participate would certify their timberland and would propose a profit per tonne of CO_2 eq. The best priced 79 million tonnes of CO_2 eq. would be accepted by the government. Accepted bids would be required to follow the management practices of the model and to maintain the required reserve pool.

For the loblolly pine example, optimal management for carbon sequestration is to plant 476 TPA (1176 TPH), to thin at year 21 leaving a residual basal area of 120 square feet/acre (27.6 square meters/hectare), and to harvest at year 39. As stated earlier, the electricity generation sector would be capped and allowed to trade, and thus would be interested in buying the offsets from forest landowners if the offsets were more economical than decreasing emissions or buying offsets from other electricity generating entities. Any government accepted loblolly pine CO_2 eq. offset not bought within the five year period by the electricity generating sector would be bought by the government.

A landowner with 5000 acres (2023.5 hectares) would produce an extra savings of 685 tonnes of CO_2 eq. per year (.137 tonnes of CO_2 eq./acre/year or .339 tonnes of CO_2 eq./hectare/year). At $24/tonne of CO_2 eq., the landowner could expect to receive at least $82,200 over five years for his carbon offsets. Approximately, 181,780.7 million gallons of mobile fuel were estimated to have been consumed in the U.S. in 2009 (EPA 2011b). Using these consumption rates, mobile fuels could be increased by a little over $0.01 a gallon to cover the 79 million tonnes of CO_2 eq. in emission savings produced by participating loblolly pine landowners.

To determine the potential of carbon dioxide savings from product carbon and substitution resulting from the optimized multiple-rotation, multiple-objective management model for loblolly pine (Gharis et al. 2012), a comparison was made between the forest sector and the two largest U.S. GHG emission sectors. In 2009, the U.S. electricity generation sector was estimated to have emitted 2146.4 million tonnes of CO_2 eq. and the U.S. transportation sector to have emitted 1720.1 million tonnes of CO_2 eq. (EPA 2011a). The optimal management solution for the loblolly pine example provided 1.934 tonnes of CO_2 eq./acre/year (4.779 tonnes of CO_2 eq./hectare/year) in emission savings from product storage and substitution; of this amount 0.137 tonnes of CO_2 eq./acre/year (0.339 CO_2 eq./hectare/year) was additional compared to the BAU baseline (Gharis et al. 2012). The 30 million planted acres (12 million hectares) of loblolly pine in the U.S. (Smith et al. 2009) could amount to a savings of 58.02 million tonnes of CO_2 eq. per year in emission savings from product storage and substitution but only 4.11 million tonnes of the CO_2 eq. would be considered additional. The total sequestration of U.S. planted loblolly pine from product storage and substitution is 2.7% (0.19% additional) of electricity emissions or 3.37% (0.24% additional) of transportation emissions. It is important to remember in this example that planted loblolly pine only make up a small portion (approximately 8%) of the nearly 355 million acres (144 million hectares) of timberland in the U.S. (Smith et al. 2009) whereas the emissions are nationwide.

Conclusion

The Obama Administration has stated that by the year 2025, the fleet-wide average standard will be 54.5 miles per gallon, which will eliminate 6 billion tonnes of carbon dioxide pollution (The White House 2012). However, if people continue to drive more miles as has been the case in the past (EPA 2011b) and fuel prices continue to be cheap, then high efficiency vehicles will not necessarily decrease carbon dioxide emissions from vehicles. On the other hand, a carbon price as found in a carbon tax or cap-and-trade program could be an efficient climate change policy mechanism because it has a positive impact in reducing GHGs, oil use, and government expenditures (Galik 2009a).

A policy such as this of course will face significant political and practical challenges to implementation, but the theory, compromise programming approach, and application described here can foster more discussion about how such an approach could be crafted. As shown in Gharis et al. (2012), it is possible to calculate a cost for multiple-objective management to include carbon. Climate change policies that pay less than the amount forgone by forest landowners managing for carbon rather than the BAU scenario will not be effective at enticing landowners to provide extra services. Although U.S. forest landowners currently provide carbon sequestration for free, decreased prices for wood, increased costs for forest management practices, and increases in urbanization could quickly persuade timberland owners to convert their land and to stop providing this collective good for free. If this were to happen, all benefits for the timberland would stop not just extra, carbon benefits.

