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A compromise programming model for developing the cost of including carbon pools and flux into forest management

L. Gharis · J. Roise · J. McCarter

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Abstract 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 developed 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 was to produce an accurate and usable analytical product for Southeastern U.S. foresters growing loblolly pine (*Pinus taeda*) in the presence of carbon policies. The decision variables were traditional stand level management variables: 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 multiple-objective problem and to demonstrate the tradeoffs between the competing objectives. This type of model demonstrates a practical method for comparing tradeoffs associated with adjusting forest management for a carbon market. The difference in costs among objectives is important for decision makers considering climate change policies, as it represents the minimum value a rational landowner would accept to sequester a unit of carbon.

Keywords Compromise programming · Forest management · Decision analysis model · Policy · Unit level analysis · Product substitution

L. Gharis (✉) · J. Roise · J. McCarter
Department of Forestry and Environmental Resources, North Carolina State University, 3120 Jordan Hall, Campus Box 8008, Raleigh, NC 27695, USA
e-mail: lauriegharis@gmail.com

1 Introduction

The United Nations Secretary-General recently called climate change "a very credible threat to peace and security around the world" (UNFCCC Secretariat 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 becomes imperative for effective climate change policies. Forests 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 2007).

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; 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.

In addition, 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 price 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), 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, to optimize one objective and to make the other objectives constraints, or to apply a form of goal programming such as compromise 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 business as usual 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. This type of operational level, multiple-objective model demonstrates the tradeoffs between competing management objectives and will be important for decision makers managing forests for multiple values and for decision makers considering climate change policies, which include multiple stakeholders and objectives.

We applied the proposed model to the management of one acre of loblolly pine (*Pinus taeda*) 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 the U.S.'s growing stock removals in 2001. The majority of harvested volumes in the U.S. were produced by non-industrial private forest (NIPF) landowners (Smith et al. 2003). The loblolly pine tree is found in the majority of Southern U.S. plantations (Del Lungo et al. 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 and practical economic incentive aimed at increasing carbon sequestration by private landowners.

2 Optimization model

We developed a multiple-objective forest management model to investigate optimal stand level management with the 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.

2.1 Theoretical framework

A theoretical framework was developed to manage a forest stand 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. The theoretical framework (Fig. 1) illustrates the uses of forest products (paper, construction lumber, and biofuels).

2.2 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

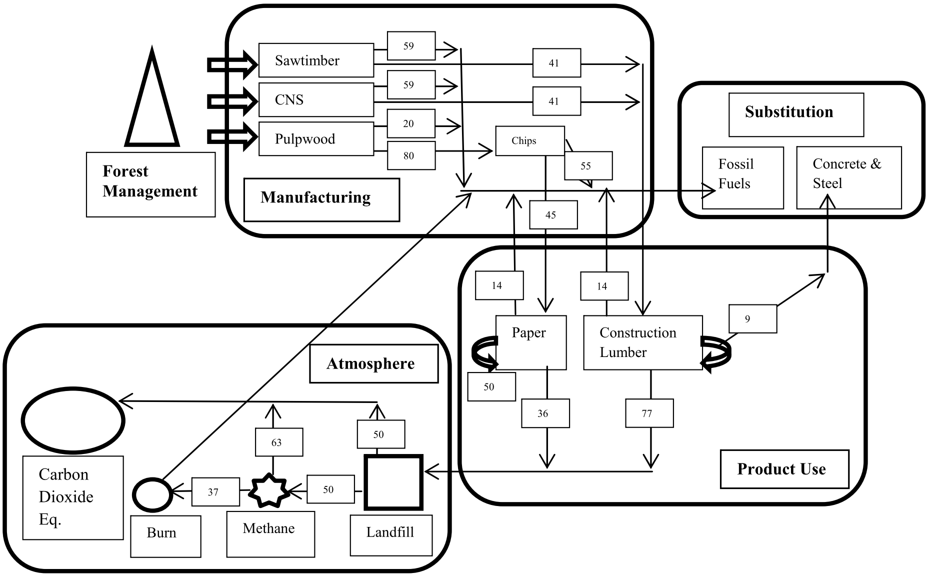

Fig. 1 Theoretical framework. Drawing adapted from Hennigar et al. (2008). A forest stand is managed sustainably and optimally for SEV, carbon storage in the forest, and carbon dioxide emission savings through product storage and substitution of more fossil fuel intensive products by biofuels and wood construction products. A certain percentage of sawtimber, chip-n-saw, and pulpwood is produced according to the optimal management regime. 100 % of the 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

