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Incorporating water production and carbon sequestration into forest management planning: a case study in Yalnızçam planning unit

E. Z. Başkent[1]* and D. Mumcu Küçüker[2]

[1] *Professor. Faculty of Forestry. Karadeniz Technical University. 61080 Trabzon. Turkey*
[2] *Research Assistant. Faculty of Forestry. Karadeniz Technical University. 61080 Trabzon. Turkey*

Abstract

Sustainable management of forest resources requires smart integration of various forest values into forest management plans both to control forest ecosystems and to satisfy the needs and expectations of stakeholders. This research initiative aimed to integrate water, carbon and timber values into a forest management plan and explain their effects on forest dynamics. Alternative management strategies with a mix of management objectives maximizing the amount or NPV (Net Present Value) of timber, carbon and water production along with constraints such as area, volume control and ending inventory were developed. A linear programming model with a planning horizon of 100 years and periods of 10 years was developed. Model outputs as NPV and amounts of timber, water and carbon were used as performance indicators to discuss forest dynamics under various management strategies. The results showed that water NPV aimed strategies (*W) provided the minimum timber production and the maximum water production level. Besides, even though timber NPV aimed strategies (*T) generated maximum NPV of timber as expected, surprisingly maximum timber and carbon production were provided by carbon NPV aimed strategies (*C) due mainly to afforestation of large forest openings in the case study area. The results indicated that the performance of a management strategy depends highly on the contents of a strategy as well as the initial forest structure aside from the growth rate.

Key words: linear programming, carbon sequestration, water production, forest management, net present value.

Resumen

Incorporación de la producción de agua y el secuestro de carbono en los planes de gestión forestal: estudio de caso en la unidad de planificación de Yalnızçam

La gestión sostenible de los recursos forestales requiere la integración de varios valores del bosque en los planes de gestion forestal tanto para controlar los ecosistemas forestales como para satisfacer las necesidades y expectativas de los grupos de interés. Este artículo pretende integrar los valores del agua, el carbono y de la madera en un plan de gestión forestal y explicar sus efectos en la dinámica forestal. Se han desarrollado estrategias de gestión alternativas con una mezcla de objetivos de gestión de maximizar la cantidad de NPV (Valor Actual Neto) de madera, carbono y producción de agua junto a limitaciones como la superficie, el control del volumen y la finalización del inventario. Se ha desarrollado un modelo de programación lineal con un horizonte de planificación de 100 años y períodos de 10 años. Las salidas del modelo tales como el NPV y las cantidades de la madera, el agua y el carbono se usaron como indicadores de comportamiento para analizar la dinámica forestal conforme a varias estrategias de gestión. Los resultados mostraron que las estraegias enfocadas al NPV del agua (*W) proporcionan la mínima producción de madera y el máximo nivel de producción de agua. Además, aunque la estrategia enfocada al NPV de la madera (*T) generan un máximo de NPV como se esperaba, sorprendentemente la máxima producción de madera y carbono las proporcionaron las estrategias dirigidas al NPV de carbono (*C) debido principalmente a la repoblación de grandes áreas abiertas en área del estudio de caso. Los resultados indicaron que el comportamiento de una estrategia de gestion depende mucho de los contenidos de la estrategia así como la de la estructura forestal inicial y de la tasa de crecimiento.

Palabras clave: programación lineal, secuestro de carbono, producción de agua, gestión forestal, valor neto actual.

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* Corresponding author: baskent@ktu.edu.tr
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Introduction

Water is an indispensable resource for the life of humanity. Because of proliferation of industrialization, migration and population, water consumption increases quite rapidly. Forest ecosystems play an important role particularly in the management of water resources as forested headwater streams are the source of water flow. Human-induced or natural disturbances have, however, the potential to impact on both the quantity and quality of water resources. The water-forest relationship has attracted great attention to the role of forest ecosystems in multiple-use forest management as well as climate change. Researchers have shown that water quantity or quality is influenced by the activities such as reforestation, afforestation and deforestation. Water yield from afforested catchments, for example, declines with increasing plantation age (Vertessy *et al.,* 2001; Brown *et al.,* 2005; Farley *et al.,* 2005; Dijk and Keenan, 2007).

In addition, increases in the atmospheric carbon dioxide (CO_2), nitrous oxide (N_2O) and methane (CH_4) concentrations are believed to be the primary drivers of the greenhouse gas effects related to the increasing variability in global climate conditions. Over the last few years, there has been an increasing tendency to consider forest ecosystems as sink of carbon dioxide. Therefore, several initiatives have focused on studies to reduce the dramatic increase of global CO_2 emissions particularly in industrialized countries and consequently to contribute to the mitigation of climate warming (Díaz-Balteiro and Romero, 2003). Because of their importance in carbon cycle, the Kyoto protocol affirmed the importance of forest ecosystems for meeting greenhouse gas emissions targets over the commitment periods for signatory countries of the UN Framework Convention on Climate Change (UNFCCC) (Brown *et al.,* 1999). *«Forest biomass represents the potential amount of C that can be added to the atmosphere or conserved or sequestered on the land when forests are managed for meeting emission targets»* (Brown *et al.,* 1996). In pursuit of minimizing net greenhouse gas emissions, the Kyoto Protocol provides specific incentives for maximizing afforestation and reforestation activities and minimizing deforestation of forest ecosystems (Huston and Marland, 2003). Different management regimes can affect the amount of carbon sequestrated in forest vegetation and soil by controlling the forest management practices, *e.g.* by changing rotation lengths or intensifying thinning operations (Backeus *et al.,* 2005; Swanson, 2009). In addition, land use activities and forest ecosystem planning are increasingly considered an option for limiting greenhouse gas concentration in the atmosphere (Hu and Wang, 2008; Kaul *et al.,* 2009) as illustrated by several researches. They quantified and demonstrated the effects of various land use changes on the global carbon stocks (Achard *et al.,* 2004; Houghton, 2008).

