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Letter to Editor

Modelling and Analyzing Timber Production and Carbon Sequestration Values of Forest Ecosystems: A Case Study

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Abstract

The integration of carbon captured by forest ecosystems into forest management planning models has become increasingly more important, particularly in the areas of climate change, land use, and sustainable forest management. The main objective of this work is to develop a multiple-use forest management planning model that focuses on the interactions of net carbon sequestration and timber production opportunities in a forest ecosystem including forest openings. The linear programming model is used to develop various forest management scenarios for a forest that yields timber and carbon objectives. The results of forest management planning scenarios showed that increased net carbon sequestration can be attained at a significant cost in terms of forgone timber harvest and financial returns. Results also showed that reforestation of forest openings and long-term protection of forest ecosystems provides high biomass and carbon storage over the planning horizon.

Keywords: forest management, linear programming, carbon sequestration, reforestation

Introduction

Over the next 50 years carbon, along with other greenhouse gas emissions resulting from anthropogenic activities, are projected to lead to important changes in the global climatic system. Increases in global mean surface temperatures of 1.5-4.58°C, a rise in sea level between 13 to 94 cm, changes in global precipitation and global evapotranspiration of 3-15 and 5-10%, respectively, and average decreases in summer soil moisture are expected to have widespread impacts on human habitat, the environment, biodiversity and economic development [1-3].

Issues of climate change and loss of biodiversity are increasingly prompting nations to focus on accounting for and managing greenhouse gas emissions [4, 5]. Many mitigation responses to climate change have been proposed, including land use, land-use change, and forestry policies that increase carbon sink functions of terrestrial ecosystems [6]. For example, the Kyoto Protocol to the United Nations Framework Convention on Climate Change establishes the principle that carbon sequestration can be used by participating nations to help meet their respective net emission reduction targets for carbon dioxide and other greenhouse gases.

Forests cover nearly one-third of Earth's land area, containing up to 80% of the total above-ground terrestrial carbon and 40% of below-ground carbon, thus having a critical role in the global carbon cycle. The forest ecosystem absorbs carbon dioxide from the atmosphere through the process of photosynthesis in which green leaves produce carbohydrates [7]. Several studies have found that growing trees to sequester carbon could provide relatively low-cost net emission reductions for a number of coun-

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tries [8]. In this sense, the most important contribution to the global greenhouse gas balance can be considered forest management that enhances forest biomass growth and reforestation because forests play an important role in the global carbon cycle.

In the past two decades, carbon budget studies have become increasingly more important, particularly in the areas of climate change, land use, and sustainable forest management. Several global and international carbon budget studies have been implemented in the past decade [1, 2, 7, 9-13]. In addition, the integration of carbon sequestration in forests into forest management planning models is a recent consideration. Hoen and Solberg [14], Krcmar et al. [15], Diaz-Balteiro and Romero [16] and Raymer et al. [17] have incorporated a carbon benefit objective explicitly into a forest management optimization model using constrained optimization, linear and goal programming.

The main objective of this work is to develop a multiple use forest management planning model that focuses on the interactions of net carbon sequestration and timber production opportunities in a forest ecosystem. Firstly, carbon value of forest ecosystem is linked to forest stand biomass and incorporated into linear programming (LP) – based harvest scheduling process. Secondly, a number of alternative forest management scenarios with the objective of maximizing the NPV of timber and various constraints are developed and conducted. Finally, the results are presented and examined by the amounts and the NPV of forest ecosystem values.

Material and Methods

Study Area

The study area of Artvin Forest Planning Unit comprises 5175.68 hectares. In the context of this paper, only 1224.84 ha are subjected to harvest scheduling. The forest contains coniferous and broadleaf trees along with forest openings (denuded forestlands). The main tree species are spruce (*Picea orientalis)* and beech (*Fagus orientalis*). Of the total area, 1126.335 ha are forested comprising spruce (643.205 ha), beech (483.13 ha), and the rest is forest openings (98.489 ha). Of the total initial growing stock of 462,997 m^3, the initial growing stocks of spruce and beech forests are 258,687 and 204,310 m^3, respectively. Planning area consists of 440 sub-compartments (polygons or stands) that are subject to certain management interventions, which include 102 polygons of forest openings. Each stand has different species, age, development stages and site qualities.

Quantification of Forest Values

Timber yields are estimated using the yield tables of Ercanli [18] for spruce (*Picea orientalis*), the yield tables of Carus [19] for beech (*Fagus orientalis*). In calculating volumes of various timber products (sawlogs, mining pole, industrial wood and firewood.) as a result of clearcutting and thinning at any age are determined by product rates of stand age and mean stand diameter of the relevant species [20]. In our model, different species and site qualities result in a different proportioning of timber into forest products even for the same species.