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 (Hafley et al. 1982; Hafley and Buford 1985) was integrated into the optimization model. 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 at a base age of 25 years, ages 5 to 50 years, and densities of 100 to 2722 trees per acre (TPA) (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 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. 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 or no removal would occur. Ranges for thinning were considered for residual BA above 40 square foot per acre at 5 square foot increments. Rotation lengths were included from 20 years to 50 years at 1 year increments, and harvests (both thinnings and final harvests) 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 growth and yield equations for SI 65, which have model p values of less than .0001, can be seen below (Table 1).

2.3 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

Table 1 SAS beta coefficients for growth and yield equations developed with Hafley and Smith NCSU Growth and Yield model simulations (SI 65)

Product	Intercept	Start density (trees per acre)	Start density^2 (trees per acre)	Thin year	Thin year^2	Thin year^3	Thin residual basal area (cubic feet/acre)	Thin residual basal area^2 (cubic feet/acre)	Thin residual basal area^3 (cubic feet/acre)	Rotation length (year)	Rotation length^2 (year)
Thin-chip-n-saw (cubic feet)	−560.78	3.1674	−0.00385	−72.095	7.9588	−0.14021	4.4377	−0.14728	0.00054	–	–
Thin-pulp (cubic feet)	−587.67	2.3255	−0.00105	−2.4281	5.825	−0.16494	−8.261	0.00493	–	–	–
Final felling-sawtimber (1000 board feet)	−12.618	−0.01452	0.00001	0.10018	−0.00703	–	0.0336	−0.00015	–	0.8399	−0.00329
Final felling-chip-n-saw (cubic feet)	1941.0	−1.1562	0.0027	−31.890	0.57653	–	2.0505	0.00298	–	−78.970	0.9487
Final felling-pulp (cubic feet)	−641.15	4.3186	−0.00451	−197.27	3.3771	–	27.69	−0.05482	–	103.24	−1.6767

land that is assumed to repeat in perpetuity. The value is important for forest investments, which often pay on a recurrent cycle for an extended period (Davis et al. 2001).

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 et al. 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 below ground 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 of slash pine (SI 70 at age 25), with 700 TPA 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 of loblolly pine (SI 70 at age 25), with 700 TPA 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, products uses 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 Fig. 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 carbon fraction of .5 was used (IPCC 2006). 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 products 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 below (Table 2).

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.

Table 2 Half-lives for product usage and disposal as used 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 chip-n-saw	Single family house	33 %	97.75	77 %	14 %	9 %	29	23 %
Sawtimber and chip-n-saw	Upkeep and improvement on houses	33 %	31.42	77 %	14 %	9 %	29	23 %
Sawtimber and chip-n-saw	Sawn-wood other uses	33 %	30	77 %	14 %	9 %	29	23 %
Pulpwood	Paper	100 %	2	36 %	14 %	50 %	14.5	56 %

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 % over fossil fuels (Dwivedi et al. 2011).
- GHG emissions of the fossil reference chain of bioliquids used for cogeneration (electricity and heat) was 82 g CO_2 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 (EC 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) (EC 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 Associates 2011), only decay emissions (no savings) were input into the model.