Protecting as well as sustaining forest ecosystems along with controlling global carbon balance becomes a highly crucial endeavor in sustainable forest management. Sustainability can be achieved through holistic management of ecological, economic and socio-cultural values of forest ecosystems. In this way, the integration of water production and carbon sequestration into forest management planning is an important step. Here, multiple use forest management planning approach focuses on the integration of timber and non-wood forest products such as carbon, oxygen, water and soil production. But so far few studies attempted to integrate carbon sequestration and water production into forest planning (Díaz-Balteiro and Romero, 2003; Backeus *et al.,* 2005; Keleş and Başkent, 2007; Keleş *et al.,* 2007; Seidl *et al.,* 2007; Hennigar *et al.,* 2008; Başkent *et al.,* 2008). Similarly, few other studies developed a forest management planning model to integrate carbon, water and timber into forest management planning (Yolasığmaz, 2004). Most of these studies focused on the mathematical formulation of a harvest scheduling model but not much on the dynamics of such integration towards the understanding of functional relationships between forest values and forest structure. Therefore, the contribution of forest ecosystem on carbon sequestration and water production in addition to timber production is considered to be necessary in this study.

The objective of this study is to analyze forest dynamics under the integration of carbon sequestration, timber and water production with alternative forest management strategies. In this context, a number of forest management strategies with different objectives and constraints were developed and solved by linear programming (LP) technique. Results were examined in terms of the amount and net present value (NPV) of three forest values (water, timber and carbon) over a 100-year planning horizon. Besides, effects of various management strategies on age class distribution at the end of a planning horizon were examined.

Materials and methods

Study area

The study area covers the Yalnızçam Forest Planning Unit with an area of 44.679,2 ha in the North-eastern Turkey. Of the total area, 6.752 ha is forested with a dominant tree species of Scots pine (*Pinus Sylvestris L.*) and the rest is forest openings or bare forest lands, residential areas, water courses, agriculture and grassland areas (37.927 ha). The area has an average slope of 33% and the altitude varies from 1,800 m to 2,806 m. The area consists of 190 compartments with 1,275 subcompartments (stands) of forested areas which are subject to forest management interventions (OGM, 2007). The study area has 189,679 m^3 initial growing stock mostly distributed on the old age classes and low crown closure (< 40% closure) as illustrated in Figures 1 and 2, respectively. Historical legacy of forest management interventions has generated such irregular age class distribution pattern of Yalnızçam planning unit. The major reasons for such old age class structure stem mainly from the lack of management incentives, insufficient field foresters and existence of social conflicts that highly impeded the application of forest management plans on the ground. Besides, regional poverty with a very low level of social welfare coupled with the harsh terrain and climatic conditions generated high social pressure towards the creation of irregular structure of the forested areas. Thus, the average growing stock of the forested areas of planning unit has become as low as 28,1 m^3/ha which is quite low as compared to similar other forest conditions.

Timber values

The future forest condition was predicted based on the initial forest structure. When a stand is regenerated, the future stand was assumed to follow the empirical yield table developed by Alemdağ (1967) for Scots pine. However, the growth of the current stands that

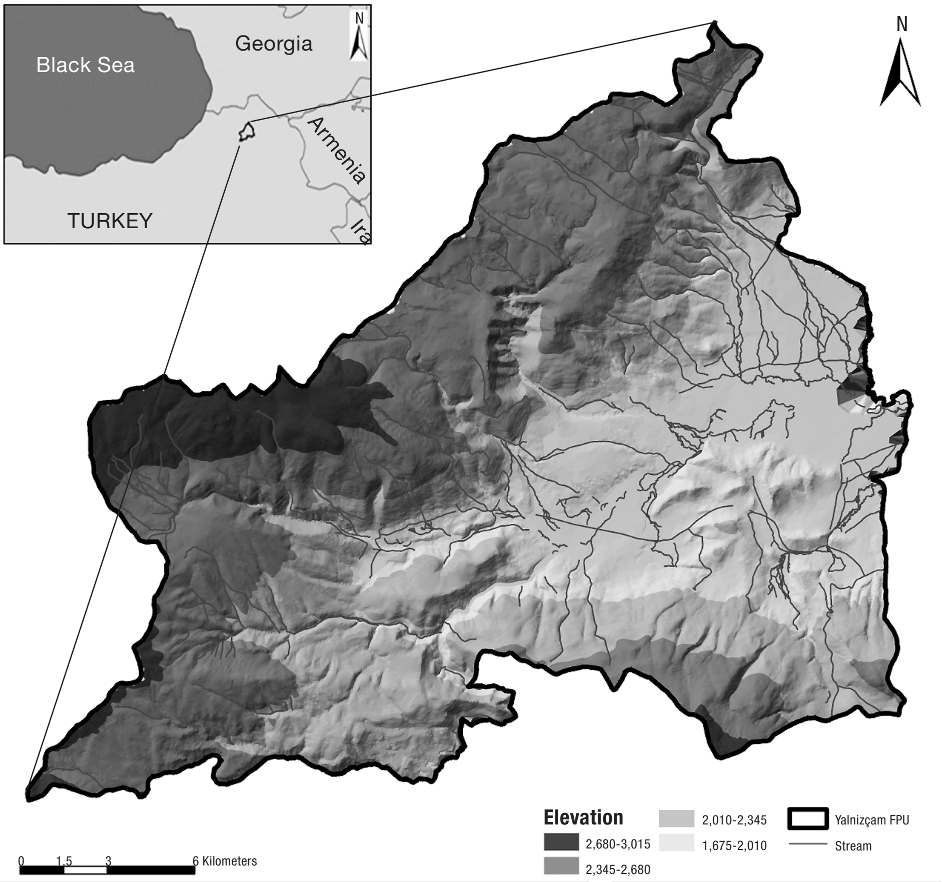

Figure 1. The spatial layout of the study area.