Future research should focus on categorizing private timberland so that multiple-objective compromise programming models can be built. Models should include product carbon and substitution. If models can be built for all timberland categories, the cost of managing for multiple objectives including carbon will be better understood. Forests could be effectively integrated into a climate change policy employing this type of model. Future policy research could assess whether such mathematically elegant approaches are politically and practically realistic, and if so, how they could be funded and implemented. These are of course key to using such a policy eventually. The approach discussed here, however, does identify technically superior means to use forests to meet carbon reduction goals.

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CHAPTER 4

Concluding Remarks

A recent study conducted to consider the climate change mitigation potential of forest management practices recommended obtaining and continuously harvesting the maximum possible, sustainable increment in the forest, while still considering biodiversity, soil quality, and growth performance for the best overall mitigation potential (Werner et al. 2010). Due to scarce resources and many different stakeholders, a climate change policy will focus on more than carbon sequestration, and similar to what Werner et al. (2010) suggested, other objectives will be considered. It will be important for decision analysis models for forest carbon to be multiple-objective, so that trade-offs can be seen and discussed.

It is also important to recognize that non-decision parameters are necessary to develop models; these parameters can change the output of the model. For the developed model in this dissertation, many non-decision parameters were employed in order to calculate the cost of carbon. Objective weights, site indices, discount rates, timber prices, and management costs are a few of the non-decision parameters employed in this model. As discussed in chapter 2 changing the discount rate and the site index did affect the cost of carbon. The cost calculated in the dissertation is not necessarily the cost that the U.S. government (or any government) would pay to loblolly pine landowners, but the theoretical framework, multiple-objective solution approach, and the application of both the model and policy may provide more information on how a cost can be calculated so that forests can be effectively and efficiently integrated into climate change policy.

Malmsheimer et al. (2011) noted that the three tenets necessary for ensuring that U.S. forests continue to yield sustainable carbon and environmental and societal benefits are to maintain forests as forests and to manage appropriate forests for carbon, to acknowledge that significant quantities of carbon are stored in wood products for extended periods of time, and that the substitution of wood products for more fossil fuel intensive products is real, irreversible, and cumulative.

In 2010, 925 million people worldwide suffered from chronic hunger. Although this number has decreased due to recent rises in economic growth and decreases in food prices, this trend could increase if food prices increase as shown in previous years (FAO 2010). A climate change policy that favors production could prevent reductions in food and fiber productions and shifts in productions to other parcels of land (Murray and Baker 2011). However, carbon policies that favor reduced forest production through non-management scenarios or greatly lengthened rotations could encourage leakages and do not follow the three tenets necessary to ensuring forests continue to yield sustainable carbon and environmental and social benefits.

CRP, the nation's largest private lands carbon sequestration program, currently employs a non-production approach. Although, the Food Security and Rural Investment Act of 2002 allowed the haying, grazing, and biomass harvest of CRP lands if conducted in accordance to soil conservation, water quality, and habitat quality requirements (Campiche et al. 2011), acres which are employed for grazing, haying or biomass harvests are limited and economically penalized (Mapemba et al. 2007). Policies such as this do not encourage increases in carbon sequestration for forests, and they can lead to more fossil fuel intensive products being employed.

A production approach is important for maximum carbon sequestration in forests because forests provide carbon storage in products and product substitution savings (Lippke et al. 2011). A substitution effect is yielded when wood products with comparable heating and cooling requirements are substituted for non-wood products because wood products yield the least greenhouse gas emissions. Substitution of wood products for more fossil fuel intensive products and biofuels for fossil fuels prevents the flow of fossil carbon to the atmosphere. Furthermore, management can decrease probabilities of loss and can maintain additional climate benefits longer (Malmsheimer et al. 2011).

To curb externalities stemming from carbon dioxide emissions and to increase carbon sequestration by forest landowners, an effective and efficient climate change policy is necessary. To be both effective and efficient the policy will have to provide some level of flexibility to meet the standards but will need to maintain accuracy and precision (Pearson et al. 2008); it will have to be quantifiable in terms of carbon dioxide emissions, practical to implement, and both the policy and policy process will need to be transparent (Gosnell et al. 2011). Product carbon storage, substitution (Lippke et al. 2010), permanence, leakage, and uncertainty (Murry and Baker 2001) will need to be addressed, and the maintenance of good land stewardship should be encouraged (Gosnell et al. 2011). An effective climate change policy will be challenging to design and to pass, but this type of policy is possible and is necessary to curb carbon dioxide emissions and to encourage carbon sequestration.

