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ARTÍCULOS

Optimization of water yield, carbon storage and wood production in forest planning by mixed integer programming

Optimización del rendimiento hídrico, el almacenamiento de carbono y la producción de madera en la planificación forestal mediante programación entera mixta

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SUMMARY

Interventions to the forest also affect the amount and quality of water and carbon storage; revenues to be obtained from these areas as well. Therefore, for the long-term estimation of the harvest plans to be organized, it is necessary to eliminate the lack of information for other functions provided by the forests and to quantify their relationship with forest dynamics. In this study, it was intended to determine how forest functions, such as wood production, hydrologic and carbon storage functions, changed according to different objective functions and constraints and what kind of harvest scheduling is prepared in line with a planning process. Seven different planning strategies have been developed for the Çiçekli planning unit, aimed at maximizing profit according to these different strategies. Among the developed strategies, the highest objective function value (500,704,847 TL) was obtained in the strategy 6 (ST6), where there is no Optimal Periodic Area (OPA) constraints. The highest amount of water (894,728,400 m^3) was obtained in the strategy 7 (ST7), which has a constraint on the amount of area to be regenerated. While the amount of carbon stored in the planning unit decreased due to the high amount of regenerated area in most planning strategies, only in ST7 it has increased in all periods, showing periodic regeneration constraints. At the end of the planning horizon, the amount of growing stock (2,446,402 m^3) has increased only in ST7 with regeneration constraints, whereas the amount of growing stock has decreased in all other strategies.

Key words: forest planning, harvest scheduling, carbon, water, wood production.

RESUMEN

Las intervenciones en el bosque también afectan a la cantidad y calidad del agua y del almacenamiento de carbono, así como a los ingresos que se obtienen de estas zonas. Por lo tanto, para organizar la estimación a largo plazo de los planes de aprovechamiento, es necesario eliminar la falta de información de otras funciones que proporcionan los bosques y cuantificar su relación con la dinámica forestal. En este estudio, se ha pretendido determinar cómo cambian las funciones forestales, como la producción de madera, la función hidrológica y la de almacenamiento de carbono de los bosques, a partir de diferentes funciones objetivas y limitaciones, y qué tipo de programación de aprovechamientos se prepara de acuerdo con un proceso de planificación. Se han desarrollado siete estrategias de planificación diferentes para la unidad de planificación de Çiçekli, y se pretendía maximizar el beneficio de acuerdo con estas diferentes estrategias. Entre las estrategias desarrolladas, el mayor valor de la función objetivo (500.704.847 TL) se obtuvo en la estrategia (ST6), en la que no hay restricciones de Área Periódica Óptima (OPA). La mayor cantidad de agua (894.728.400 m3) se obtuvo en la estrategia (ST7), que tiene una restricción sobre la cantidad de superficie a regenerar. Mientras que la cantidad de carbono almacenado en la unidad de planificación disminuyó debido a la elevada cantidad de superficie regenerada en la mayoría de las estrategias de planificación, ha aumentado en todos los periodos solo en la estrategia (ST7), que tiene limitaciones de regeneración periódica. Al final del horizonte de planificación, la cantidad de existencias en crecimiento (2.446.402 m3) ha aumentado solo en la estrategia (ST7) con restricciones de regeneración, mientras que la cantidad de existencias en crecimiento ha disminuido en todas las demás estrategias.

Palabras clave: planificación forestal, programación de aprovechamientos, carbono, agua, producción de madera.

INTRODUCTION

Due to the increasing and diversifying demands for forest resources, the potential effects of the decisions to be taken concerning biological diversity, wood production, carbon storage, hydrological and recreational values –as well as other values– should be included in various decision-making stages related to forestry. The complex spatial and temporal relationships among these features, and the lack of general information and data about the nature of these relationships make the nature of these relationships make this process difficult. The increasing tendency towards multi-purpose forest management requires the development of decision support systems that will reconcile time-space complexity with developing and evaluating alternative management scenarios. It requires that the obtained information needs to be well-designed in the planning processes to reveal various relationships in the forest ecosystem and ensure sustainable benefits with interdisciplinary studies.

In this context, it is first aimed at determining functions of forests including wood production, carbon storage and hydrological functions within ecosystem-based functional planning and afterwards integrate them into forest management plans to meet demands of the society for different functions of forests by combining the scientific data produced in different interdisciplinary studies under the planning framework.