2.4 Modeling objectives

The objective is to maximize the compound outcome of three non-congruent utilities. These utilities are: (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 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 S represents maximization of SEV. The discounted net revenues were calculated over an infinite time horizon with rotation age T and a discount rate r and includes (at time t, whenever there is a harvest) the value h_t for sawtimber, CNS, and pulpwood (from thinning and final felling) and regeneration costs r_c (cost of site preparation, planting, and seedlings). h_t is a function of the Hafley and Smith NCSU Growth and Yield model with the decision variables: planting density (w), thin year (x), residual thinning density (y), and rotation length (T), and of the non-decision variable, $v_{k,t}$, price of product k (sawtimber, CNS, and pulpwood) at time t. The decision variables can be manipulated to change economic value, stand level carbon value, and product substitution. A 3 % real discount rate was employed in the example (Backeus et al. 2005; Pohjola and Valsta 2007; Cao et al. 2010).

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

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

Forest carbon (kg of CO_2 eq.) was measured as the sequestration of one acre of forestland. Objective C represents maximization of forest carbon benefits. Carbon benefits are modeled as the ending inventory g at T; g is a function of the Hafley and Smith NCSU Growth and Yield model with the four decision variables. Note that h_t equals g_T multiplied by $v_{k,t}$. Objective C favors the longest rotation length possible while growth is still occurring.

$$C = (g_T) \tag{3}$$

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

Product carbon storage (kg of CO_2 eq.) 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. 2009). Objective P represents mean annual flux of carbon in products 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 $\boldsymbol{s}_f$. Emission savings were based on the theoretical framework (Fig. 1), half-lives for product usage and disposal (Table 2), and product substitution savings as stated in monetary and carbon values (Sect. 2.3). w_p, $\boldsymbol{s}_c$, and $\boldsymbol{s}_f$ are functions of the Hafley and Smith NCSU Growth and Yield model with the four decision variables. Formula (5) divides the sum of the fluxes to the permanent wood product pool and the substitution pools by the rotation T in order to calculate a mean annual value.

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

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

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

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

The feasible set for each objective included constraints on the growth of the loblolly pine due to site productivity (SI 55, SI 65, SI 75 at base age 25), forest management practices, and non-negativity. Forest management practices were constrained to the following ranges: planting densities between 200 TPA and 1000 TPA, thinnings between 8 and 22 years, residual BA after the thinning treatment between 40 square feet per acre and 200 square feet per acre, and rotation lengths between 20 and 50 years. Additionally, harvests (both thinnings and final harvests) had to be five years apart and to produce at least 6 cords of wood to be economically feasible.

3 Solution approach

3.1 Optimization solver

The optimization solver has to be able to solve an optimization model with operational constraints on the ranges of the four decision variables, constraints on growth due to site productivity, economic constraints on the harvests, and with discrete, nonlinear, and nonconvex characteristics. Beginning with many different starting points, and employing evolutionary algorithms can help overcome the challenge of finding the global extremum rather than the local extremum for nonlinear with multiple local optimal solutions (Winston 2004). 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). Although we could have employed a more advanced solver, we wanted to employ a solver that is widely available and employed. Thus, Microsoft solver was chosen as the optimization solver.

3.2 Compromise programming

Compromise programming, a form of goal 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:

$$f_q,\ q \in Q = \{S, C, P\} \tag{9}$$

where:

$$f_S = S \tag{10}$$

$$f_c = C \tag{11}$$

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

The ideal point L_p is calculated as follows:

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

Where: n is the number of objectives, a_i is the weight; f_i^* is the best value of the ith criterion; $f_{i,w}$ is the least optimal criterion, and $f_i(x)$ is the result of implementing decision x with respect to the ith criterion (Gershon 1982). There are three objectives in this analysis. The distance parameter 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 p equals 1 the decision maker is considered risk neutral, and the solution is considered the compromise min sum or compromise average program. If p equals infinity, the decision maker is considered to have a high risk aversion (Krcmer et al. 2005). For this model, a 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. Then the values of the remaining criteria were computed at each objective's optimal solution. The results can be seen below (Table 3).