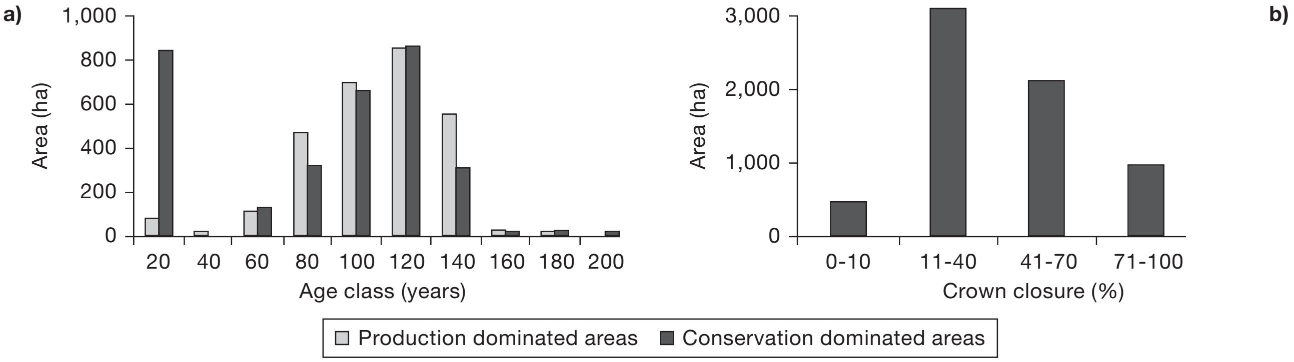

Figure 2. a) Initial age class distribution and b) crown closure of study area.

are not regenerated was predicted based on the functional relationship between the actual basal area and optimal basal area, coming from yield table. In this way, the existing stands were modeled to grow according to both the inventory data and yield table data as there was no growth and yield models developed for Scots pine in the country. Yield tables are prepared for all commercial tree species based on temporary sampling points. Normal yield tables provide correct estimates of the expected growth and yield information based on stand age and site index only for the fully stocked and pure forest stands. The empirical yield tables do not, of course, exactly show the dynamic structure of stands that have various growth conditions and structure. Therefore, growth and yield models are usually developed based on the permanent sample plots to predict appropriately the growth and yield information of stands with various conditions. As there was no permanent sample plots established for this purpose in the country, we used the functional relationship between the current inventory data and the empirical yield table date as a proxy to project the future conditions of stands.

Volumes of different product types such as sawlogs, mining pole, industrial and firewood were determined by product rates based on stand age and mean stand diameter for the relevant species prepared by Sun *et al.* (1977). Financial values of timber were calculated based on the total revenues and costs from timber sales. In this study, the discount rate of 3% was used to calculate the net present values of timber products as a general guiding rate accepted in Turkish forestry (Türker, 2000).

Water values

The amount of surface water yield from the forest ecosystems has been affected by a number of stand parameters such as number of stems, tree species, crown closure and basal area of stands. There exists a reverse relation between stand basal area and the amount of surface water yield. When stand basal area increases, for example, water yield decreases (Kalıpsız, 1982). The functional relationship between stand structure and water production was developed using a regression model between water properties and basal area [1]. The regression model was developed using SPSS v.11.5 software to estimate the per area amount of water production that runs off the surface for Yaln›zçam planning unit (Mumcu, 2007). To create this formulation, first of all, 63 sample plots were taken in planning unit to calculate soil water holding capacity. Then, Thorntwaite method was used to generate water tables produced for six different soil series of the planning unit (Günlü *et al.,* 2009). As Yalnızçam planning unit covers only one bedrock type, Thorntwaite method did not include such parameter in the analysis. However, the soil type and water holding capacity (WSC) were used as important parameters in Thorntwaite analysis to incorporate the permeability of main bedrock. Finally, evaporation and annual precipitation estimated from the Thorntwaite tables were used in the formulation [2] (Çepel, 1988) to calculate the amount of water values for each sample area.

$$WP = 1797{,}97 * e^{-0.0196 * BA} \qquad [1]$$

where WP is the amount water production (m^3) and BA is the basal area (m^2) of stand.

$$F = R - (E + WSC) \qquad [2]$$

where F is the amount of flow (runoff) (mm), R is the amount of annual precipitation (mm) and E is the evaporation (mm).

All revenues and costs used to determine NPV of water were taken from the general directorate of state hydraulic works (DSI) and municipality of Ardahan

Province. To calculate net income for one m^3 drinking, irrigation and industry water, a rate developed by state development agency (DPT) of Turkey (half of the sale price) was used (anonymous, 2001). In this way, one m^3 net income of drinking-use, industry and irrigation water was calculated respectively. Consequently, based on the average use rates of %75, %15 and %10 breakdown in Turkey (anonymous, 2001) for irrigation, drinking-use and industry respectively, the average value of one m^3 water calculated as an average net income from three different utilization of water as drinking, industrial and irrigation was found 0,542 TL. In addition, 3% guiding rate was used as an accepted discount rate of water.

Carbon values

The carbon balance was estimated as the amount of net carbon sequestered in forest biomass based on the biomass growth, harvested biomass and the amount of carbon emitted to the atmosphere according to different uses of the timber harvested [3] (Díaz-Balteiro and Romero, 2003; Keleş and Başkent, 2006). As known, soils in forest ecosystem have high carbon densities. However, sequestered carbon in soil was not included in the model due to lack of data as well as high uncertainty associated with the appropriate calculation of the soil carbon.

$$CB_t = [\gamma(V^t - V^{t-1} + H_t) - CE_t] \qquad [3]$$

where CB_t is net carbon balance at the tth planning period, CE_t is carbon emissions for tth period, H_t is the timber volume harvested at tth period, V^t is the growing stock at the end of tth period, γ is the conversion factor from biomas to carbon.

Amount of carbon emitted to the atmosphere was estimated according to equation [4] (Masera *et al.,* 2003).

$$Cp_{mt+1} = Cp_{mt} \times (1 - a_m) \qquad [4]$$

where Cp_{mt} is carbon stored in wood usage product category, m at time t and a_m is the share of the product that composes each period.

The amount of biomass was estimated simply based on the amount of growing stock. This study is limited to above and below ground carbon sequestration as well as to the biomass of trees over diameter of 8 cm at dbh. Therefore, the amount of biomass for each forest type was calculated using allometric equations from the literature. The above ground biomass was estimated by multiplying timber volume by 1.2 for Scots pine stands. Fresh-weight biomass was multiplied by species-specific conversion factor of 0,473 to yield dry-weight biomass. The root biomass was predicted according to the above-ground biomass by predetermined root to shoot ratio of 0,20. Total dry weight biomass of Scots pine was converted to total stored carbon by multiplying by 0,45. All the conversion factors used in this study are generally specific to Turkish forest ecosystems and have also been used in some scientific researches (Asan *et al.,* 2002; Başkent *et al.,* 2008; Yolasığmaz, 2004). 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 carbon emissions from different timber products were computed based on the lifetime of timber products for Scots pine. 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 (Krcmar *et al.,* 2005). The financial value of carbon per ton was accepted and used to be US $20 according to UN-ECE/FAO (2000). In determining of net present value of sequestered carbon 3% discount rate was used.