Incomes from timber are determined by the volume of various timber products and their associated values. The expenses are determined by harvesting costs, reforestation costs, and maintenance costs of the relevant state forest enterprise that is responsible for managing the forest area. All financial calculations are discounted to today's value with a 3% interest rate as generally applied to the financial evaluation of forestry projects in Turkey and in most other countries [21].

In this paper, net carbon sequestration in forest is considered and calculated as the difference between the carbon captured by the biomass and the carbon emitted according to the different uses of the timber harvested. The following equation measuring the balance of net carbon in the *t*th cutting period was used in this study [16].

$$CB_t = \left[\gamma(V^t - V^{t-1} + H_t) - CE_t\right] \quad (1)$$

where γ is the proportion of carbon contained in timber biomass, CB_t is the carbon balance at *t*th cutting period, CE_t is the carbon emission at *t*th cutting period, H_t is the volume harvested at *t*th cutting period and V^t is the volume of forest inventory at the end of *t*th cutting period.

In this paper, biomass for each forest type was calculated using allometric equations from literature [22, 23]. Total dry weight biomass of a tree was converted to total stored carbon by multiplying by 0.45. The carbon emissions from various forest products were also taken into consideration and estimated in this study based on the lifetime of wood products for each species. The lifetimes of wood products suggested in the literature are used as 50 years for sawlogs, 40 years for mining pole, 15 years for boards, and 1 period for firewood, bark and harvest residues [4, 12, 24, 25]. The decomposition rates of wood products were used in the equation proposed by Masera et al. [13]

$$Cp_{mt+1} = Cp_{mt} x(1 - a_m) \quad (2)$$

where Cp_{mt} is the carbon stored in a wood product m at time *t* and a_m is the share of the product that decomposes each year.

Because of the uncertainty regarding carbon storage in the soil it was not included in the model. This study is only limited above and below ground carbon sequestration. The biomass calculated here relates to the biomass of trees over diameter of 8 cm at dbh. However, the possible recycling of products was not considered in the analysis due to the lack of reliable data on the current situation.

Forest Management Planning Model

In developing alternative forest management scenarios connected to timber production and net carbon sequestration, Linear Programming (LP) was used. For this reason, all alternative model scenarios were developed according to the Model I approach [26]. In this study, before alternative forest management scenarios were developed, some assumptions in addition to pre-defined decisions were accepted.

The planning horizon of 100 years is divided into 10 periods of equal length. Timber, carbon, and other stand characteristics are calculated at stand (sub-compartment) level. Possible management interventions are thinning, clearcutting, planting and do nothing. Stands whose crown closure is 11%-40% cannot be thinned, but can be regenerated. It was assumed that regeneration is to follow immediately after harvesting. The minimum ages of final harvest for spruce are 90 and 100 years for good sites and other sites, respectively. These ages for beech are 100 and 120 years. However, there is no limit on the maximum age before which a stand must be harvested. Regenerated areas are assumed to develop according to empirical yield tables. Growth and yield projection of actual stands is forecasted according to typical simulation of growth potential of stands. All stand parameters and forest values are calculated at the mid-point of each period. Forest openings can be reforested in any period, and it is possible to leave an open space untouched during the planning horizon.

It is possible to produce a number of forest management planning scenarios by means of the model developed in this paper. An LP model that incorporates various land management practices with certain timber output and carbon benefit objectives has been formulated. The model maximizes the cumulative NPV of timber over the planning horizon, as well as an even flow of timber production. The model objectives include a certain target on carbon objectives. The linear programming problems in the study are presented in Table 1.

Results

No Restrictions on Harvest Level

The NPV of timber and the corresponding volumes of forest management scenarios are shown in Table 2. Scenario A1 produces more NPV of timber than the other scenarios do over the planning horizon. The carbon objectives cause a negative effect on the NPV in other scenarios, and the reductions on this output are 1%, 4.4%, 13.4%, 24.8% and 51.8%, respectively. In addition, when the carbon objectives are incorporated into scenario A1 in other scenarios, timber harvest volumes decrease except for scenario A2 (Table 2). Maximizing carbon objective in Scenario C makes the optimal harvest level much lower, 89.3% of the optimal harvest level when timber revenue is maximized.