Table 3 Values obtained from the developed model (SI 65) by optimizing each objective separately

Model objective	Soil expectation value ($/acre)	Forest carbon (kg of CO_2 eq./acre)	Emission savings from product storage & substitution (kg of CO_2 eq./acre/year)
Maximize soil expectation value ($/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 emission savings from product storage & 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)

Table 4 Management regimes for the four decision variables for each scenario (SI 65)

Scenario	Planting density (trees per acre)	Residual thinning density (basal area in square feet/acre)	Thin year	Rotation (years)
Maximize soil expectation value ($/acre)	381 (941 trees per hectare)	65 (15 square meters/hectare)	20	37
Maximize carbon in forest (kg of CO_2 eq./acre)	575 (1421 trees per hectare)	131 (30 square meters/hectare)	22	50
Maximize emission savings from product storage & substitution (kg of CO_2 eq./acre/year)	575 (1421 trees per hectare)	130 (30 square meters/hectare)	22	28

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

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

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.

4 Application results and discussion

After solving for the optimal solutions for each objective, compromise programming was employed to solve for $p = 100$. For this problem, an additional constraint was added to

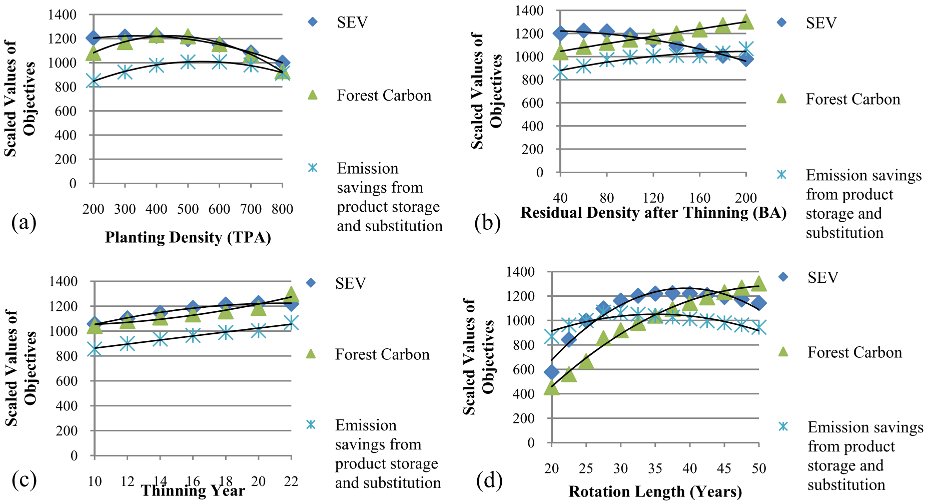

Fig. 2 (**a**) The developed model results for planting density, (**b**) residual density after thinning, (**c**) thinning year, and (**d**) rotation length. The values of forest carbon sequestration and emission savings from product storage and substitution have been scaled. Forest carbon sequestration (kg of CO_2 eq./acre) was divided by 300, and emission savings from product storage and substitution (kg of CO_2 eq./acre/year) was divided by 2. Soil Expectation Value (SEV) ($/acre) was not scaled

make all changing decision variables integers and operationally possible. For example, the integer constraint only allows whole trees to be planted and harvested. This constraint was not employed earlier in order to find the best possible benchmark runs for each objective. To help overcome the challenge of finding the global extremum rather than the local extremum, the model was run multiple times using the values from the four decision variables for the three benchmark runs as starting points. Solution times were less than 1 minute.

Utilizing compromise programming for SI 65, the optimal management regime was to plant 476 TPA, thin at year 21 to a BA of 120 square feet/acre, and to conduct a final felling at year 39. The compromise solution improved SEV by $194/acre over maximizing only emission savings from product storage and substitution. It improved forest carbon by 86,789 kg of CO_2 eq./acre over maximizing only SEV. It improved emission savings in product storage and substitution by 137 kg of CO_2 eq./acre 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 compared to the SEV (business as usual) solution; average cost per tonne of CO_2 eq. is $24. The results of the multiple-objective solution compared to the single objective solutions can be seen below (Table 5).