Multiple-use forest planning model

In this study, the ecosystem based multiple objective planning approach (ETÇAP) was used as the management framework (Baskent *et al.,* 2000; Baskent and Jordan, 2002). The approach simply aims to sustain various forests based on participation of stakeholders to achieve multiple forest objectives without jeopardizing the long term sustainability of forest ecosystems. The management objectives were then formed to maximize the amount and the NPV of timber, carbon or water values separately subject to conservation of important areas such as sensitive ecosystems and riparian areas. In this context, Yalnızçam planning unit was divided mainly into two management sub-units as timber production dominated areas (47%) and conservation dominated areas (53%) with specific management prescriptions assigned for each of them.

The management model was developed based on a parametric LP technique. Timber and water productions as well as carbon balance were systematically used as the leading management objective. Specifically, when the amount or the NPV of timber was set to maximize,

Table 1. Forest managements planning strategies

Strategies	Objectives	Constraints
TNPV1 TNPV2 TNPV3	Max NPV^{timber}	Even-aged class structure in timber production management unit 20% volume fluctuation among periods Ending inventory ≥ initial inventory
WNPV1 WNPV2 WNPV3	Max NPV^{water}	Even-aged class structure in timber production management unit 20% volume fluctuation among periods Ending inventory ≥ initial inventory
CNPV1 CNPV2 CNPV3	Max NPV^{carbon}	Even-aged class structure in timber production management unit 20% volume fluctuation among periods Ending inventory ≥ initial inventory

for example, then the other objectives would become as constraints. When a desired level for an objective function is found then the level would be used as constraints for the other objective function. Such a parametric LP model was developed according to Model I approach (Leuschner, 1990; Davis *et al.,* 2001). While a number of management strategies would easily be developed in the model, nine major strategies were used in this study to focus on the interaction of three different management objectives (Table 1). The model was formulated based on even-aged class structure, volume flow policies and ending inventory condition in the form of constrains. As the planning unit is dominated by old age class structure, 20% volume flow in each period was used in model to reach a regulated forest over a planning horizon. The model accommodated nine management strategies and solved with Lindo software (Lindo 6.1).

Some assumptions were accepted in the model to understand the interactions among various management strategies in this study. These are given below:

— The planning horizon is 100 years and the planning period is 10 years.

— Regeneration method of the stands is clear-cutting and the response of stands after regeneration is assumed to follow the empirical yield table.

— Timber, water, carbon products and their monetary values for each sub-compartment are calculated separately at the midpoint of each period.

— Stands whose crown closure is between 11% and 40% can not be thinned but, can be regenerated as soon as they reach the minimum harvesting age.

Given these assumptions, some management prescriptions are determined as follows (Mumcu, 2007):

1. Do nothing in some conservation areas over the planning horizon. These areas are forest openings (FO) and degraded areas (D) in recreation forests, biodiversity conservation areas, esthetics areas, riparian areas, social conflicts areas and stands in alpine zone.
2. Other degraded areas, poor regeneration areas and FO areas under social conflict areas can be regenerated in the first period or no prescription at all.
3. Other FO areas can be reforested at any period.
4. Area control constraint was realized only in timber production dominated areas.
5. Do nothing in other areas under social conflict at the first planning period.
6. Minimum harvesting age (rotation age) is 100 years and maximum harvesting age is 200 years for timber production dominated areas, 180 years and 300 years, respectively for the conservation dominated areas.
7. The possible management interventions are thinning, clear-cutting and no treatment.
8. In regenerated stands, pre-commercial thinning action was designed for the stands whose ages range from 0 years to 30 years but commercial thinning was designed from 30 years to minimum harvesting age.

Objective functions:

$$Z_{max} = NPV^{timber},\ Z_{max} = NPV^{water},\ Z_{max} = NPV^{carbon} \quad [5]$$

Constraints and accounting variables:

$$\sum_{i=1}^{m}\sum_{j=1}^{n} a_{ij}^{x} x_{ij} - NPV^{x} = 0 \quad [6]$$

$$\sum_{i=1}^{m}\sum_{j=1}^{n} b_{ij}^{x} x_{ij} - V^{x} = 0 \quad [7]$$

$$\sum_{i=1}^{m} x_{ij} = T_i \quad [8]$$

$$\sum_{j=1}^{m} x_{ij} - A_i = 0 \quad [9]$$

$$\sum_{j=1}^{n} [-(1-y)\ V_J + V_{J+1}] \geq 0 \quad [10]$$

$$\sum_{j=1}^{n} [-(1+y)\ V_J + V_{J+1}] \leq 0 \quad [11]$$

$$\sum_{i=1}^{m}\sum_{j=1}^{n} V_{ij}\, x_{ij} = EI \quad [12]$$

where equation [5] indicates objective functions for various forest values to maximize the NPV of total timber, water and carbon values separately over the planning horizon. Specifically, each forest value is treated as an independent objective function for the model. Equations [6] and [7] are accounting variables. While equation [6] holds the NPV of timber, water or carbon from planning area in period j, equation [7] expresses the amount of these products. Equation [8] is the area constraint for each stand. Equation [9] is the area control constraint to generate even-aged class distribution at the end of 100 years. Equations [10] and [11] are volume control constraints between sequential periods; (y) shows the flow rate as 20%. Equation [12] is ending inventory constraint to guarantee the amount of volume at the end of the planning horizon not less the initial amount. Additionally, m is the number of sub-compartments, n is the number of periods, x_{ij} is the area of stand i treated at period j, a_{ij} is the financial value of products (timber, water, carbon) from stand i in the period j, b_{ij} is the per area production rate of stand i at the period j and A_i is the area of stand i, V_{ij} is the volume per hectare of timber left as ending inventory for stand i under silviculture regime j, EI is the required level of ending inventory.

Results

All management strategies were compared to each other based on the achievement of the economical value of timber, water and carbon sequestered and the amounts of these forest ecosystem values. The regenerated areas, reforested areas, age class structure at the end of planning horizon and ending inventory values for each alternative strategy are documented as forest performance indicators for a better comparison of management strategies.