The ending inventories for Scenarios A1 through A6 are 503,446, 530,466, 589,648, 652,772, 714,557 and 812,513 m^3, respectively. These results show that ending inventories are higher when carbon objectives are incorporated into a timber production-based forest management planning model. Standing timber volumes are also shown in Table 3. According the outputs in this table,

Table 1. An overview of linear programming-based forest management scenarios

Scenarios	Objective	Carbon sequestration targets	Timber Harvest
A1	Maximize NPV of timber	No restriction	No restriction
A2	Maximize NPV of timber	The level in A1 + 10% of difference between A1 and C	No restriction
A3	Maximize NPV of timber	The level in A1 + 30% of difference between A1 and C	No restriction
A4	Maximize NPV of timber	The level in A1 + 50% of difference between A1 and C	No restriction
A5	Maximize NPV of timber	The level in A1 + 70% of difference between A1 and C	No restriction
A6	Maximize NPV of timber	The level in A1 + 90% of difference between A1 and C	No restriction
B1	Maximize NPV of timber	No restriction	Even flow
B2	Maximize NPV of timber	The level in B1 + 10% of difference between B1 and D	Even flow
B3	Maximize NPV of timber	The level in B1 + 30% of difference between B1 and D	Even flow
B4	Maximize NPV of timber	The level in B1 + 50% of difference between B1 and D	Even flow
B5	Maximize NPV of timber	The level in B1 + 70% of difference between B1 and D	Even flow
B6	Maximize NPV of timber	The level in B1 + 90% of difference between B1 and D	Even flow
C	Maximize carbon sequestration	No restriction	No restriction
D	Maximize carbon sequestration	No restriction	Even flow

Table 2. Some important model outputs of forest management scenarios at the end of the planning horizon.

Scenarios	Timber Production (m^3)	NPV of Timber ($)	Carbon Sequestration (ton)	Reforested Area (ha)	Harvested Area (ha)	Ending Inventory (m^3)
A1	670949	3539270	39543	0	1126	503446
A2	671627	3535539	50013	84	1126	530466
A3	617689	3384533	70954	98	1023	589648
A4	528029	3064599	91895	98	879	652772
A5	433552	2660771	112835	98	713	714557
A6	252435	1704281	133776	98	434	812503
B1	720149	2684732	11265	10	1126	371081
B2	721276	2681278	24329	94	1126	404090
B3	683090	2518548	50458	98	1064	484306
B4	569474	2119578	76587	98	883	564806
B5	422997	1615955	102715	98	633	658592
B6	211100	790766	128844	98	357	795898
C	71762	314577	144246	98	163	883295
D	52200	163970	141908	98	122	878601

Table 3. Standing timber volumes of forest management scenarios over time.

Periods	Forest management scenarios													
	A1	A2	A3	A4	A5	A6	B1	B2	B3	B4	B5	B6	C	D
1	355866	355866	356743	358042	359290	382129	414374	414261	418080	429442	444089	465279	475496	481169
2	266954	267043	271861	274535	294915	371883	387009	387146	397876	420382	449535	491555	504474	522950
3	320623	320824	332927	337067	359231	437826	366414	366830	387882	420299	462357	522552	555840	567140
4	170830	171124	211804	290714	383542	506574	356161	357210	389962	430436	482610	557748	601139	612147
5	225691	226054	274363	353887	445709	563563	353602	357834	398038	445494	506160	593889	643002	656044
6	252512	255539	323929	407822	493796	621249	356058	365913	409292	463239	531685	631020	692808	699296
7	324164	332669	399644	478020	556634	674593	358709	375269	421140	482402	558197	668628	742079	741737
8	378603	393365	467554	540192	612404	721047	358693	381552	433447	502603	585859	706091	787209	782884
9	436213	456601	525261	592914	660062	760891	354727	382495	447384	523277	612444	742294	827745	822186
10	483475	508562	570729	634989	698179	796238	348981	380644	458591	540801	636016	775449	865314	859740

when carbon objectives are included in Scenario A1 in other scenarios or carbon benefit is maximized in Scenario C, standing timber volumes of forest management scenarios are higher.

No forest openings are reforested in Scenario A1 because of high reforestation costs, but all forest openings except for Scenario A2 are reforested to meet the carbon objectives in other scenarios (Table 2). Furthermore, some forest stands potentially candidate for harvesting are leaved to age over the planning horizon in these scenarios (Table 4). For example, while all forested stands (1126 ha) are harvested in Scenario A1, only 434 ha area is harvested in Scenario A6 (Table 2).

Even Flow of Harvest Level

The outputs of forest management planning scenarios with the constraint on harvest level are shown in Table 2. When these scenarios are compared to scenarios A1-A6 with no restrictions on harvest level, the NPV of timber is lower in all scenarios, but timber harvest

Table 4. Age class distributions of forest management scenarios at the end of the planning horizon (hectare).