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 in construction material from the thinning and final felling, while the optimization model predicted 2669 cubic feet/acre; 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 versus 2100 cubic feet/acre for the optimization model; the results were within 9 % of each other. Overall, Hafley & Smith NCSU predicted a total of 4818

Table 5 Difference between the model (SI 65) results for compromise solution and maximizing each objective separately

Model objective	Soil expectation value ($/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)

cubic feet/acre whereas the optimization model predicted 4769 cubic feet/acre; 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 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 would go to products in use. Our model produced a lower estimate; 4313 cubic feet/acre could be harvested with a 25 year rotation of loblolly pine (SI 75), and 11.9 tonnes of carbon/acre would go to products in use; the results are within 25 % of each other.

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 led to an approximate decrease of $550–$730/acre in SEV, of 87,000–117,000 kilograms of CO_2 eq./acre in ending forest carbon, and of 590–640 kilograms of CO_2 eq./acre/year of emission savings from product storage and substitution. The compromise solution for each of the site indices are shown below (Table 6).

5 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

Table 6 Compromise solutions for models with site indices of 55, 65, and 75 at base age of 25

Model	Soil expectation value ($/acre)	Forest carbon (kg of CO_2 eq./acre)	Emission savings from product carbon & substitution (kg of CO_2 eq./acre/year)	Planting density (trees per acre)	Thin year	Residual thinning density (basal area isquare feet/acre)	Rotation (years)
Site index 55	$549 ($1357/hectare)	199750 (493575 kg of CO_2 eq./hectare)	1340 (3311 kg of CO_2 eq./hectare/year)	424 (1048 trees per hectare)	22	89 (20.4 square meters/hectare)	40
Site index 65	$1096 ($2708/hectare)	286502 (707937 kg of CO_2 eq./hectare)	1934 (4779 kg of CO_2 eq./hectare)	476 (1176 trees per hectare)	21	120 (27.6 square meters/hectare)	39
Site index 75	$1821 ($4500/hectare)	403518 (997079 kg of CO_2 eq./hectare)	2578 (6370 kg of CO_2 eq./hectare)	487 (1203 trees per hectare)	17	124 (28.5 square meters/hectare)	41

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.

Our developed model maximized the mean annual emission savings for product storage and substitution rather than the total at the end of a rotation as some previous studies have done. If our study had maximized emission savings for product storage and substitution as a sum at the end of the rotation rather than the mean annual emission savings, the rotation length would have been increased from 39 years to 46 years (SI 65). Emission savings over 100 years is larger when the mean annual increment is maximized. For example, the 39 year rotation length saved 1.934 tonnes of CO_2 eq./acre/year due to product storage and substitution whereas the 46 year rotation saved 1.796 tonnes of CO_2 eq./acre/year. Over 100 years, an additional 414 million tonnes of CO_2 eq. would be saved, if the 30 million planted acres of loblolly pine in the U.S. (Smith et al. 2009) were optimized for mean annual emission savings management as opposed to a sum of emission savings at the end of the rotation.

Our multiple-rotation multiple-objective model estimated a cost of \$24/tonne of CO_2 eq. for an increased optimal rotation of 2 years for 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 indices, 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 Krcmer et al. (2005) equal weights were employed in the compromise programming solution for our loblolly pine example. The choice of a preferred alternative solution, found using a set 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 among, it does not make political decisions.

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 be able to evaluate the tradeoffs between multiple objectives for each forest type. This type of model demonstrates a practical method for comparing tradeoffs associated with forest management for different objectives. With the model, we can estimate the additional cost of carbon as management changes from an economic objective to a carbon objective. Measuring additional carbon, and its cost, associated with a change in management is significantly more practical than any direct measure of carbon in the forest. Measurement can be associated with certification, where detailed management records are a standard best practice. The estimated cost represents the minimum value a rational land owner would accept to sequester a unit of carbon. Although tradeoffs 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 decision makers to compare tradeoffs will be beneficial in ensuring the development of economically viable management practices for forest landowners and effective and practical carbon sequestration policies for the environment.

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