Timber production and NPV

Forest dynamics under the interactions of three forest management objectives with the same constraints were analyzed to establish the causative basis. Surprisingly, among all management strategies, strategies with carbon objectives CNPV1, CNPV2 and CNPV3 produced the highest amount of timber volume 4,481.9 m^3, 4,718.5 m^3 and 4,709.8 m^3 respectively (Table 2). Especially CNPV2 strategy produced more timber volume than other *C strategies did, as the volume constraint had less restriction than the area and ending inventory constraints. Although all *C strategies had the same objective and reforested all forest opening areas (FO) at the end of planning horizon, CNPV1 strategy reforested less FO areas in the first period and thus provided the least amount of timber volume (Table 4). In addition, even though *C2 and *C3 strategies reforested and regenerated the same amount of areas over 100 years, volume constraint (*2) forced the model to generate more timber volume (Tables 3 and 4). The main reason of less amount of timber product in *T strategies as compared to *C strategies is the objective function. Because the management objective is the maximization of timber NPV, *T strategies reforested less FO areas. As known, reforestation of forest openings has negative effect on NPV of timber when an objective function relates to NPV of forest values and thus *T strategy provided less amount of timber volume over planning horizon.

Table 2. Total production and NPV of timber, water and carbon for each planning strategy

Strategies	Timber		Water		Carbon	
	Production (10^3 m^3)	NPV (10^4 TL)	Production (10^3 m^3)	NPV (10^4 TL)	Production (10^3 m^3)	NPV (10^4 TL)
TNPV1	4.092,3	3.512,8	13.842,6	2.878,8	3.470,4	29.641,9
TNPV2	4.366,0	4.053,9	13.374,3	2.886,5	3.801,5	33.151,1
TNPV3	4.453,3	**4.305,6**	13.655,4	2.979,5	3.932,8	34.845,6
WNPV1	2.302,6	2.396,8	**25.333,8**	4.419,4	1.022,3	8.760,6
WNPV2	2.360,1	2.823,0	25.209,6	**4.443,3**	1.082,4	9.897,2
WNPV3	2.367,3	3.162,9	25.155,9	4.459,0	1.125,6	10.768,2
CNPV1	4.481,9	2.711,6	16.447,4	3.395,3	4.005,5	32.907,5
CNPV2	4.718,5	3.808,2	16.522,2	3.530,3	4.295,0	37.274,4
CNPV3	4.709,8	4.174,1	15.985,3	3.464,1	**4.308,0**	**37.817,8**

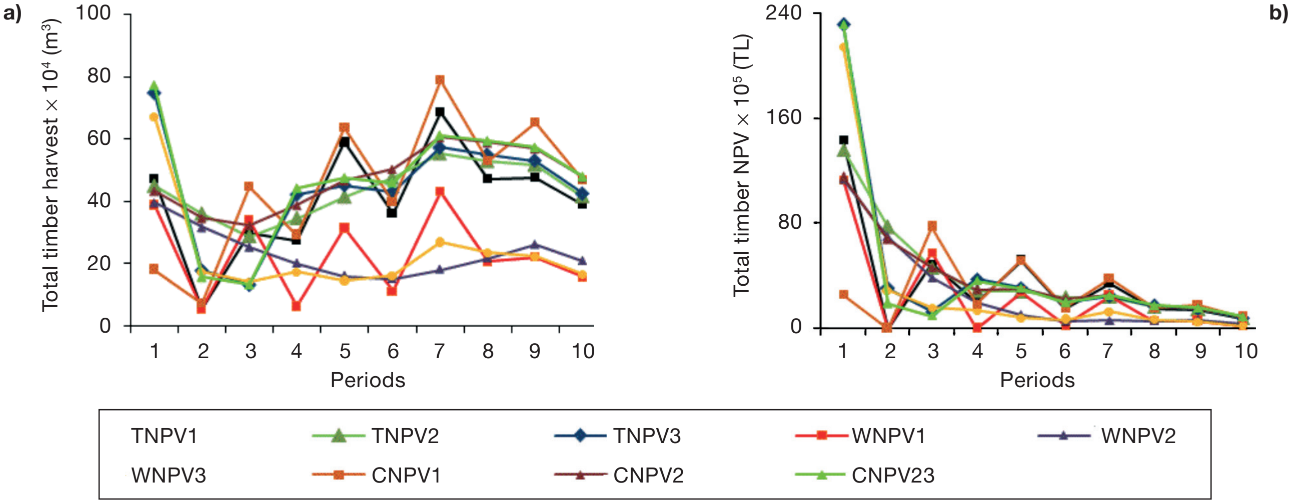

Figure 3. a) Total timber production per 10 year period. b) Total NPV of timber production per 10 years.

In short, the fact that the *C strategies maximize NPV of carbon sequestration lies on the current forest structure and more reforested areas from open areas (Fig. 2).

As expected, the lowest amount of timber volume was generated by *W strategies (Table 2). As the objective function of *W strategies was to maximize the NPV of water, the model tended to decrease the basal area of the forest and reforested less amount of FO areas in the first periods as compared to much areas reforested in the last period. Generated amount of timber from WNPV1, WNPV2 and WNPV3 strategies are 2,302.6 m^3, 2,360.1 m^3 and 2,367.3 m^3 respectively. The reason that *W3 strategy generated more amount of timber volume is the amount of reforested areas of 666 ha FO in the first period to satisfy ending inventory constraint (Table 4). As well, thought *W1 and *W2 strategies reforested almost the same amount FO areas, *W2 strategy generated more timber volume as it regenerated more areas over the first periods (Table 3).

Besides, among all strategies, WNPV1 resulted in the lowest amount of NPV of timber products over the planning horizon. While the objective of the strategies is the same, the area control constraints forced the model to harvest less amount of timber volume and its NPV particularly in *2 and *3 strategies (Table 2). As expected, TNPV3 produced the highest timber NPV (4,305.6 TL). However, even though CNPV2 strategy provides maximum level of timber production, it doesn't produce maximum level of NPV. *T3 strategy regenerated and reforested less areas than *C3 strategy did as afforestation and regeneration activities have negative effects on timber NPV.