Future research should focus on categorizing private timberland so that multiple-objective models can be built. Models should include emission savings from product storage and substitution. This model only considered 5 products (3 construction products, 1 paper product, and biofuel). Future research should focus on adding appropriate products with different lifespans for each category of timberland. In addition, more research could be conducted on how the effects of forest management on soil organic carbon can be integrated into the model and how each of the non-decision parameters affects the cost of carbon. If appropriate models can be built for all timberland categories, a range of costs can be developed for management of forests for carbon. With this range, forests could be more effectively and efficiently integrated into climate change policy.

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APPENDICES

Appendix A

SAS Coefficients for SI 55

Table 8 Final Felling Sawtimber Regression Coefficients for SI 55

Variable	Parameter estimate	Standard error	Type II SS	F value	Pr > F
Intercept	-4.54794	0.04652	1336.00101	9556.57	<.0001
Plantdensity	-0.01261	0.00021229	493.42301	3529.51	<.0001
Plantdensity2	0.00000925	3.20E-07	116.91021	836.27	<.0001
Thinage	0.36336	0.00254	2850.34674	20388.9	<.0001
Thinage2	-0.00826	0.00007631	1636.27626	11704.5	<.0001
Thinintensity	-0.04888	0.0005302	1188.1739	8499.15	<.0001
Thinintensity2	0.00012892	0.00000371	168.68981	1206.66	<.0001
Rotation	0.24931	0.00173	2900.89763	20750.5	<.0001
Rotation2	0.00188	0.00002366	884.45484	6326.61	<.0001

Table 9 Final Felling CNS Regression Coefficients for SI 55

Variable	Parameter estimate	Standard error	Type II SS	F Value	Pr > F
Intercept	2461.19071	14.05552	391261936	30661.7	<.0001
Plantdensity	0.1029	0.06414	32843	2.57	0.1087
Plantdensity2	0.00075348	9.66E-05	776295	60.84	<.0001
Thinage	-60.06204	0.76881	77880368	6103.19	<.0001
Thinage2	0.7268	0.02305	12682456	993.88	<.0001
Thinintensity	8.24657	0.16019	33819738	2650.33	<.0001
Thinintensity2	0.00408	0.00112	168810	13.23	0.0003
Rotation	-84.7452	0.52289	335186462	26267.3	<.0001
Rotation2	0.78965	0.00715	155718750	12203.1	<.0001

Table 10 Final Felling Pulp Regression Coefficients for SI 55

Variable	Parameter estimate	Standard error	Type II SS	F value	Pr > F
Intercept	-3358.97329	16.02433	728769461	43939.3	<.0001
Plantdensity	3.14608	0.07312	30702942	1851.16	<.0001
Plantdensity2	-0.00335	1.10E-04	15351425	925.58	<.0001
Thinage	-170.06307	0.87651	624378470	37645.3	<.0001
Thinage2	2.58115	0.02628	159954089	9644.03	<.0001
Thinintensity	36.00114	0.18262	644549302	38861.5	<.0001
Thinintensity2	-0.12298	0.00128	153494978	9254.59	<.0001
Rotation	224.22539	0.59613	2346528557	141478	<.0001
Rotation2	-2.8265	0.00815	1995120910	120291	<.0001

Table 11 Thin CNS Regression Coefficients for SI 55

Variable	Parameter estimate	Standard error	Type II SS	F value	Pr > F
Intercept	-57.04868	3.4211	342102	278.07	<.0001
Plantdensity	0.23934	0.01995	177041	143.91	<.0001
Plantdensity2	-0.000184	3.01E-05	46127	37.49	<.0001
Thinage	36.32762	1.06145	1441036	1171.33	<.0001
Thinage2	-3.38724	0.06924	2944585	2393.47	<.0001
Thinage3	0.1177	0.00151	7480583	6080.49	<.0001
ThinIntensity	-3.90189	0.24635	308621	250.86	<.0001
Thinintensity2	0.01304	0.00346	17419	14.16	0.0002
Thinintensity3	-0.00006647	0.00001551	22595	18.37	<.0001