Age Classes	Forest management scenarios													
	A1	A2	A3	A4	A5	A6	B1	B2	B3	B4	B5	B6	C	D
0-20	0	0	0	0	0	0	234	223	135	103	69	32	0	7
21-40	24	24	0	0	0	0	179	175	160	132	96	49	0	14
41-60	144	227	100	86	86	28	211	236	251	210	149	85	28	27
61-80	447	447	412	282	142	42	290	364	291	244	168	95	42	37
81-100	511	512	609	609	584	462	222	223	325	292	250	194	191	136
101-120	0	0	0	0	0	0	0	0	0	0	0	0	0	0
121-140	0	0	24	24	24	24	0	0	0	0	5	24	24	24
141-160	0	0	0	14	14	72	0	0	0	0	14	14	72	74
161-180	0	0	44	44	44	85	0	0	19	21	57	79	85	85
181-200	0	0	35	165	305	452	0	0	43	189	349	475	516	554
201-220	0	0	0	0	26	59	0	0	0	33	55	165	249	249
221-240	0	0	0	0	0	0	0	0	0	0	12	12	18	18
Total	1126	1210	1225	1225	1225	1225	1136	1220	1225	1225	1225	1225	1225	1225

volumes are higher in some scenarios. For example, while a NPV of $3,539,270 in Scenario A1 is provided, $2,684,732 with a decrease of 24% in Scenario B1 is obtained. Maximizing carbon objective in Scenario D makes the optimal harvest level much lower, 92.8% of the optimal harvest level when timber revenue is maximized.

As seen in earlier forest management scenarios with no restrictions on harvest, ending forest inventories and standing timber volumes are higher when carbon objectives are incorporated into timber production-based forest management scenarios (Scenario B1). These outputs can be shown and compared in Tables 2 and 3. Also, all forest openings except for Scenario B1 are reforested to meet the carbon objectives in these scenarios (Table 2), and some forest stands that are potential candidates for harvesting are leaved to age over the planning horizon in these scenarios (Table 4). Even though harvest level and area allocated to harvest decreases, area allocated to reforestation increases when carbon objectives are given more weight.

Discussion and Conclusions

This study formulates a multiple-use forest planning model that incorporates various forest ecosystem values with certain timber and carbon objectives. There are a number of different ways for accommodating multiple objectives in forest management planning models. LP is one of them. LP is to specify one objective to be optimized while the others were included as constraints. It is also possible to examine tradeoffs among various objectives (sensitivity analysis). With the linear programming-based forest management model developed here, several forest management scenarios can be employed to meet economic, timber and carbon objectives within the model.

Results of forest management scenarios show that increased net carbon sequestration can be attained at a significant cost in terms of forgone timber harvest and financial returns. Net present value of timber revenue decreased gradually as the restriction on minimum level of carbon objective increased. Even though reforestation of forest openings has negative effects on the NPV of timber over a planning horizon, it provided high biomass and carbon storage over the planning horizon. Similar results were found in another study by Raymer et al. [17] showing that the NPV of timber revenue decreased as the constraint on carbon benefit increased. The results of Hoen and Solberg [14] also showed that NPV of costs and income decreased by 8.1%-14.9% when carbon benefit was maximized instead of profit.

When the constraints on timber harvest level in scenarios B2 through B6 are incorporated into forest management planning model, the NPV of timber decreased. As expected, the integration of regulatory constraints into timber-based forest management planning causes losses in economic profit [27-30]. For example, Haight et al. [29] found that a model with a volume regulation constraint resulted in a minimum NPV reduction of 5% compared to an unconstrained model.

Long-term protection of forest ecosystems played an important role on carbon sequestration. With increasing restriction on minimum carbon objective, optimal forest management gradually changed toward less harvesting and more reforestations. Namely, when carbon objectives are incorporated into timber production-based models, standing timber volumes and ending forest inventories of forest management scenarios increased with increased carbon objective. Almost all forest openings were reforested and less forested area are harvested in these scenarios. This important difference may be explained by the fact that these scenarios have to leave and age some of the forest stands potentially candidate for harvesting to meet carbon objective. Timber harvested from forests managed under short rotations is used as either firewood or for short-lived products such as paper. As a result, all the carbon sequestered over the length of the rotation is assumed to be released instantaneously. With longer rotation length the quality of the timber improves, so that higher proportions of the timber can be used as sawlogs and the instantaneous carbon release decreases [31]. The preservation of biological diversity and the maintenance of other ecosystems are other important ways to minimize atmospheric carbon dioxide [32]. Furthermore, reforestation of forest openings, especially in early periods, guarantees high biomass and carbon storage over the time horizon in spite of high costs of planting [15].

Forest management planning in the world evolved from relatively classical timber production approach to procedures that reconcile various conflicting demands on timber and nontimber resources. Carbon storage is an important nontimber forest value. Forests play an important role in the global carbon cycle. For this reason, accurate estimates of the potential dynamics of carbon flows in forest ecosystems and reforestation or afforestation projects are also needed. Forest management planning today makes necessary the inclusion of carbon sequestration into forest management planning models.

This paper is limited to two forest values rather than incorporating many other forest values such as soil protection, biodiversity and recreation. Other forest values should likewise be incorporated into forest management planning process with quantitative methods. Developing forest planning models based on different simulation or mathematical optimization techniques are extremely important in forestry and sustainability of forest ecosystems.

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