Table 3. Regenerated areas (ha) over 100 years

Periods	TNPV1	TNPV2	TNPV3	WNPV1	WNPV2	WNPV3	CNPV1	CNPV1	CNPV3
1	1,770	1,765	3,143	899	993	1,749	1,748	2,803	3,510
2	53	944	391	49	630	394	45	727	325
3	643	753	278	652	580	323	794	583	278
4	10	112	195	46	457	283	0	119	195
5	790	217	255	702	359	214	831	248	255
6	112	241	119	209	321	308	112	202	119
7	1,142	499	499	1,175	224	543	1,193	502	502
8	259	289	289	312	257	324	259	289	289
9	409	358	358	462	547	363	713	353	353
10	125	113	113	113	239	113	153	123	123
Total	5,314	5,289	5,640	4,619	4,607	4,614	5,848	5,949	5,949

Table 4. Reforested areas (ha) over the planning horizon

Periods	TNPV1	TNPV2	TNPV3	WNPV1	WNPV2	WNPV3	CNPV1	CNPV1	CNPV3
1	7,121	7,922	7,922	0	0	666	8,457	9,046	9,046
2	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	101	0	0
6	0	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	94	0	0
8	0	0	0	0	0	0	0	0	0
9	0	0	0	0	0	0	395	0	0
10	579	0	0	671	543	0	153	0	0
Total	7,700	7,922	7,922	671	543	666	9,046	9,046	9,046

Water production and its NPV

Among all strategies, *W strategies provided more amount of water than other strategies did (Fig. 4a). Water production in WNPV1 strategy was 25,333.8 m^3 at the end of planning horizon, while it was 25,209.6 m^3 and 25,155.9 m^3 in WNPV2 and WNPV3 strategies, respectively (Table 2). The main reason of this difference simply lies on the planning policies as these strategies did not reforest FO until the last period as compared to *T and *C strategies. However, *W1 strategy provided more amount of water as *W2 strategy regenerated more areas in the first period. As the water production is correlated with the basal area, those strategies regenerated more areas in the early periods and similarly most of the FO areas were reforested in the first period (Table 3-4). In subsequent periods, the regenerated or reforested stands generated more basal area, and thus resulted in less amount of water production. The results showed that while water production in all periods for *W1 and *W2 strategies were almost the same, in *W3 strategy it had a decreasing trend as *W3 reforested 666 ha FO in the first period and the other *W strategies did not reforest FO until later periods. It can be seen, however, that the *T and *C strategies significantly reduced the amount periodic water production in the subsequent periods because of intensive reforestation activities.

The results showed that the lowest water production value was obtained by *W2 strategy. There are two main reasons for that result. First, the strategy reforested too many forest openings especially in the first period. Second, it harvested less amount of timber volume

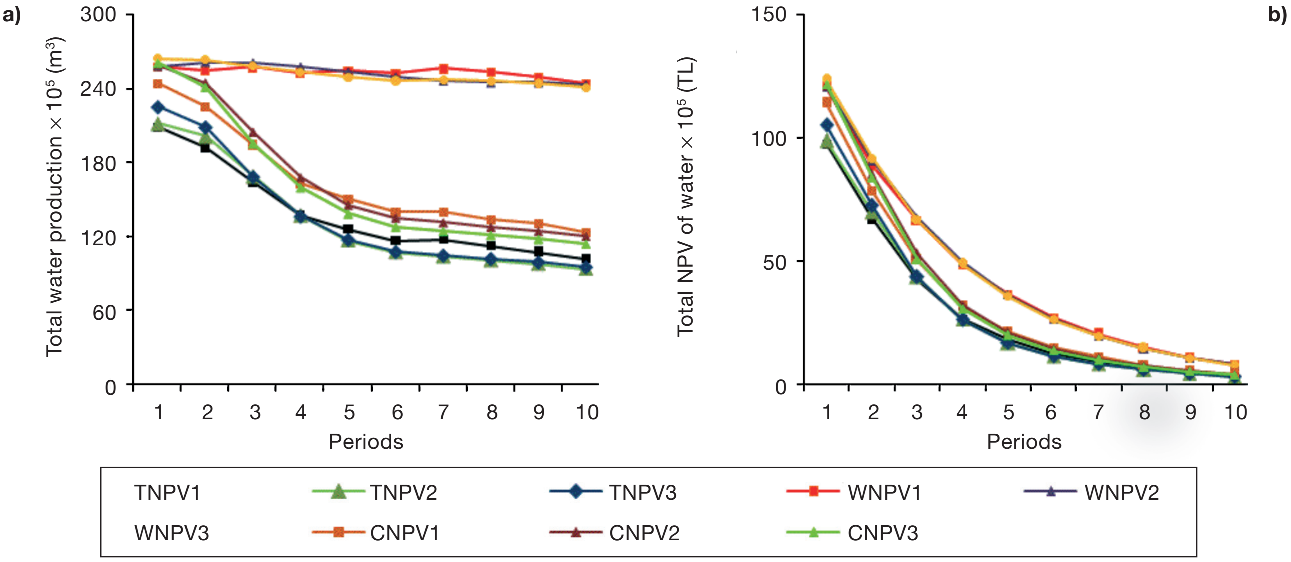

Figure 4. a) Total water production. b) Total NPV of water production over 100 years.

Table 5. Ending invenory (×10^3 m^3) of forest management strategies at the end of planning horizon

Strategies	TNPV1	TNPV2	TNPV3	WNPV1	WNPV2	WNPV3	CNPV1	CNPV1	CNPV3
Ending inventory	6,430	7,053	7,309	1,912	2,047	2,165	7,409	8,065	8,103

(Fig. 3a). In addition, the largest and the least amount of water NPV values were generated by WNPV2 and TNPV1 strategies because of similar reasons (Fig. 4b, Table 2).

Carbon sequestration and its NPV

*C strategies sequestered more carbon than did the other strategies. Since the strategies aimed to maximize NPV of carbon sequestration over the planning horizon, most of the stands that reached minimum harvesting age were regenerated particularly in the early periods. Older stands sequester less carbon due to slower growth rate as far as the amount of volume is concerned. Thus regenerated stands developing in a regulated forest sequestered more carbon. Importantly, in those strategies almost all forest opening areas were reforested in the early periods to maximize NPV.