Table 12 Thin Pulp Regression Coefficients for SI 55

Variable	Parameter estimate	Standard error	Type II SS	F value	Pr > F
Intercept	-689.90404	3.19827	50249686	46531.5	<.0001
Plantdensity	2.85929	0.01864	25398232	23518.9	<.0001
Plantdensity2	-0.00212	2.81E-05	6161297	5705.4	<.0001
Thinage	-47.8497	0.4225	13851202	12826.3	<.0001
Thinage2	9.50462	0.03696	71414133	66130	<.0001
Thinage3	-0.24146	0.00096824	67159889	62190.5	<.0001
Thinintensity	-9.56896	0.04685	45058224	41724.2	<.0001
Thinintensity2	0.00642	0.00032818	413445	382.85	<.0001

Appendix B

SAS Coefficients for SI 65

Table 13 Final Felling Sawtimber Regression Coefficients for SI 65

Variable	Parameter estimate	Standard error	Type II SS	F value	Pr > F
Intercept	-12.61803	0.08767	5849.1354	20713.3	<.0001
Plantdensity	-0.01452	0.00054265	202.1013	715.69	<.0001
Plantdensity2	0.00000889	9.49E-07	24.81047	87.86	<.0001
Thinage	0.10018	0.00359	219.87775	778.64	<.0001
Thinage2	-0.00703	0.00010975	1158.2567	4101.69	<.0001
Thinintensity	0.0336	0.00058172	941.79912	3335.15	<.0001
Thinintensity2	-0.00015186	0.00000371	473.92244	1678.28	<.0001
Rotation	0.8399	0.0024	34575	122440	<.0001
Rotation2	-0.00329	0.00003296	2811.8513	9957.49	<.0001

Table 14 Final Felling CNS Regression Coefficients for SI 65

Variable	Parameter estimate	Standard error	Type II SS	F value	Pr > F
Intercept	1941.01992	15.06175	138410325	16607.7	<.0001
Plantdensity	-1.15617	0.09322	1281892	153.81	<.0001
Plantdensity2	0.0027	0.00016299	2290968	274.89	<.0001
Thinage	-31.8901	0.61675	22282018	2673.59	<.0001
Thinage2	0.57653	0.01885	7792548	935.02	<.0001
Thinintensity	2.05052	0.09994	3508605	420.99	<.0001
Thinintensity2	0.00298	0.00063684	183033	21.96	<.0001
Rotation	-78.97045	0.41236	305660457	36675.8	<.0001
Rotation2	0.9487	0.00566	233952739	28071.7	<.0001

Table 15 Final Felling Pulp Regression Coefficients for SI 65

Variable	Parameter estimate	Standard error	Type II SS	F value	Pr > F
Intercept	-641.15085	20.28663	15101808	998.85	<.0001
Plantdensity	4.31862	0.12556	17885257	1182.95	<.0001
Plantdensity2	-0.00451	2.20E-04	6391051	422.71	<.0001
Thinage	-197.27478	0.8307	852679852	56397.2	<.0001
Thinage2	3.37707	0.02539	267375632	17684.5	<.0001
Thinintensity	27.68984	0.1346	639806530	42317.5	<.0001
Thinintensity2	-0.05482	0.00085776	61762481	4085.04	<.0001
Rotation	103.23876	0.5554	522390852	34551.5	<.0001
Rotation2	-1.67666	0.00763	730740039	48332	<.0001

Table 16 Thin CNS Regression Coefficients for SI 65

Variable	Parameter estimate	Standard Error	Type II SS	F value	Pr > F
Intercept	-560.77961	9.07012	14216769	3822.6	<.0001
Plantdensity	3.16744	0.06222	9636974	2591.18	<.0001
Plantdensity2	-0.00385	0.00010879	4.67E+06	1255.54	<.0001
Thinage	-72.09497	1.50828	8497396	2284.77	<.0001
Thinage2	7.95877	0.10188	22698234	6103.09	<.0001
Thinage3	-0.14021	0.00228	14018157	3769.19	<.0001
Thinintensity	4.43771	0.30078	809604	217.69	<.0001
Thinintensity2	-0.14728	0.00388	5372223	1444.48	<.0001
Thinintensity3	0.00054138	0.00001579	4373529	1175.95	<.0001

Table 17 Thin Pulp Regression Coefficients for SI 65

Variable	Parameter estimate	Standard error	Type II SS	F value	Pr > F
Intercept	-587.66516	5.26666	15632301	12450.6	<.0001
PlantDensity	2.3255	0.03613	5202802	4143.85	<.0001
plantdensity2	-0.00105	6.32E-05	344047	274.02	<.0001
ThinAge	-2.42806	0.43696	38768	30.88	<.0001
thinage2	5.82522	0.0364	32156516	25611.5	<.0001
thinage3	-0.16494	0.0009451	38240653	30457.3	<.0001
ThinIntensity	-8.26096	0.03893	56530191	45024.3	<.0001
thinintensity2	0.00493	0.00024823	495247	394.45	<.0001