CNPV3 sequestered more carbon than CNPV1 and CNPV2 did due to ending inventory constraint. However, the strategies whose objectives are to maximize NPV of water production sequestered less carbon as those strategies reforested less amount of FO areas particularly in the last periods and regenerated less amount of areas. In this way, they prevented the basal areas to increase. When Figure 5a is examined, it can be seen that while *W strategies displayed almost the same trend in the subsequent periods, the other strategies showed a decreasing trend from second period on as the harvested products emit carbon to the atmosphere based on the lifetime of wood products.

The standing timber volumes of *C strategies were greater than those of *T and *W strategies at the end of planning horizon. This result indicates that, especially in the initial periods, regenerated and reforested areas have a key role in carbon, water and timber values.

Besides, CNPV3 provided the largest amount of NPV of carbon, while WNPV1 generated the lowest. The reason of this can be explained with planning policies. In addition, in all strategies except *W, NPV increased in the second period because of reforestation of almost all of the forest openings in the early periods (Fig. 5b).

Growing stock and age class structure

Age class distribution of planning unit over time is an important performance indicator of forest management. In this study, the age class structures of both

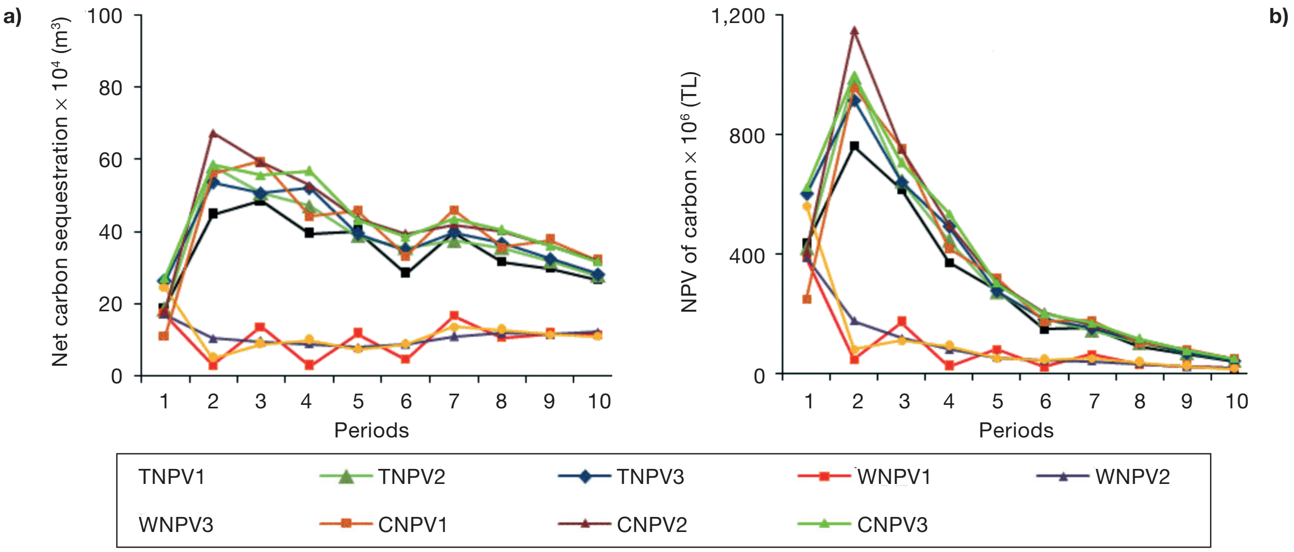

Figure 5. a) Change of total carbon sequestration. b) Total NPV of carbon over 100 years.

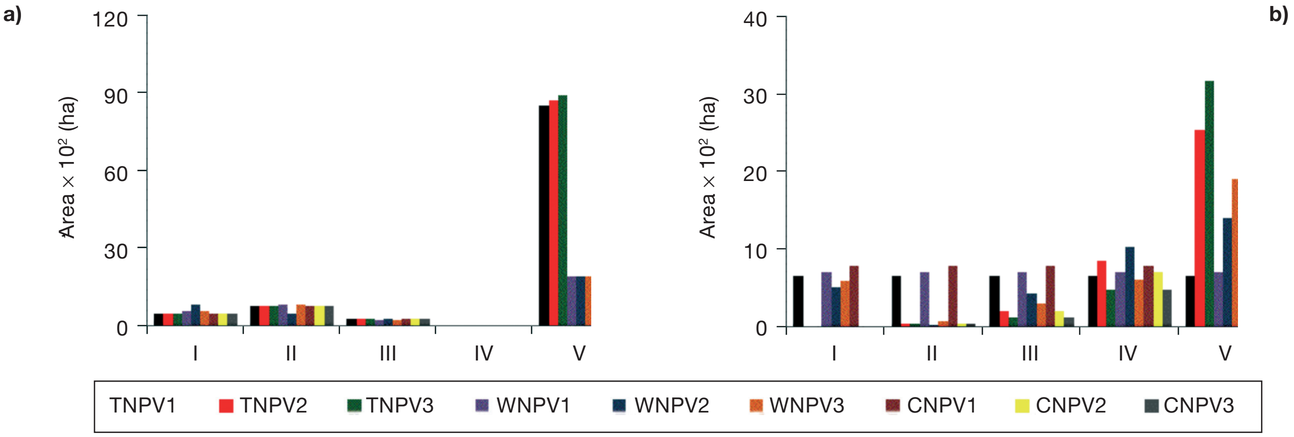

Figure 6. a) Distribution of age class in conservation dominated. b) Production dominated areas.

production and conservation dominated areas are depicted separately in Figure 6. Strategies with area control constraint generated a regulated forest in production dominated areas (Fig. 6b). As expected, however, the strategies with volume control constraint created irregular forest structure over time with regular timber flow. On the contrary, strategies with volume control constraint do not guarantee regular age class distribution as seen in *2 strategies (Fig. 6). There is, however, more area in the last period for CNPV2 strategy as almost all of forest openings were forested in the first period and most sub-compartments were regenerated in the first period too (Fig. 6b). The area control strategies (*1) generated a regular age class structure at the end of planning horizon, although the periodic harvested areas are different due to various levels of afforestation.