Appendix C

SAS Coefficients for SI 75

Table 18 Final Felling Sawtimber Regression Coefficients for SI 75

Variable	Parameter Estimate	Standard Error	Type II SS	F value	Pr > F
Intercept	-16.41547	0.08417	35744	38035.4	<.0001
Plantdensity	-0.01056	0.00010363	9760.56357	10386.3	<.0001
Thinage	-0.46361	0.00124	1.32E+05	140723	<.0001
Thinintensity	0.13342	0.00070449	33708	35869.3	<.0001
Thinintensity2	-0.0004226	0.00000409	10048	10691.8	<.0001
Rotation	1.24441	0.00433	77518	82487.3	<.0001
Rotation2	-0.00613	0.00005955	9965.28686	10604.2	<.0001

Table 19 Final Felling CNS Regression Coefficients for SI 75

Variable	Parameter Estimate	Standard Error	Type II SS	F value	Pr > F
Intercept	524.12679	8.89128	5.10E+06	3474.91	<.0001
Plantdensity	-0.38154	0.06358	52803	36.01	<.0001
Plantdensity2	0.0009803	0.00012121	95921	65.41	<.0001
Thinage	-11.48317	0.2605	2849696	1943.18	<.0001
Thinage2	0.27166	0.00807	1661036	1132.65	<.0001
Thinintensity	0.5134	0.03349	344618	234.99	<.0001
Thinintensity2	-0.00033285	0.00019445	4296.9208	2.93	0.087
Rotation	-21.11926	1.71E-01	22266584	15183.4	<.0001
Rotation2	0.26159	0.00236	18092384	12337	<.0001

Table 20 Final Felling Pulp Regression Coefficients for SI 75

Variable	Parameter estimate	Standard error	Type II SS	F value	Pr > F
Intercept	1599.49958	34.06462	47459634	2204.76	<.0001
Plantdensity	2.88304	2.44E-01	3015004	140.06	<.0001
Plantdensity2	-0.00143	0.00046439	204974	9.52	0.002
Thinage	-173.90366	0.99803	653570501	30361.9	<.0001
Thinage2	3.26103	0.03093	239345150	11118.9	<.0001
Thinintensity	16.01585	0.12831	335367837	15579.7	<.0001
Thinintensity2	-0.01046	0.00074499	4240262	196.98	<.0001
Rotation	-12.61965	0.65665	7950437	369.34	<.0001
Rotation2	-2.57E-01	0.00902	17459569	811.09	<.0001

Table 21 Thin CNS Regression Coefficients for SI 75

Variable	Parameter estimate	Standard Error	Type II SS	F value	Pr > F
Intercept	-711.34013	18.85272	10465225	1423.66	<.0001
Plantdensity	4.02226	0.1424	5.86E+06	797.85	<.0001
Plantdensity2	-0.00466	0.00027148	2163760	294.35	<.0001
Thinage	-148.43216	1.87219	46205918	6285.73	<.0001
Thinage2	20.29328	0.12995	179250722	24384.8	<.0001
Thinage3	-0.568	0.00297	268884953	36578.4	<.0001
Thinintensity	2.86029	0.3178	595446	81	<.0001
Thinintensity2	-0.10916	0.00378	6140003	835.27	<.0001
Thinintensity3	0.00043899	1.41E-05	7134194	970.52	<.0001

Table 22 Thin Pulp Regression Coefficients for SI 75

Variable	Parameter estimate	Standard error	Type II SS	F value	Pr > F
Intercept	-797.25222	1.57E+01	13152291	2594.35	<.0001
Plantdensity	3.64145	0.11822	4809889	948.77	<.0001
Plantdensity2	-0.00246	0.00022536	606161	119.57	<.0001
Thinage	50.11634	0.89848	15773133	3111.32	<.0001
Thinage2	-0.24122	0.07155	57625	11.37	0.0007
Thinage3	0.05894	0.00182	5301579	1045.76	<.0001
Thinintensity	-7.58424	0.06246	74740504	14742.9	<.0001
Thinintensity2	-1.81E-02	0.00036284	12632332	2491.79	<.0001