Discussions and conclusions

This study attempted to incorporate three forest values timber, water, and carbon using their NPV into forest management planning through the ecosystem based multiple-use planning approach. An LP based model was developed to optimize planning outputs systematically to find the optimum level of each objective that was later used as constraint. Since the relative importance of each objective function has not been pre-analyzed either by questionnaire or participatory planning approach to highlight the degree of conflicts associated with the management objectives, a multicriteria model was not developed. In fact, one way to incorporate multiple forest values simultaneously into forest management is to consider all values using appropriate modeling techniques such as goal programming, multicriteria programming or alternatively meta-heuristics. Goal programming requires the priorities and relative weights of each objective function as all other multi-criteria models do. Metaheuristics such as simulated annealing and Tabu search demand the establishment of a kind of penalty values of each objective function or goal with respect to others to incorporate multiple values into a coherent multi-utility function or global objective function. While all these could be achieved particularly in spatial planning, this study did not particularly pursue such methodology as this study focused principally on the cause and effect relationships among forest values in achieving a target forest structure and thus understanding the tradeoffs among forest values. Thus, we simply developed an LP based forest management model to specifically highlight the effects of each objective function and their interactions in achieving target forest structure. Specifically, the study examined the impacts of volume, area and ending inventory constraints with three different objective functions focusing on the production of timber, water, carbon and their NPVs. The model was implemented in a real case study area of Yaln›zçam forest planning unit, Ardahan Turkey.

The analysis of forest dynamics helped reveal some lessons from the case study as illustrated below:

— Different forest values as timber, water and carbon can be incorporated into a forest management planning model through an economic representation of objective functions as NPV.

— A number of alternative strategies can be developed and implemented using LP. The model was able to reach an even-aged class distribution as well as a regular volume flow at the end of planning horizon.

— The model allows decision makers to assess the trade-offs among the forest values as planning outputs.

Results of this study indicated that *W strategies provided the highest amount of water production although they produced the lowest amount of timber volume. The main reason of producing less amount of timber volume by *W is the reforestation of less forest openings. Similar relationships were found by other studies. Recent researches such as Vertessy *et al.* (2001), Brown *et al.* (2005), Farley *et al.* (2005), and Dijk and Keenan (2007) have postulated that water yield from afforested catchments declines with increasing plantation age. Kovner (1956) also studied the correlation between the basal area and water yield and predicted a negative relationship between them.

Reforestation of forest openings has negative effect on NPV of timber when an objective function relates to NPV of forest values. Thus, *T strategies provided relatively less amount of timber volume over the planning horizon. The main reason of producing less amount of timber volume by *T strategies is reforestation of less amount of forest openings in *T strategies compared to *C strategies. This study clearly stated that when the financial values of timber are considered, the model avoided some costs such as reforested costs. In addition, as model aimed to maximize water and carbon revenues, NPV of timber decreased. Baskent *et al.* (2008) showed that the NPV of timber revenue decreased gradually as the restriction on minimum level of carbon objective increased. Similarly, Raymer *et al.* (2005) showed that the NPV of timber revenue decreased as the constraint on carbon benefit increased.

Results showed that when NPV of carbon objectives are incorporated into management plans, all forest openings were reforested and ending inventory increased. Furthermore, Krcmar *et al.* (2001), Keles and Başkent (2007) and Başkent *et al.* (2008) demonstrated that reforestation of forest openings, especially in early periods, guarantees high amount of biomass and carbon storage in spite of high costs of reforestation. As such, the forest openings have great impact on the forest dynamics as reforestation of almost all forest openings provide positive effects on the sequestrated carbon. Similarly, Kaul *et al.* (2009) indicate that land use changes such as afforestation or deforestation affect net carbon fluxes. Consequently, different forest management activities have the ability to influence the amount of carbon sequestered in the stands (García-Gonzalo *et al.,* 2007; Swanson, 2009; Finkral and Evans, 2008). Some researches indicated that longer rotation ages would be favorable to carbon sequestration (Kaipainen *et al.,* 2004; Seely *et al.,* 2002). However, the present study showed that models incorporating carbon objective regenerated more areas in the first periods. Carbon sequestration of forests is generally related to the amount of growing stock and growth rate of forests. Newly regenerated areas may lose carbon, while young stands gain. The sequestered carbon is reduced along with the declining growth rate and thus over mature stands may lose the amount of carbon sequestration (Jarvis *et al.,* 2005). Thus, younger stands tended to sequester more carbon than older stands did according to the formulation in this study. Backeus *et al.* (2005) showed that total carbon storage increases at a slower rate when a forest matures over time, implying that the carbon flux in a forest ecosystem decreases. Furthermore, Pérez-García *et al.* (2005) showed that when carbon emissions are taken into account, shorter rotations incline to increase total carbon storage. Since the study area is composed of mainly mature stands (Fig. 2), the model naturally tended to harvest stands that exceeded the rotation age particularly in the first period as expected (Table 3). Hennigar *et al.* (2008) investigating effects of initial forest age class structure on carbon indicate that young forests store more carbon. In conclusion, all results indicate that the performance of a management strategy depends highly on the contents of a strategy and the initial forest structure in addition to the amount of forest openings and the growth rate.

The model with the current structure may have some weaknesses that need improvement. First, the current stand simulation model relates to the simple allometric relationship between the actual and the optimal development pattern of the stands. The model does not account for climate change effects during the considered 100 years planning horizon. Realistically, however, a growth and yield model should be developed based on permanent sample plots and climate information. Second, there are other forest management objectives such as controlling erosion or soil lose that may have to be integrated into the model as well. Third, the spatial arrangement or allocation of the harvest schedule from LP model needs to be controlled either by using mixed integer programming or meta-heuristic techniques.

Forest management planning evolved from classical timber production approach to multiple-use planning approach. As forests provide many socio-cultural and environmental services such as production of water and preservation of soil besides wood products, water production and sequestration of carbon have become an important global concern as forests play an important role in the water production and carbon sequestration. As such, characterizing and planning of those values in a sustainable management context is of a great concern. This paper incorporated successfully three forest values and their NPV into forest management planning. However, many other forest values such as non wood forest products, recreation and soil protection should likewise be included in forest management planning.

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