Hydrological function in forestry is defined as a function of the forest areas that contributes to ground water keeping the water clean in dams and ensuring that water resources are continuous, orderly and balanced. Generally, it is believed that the increasing density of forest cover negatively affects water yield. Many studies stated that an inversely proportional change occurs in the amount of water depending on the increase and decrease in the basal area. Increased forest cover density has positive effects on the quality of drinking water, while negatively affecting water yield (Webster *et al*. 1992). Forests are highly effective on the quality, quantity and seasonal distribution of water. It is also stated that 44 % of the precipitation in forested areas reaches streams or rivers and becomes usable water, while this rate remains at 14 % in non-forest areas (Gülcü *et al.* 2008). Besides, plant roots increase soil depth by entering cracks in rocks and breaking them and increase the dissolution power of soil water through the CO_2 it extracts (Gülcü *et al.* 2008).

It should be our main purpose to create forest areas that have the most significant impact on water yield, improve soil interception and water retention capacity, and reduce transpiration in basins, where the main objective is water yield. When only water yield is considered, it is seen that even-aged forests are more advantageous than uneven-aged forests. Actually, the contribution of broad-leaved forest trees to water yield is higher than that of coniferous trees, and light trees are more suitable among coniferous trees. These results reveal the relationship between water yield and the amount of leaves (Kalıpsız 1982).

In the determination of hydrologically functional areas, the forest areas around water bodies like dams, lakes and ponds in catchment basins are taken into consideration (OGM 2019). Many studies have been conducted around the world for paired watershed efforts and hydrological functions. The effects of vegetation removal on water yield and quality have been examined, and relationships for the hydrological function of forests have been presented (Likens *et al.* 1977, Hsia and Koh 1983, Webster *et al.* 1992, Bari *et al.* 1996, Burton 1997). In Turkey, the number of studies conducted to examine the hydrological function of forests and the inclusion of this function in forest planning is limited (Keleş 2003, Keleş *et al.* 2005, Karahalil *et al.* 2009, Zengin *et al.* 2012, Degermenci 2018). The lack of both scientific data -produced by being a multidimensional and comprehensive subject- and sufficient research cause planning work not to be at the desired level. Since the existing studies aimed at understanding the hydrological effects of forests in Turkey are often unable to demonstrate the interaction and relationships of the dynamic structure with basin properties, there is limited information reflecting the various spatial and temporal characteristics of hydrological functions into planning. The studies also make it difficult to focus on micro basins (usually two basins) and generalize the information obtained from these basins.

The total water reserve in the world is thought to be approximately 1,400 million km^3. Approximately 97.5 % of this amount of water consists of salt waters in the seas and oceans. The remaining 2.5 % freshwater supply is available for different purposes (Görcelioğlu 1992). Clean water sources have decreased significantly due to wastes arising from the technological developments, various fertilizers, chemical drugs used in farmland and misuse of lands. According to the World Bank, it is determined that approximately 450 million people are facing severe water shortage problems today. Eighty percent of deaths in developing countries were found to be the result of water-related diseases (Kiziroglu 2002).

Economically, the capacity of Turkish streams is approximately 95 billion m^3. Of this amount, 48.1 billion m^3 are produced annually from forest areas. Thus, approximately 50 % of the available superficial waters in Turkey reaches streams from forest areas covering approximately one-fourth of the country (Görcelioğlu 1992).

In addition to its hydrological function, forest ecosystems perform an essential service by sequestering and storing carbon. The increase of greenhouse gases and especially CO_2 in the atmosphere significantly affect global warming. Some measures are taken on limiting emissions to reduce the amount of CO_2 in the atmosphere worldwide. As a natural process, carbon is taken from the atmosphere by plants via photosynthesis, released back into the atmosphere through respiration, decay and burning. Forest ecosystems are vital as carbon pools, and the carbon can be stored in biomass, soil, litter and deadwood (Başaran 2004). Changes in land use reduce the amount of organic carbon of the soil to the lowest levels in the first 20 years. A hundred-year period has to pass to maximize the amount of organic carbon in the soil, which is exposed to this type of situation (Birdsey 1992).

It is necessary to determine temporal and spatial changes and calculate the amount of biomass available in the forest ecosystem to determine the carbon storage capacity of the forest. The determination of biomass by using inventory data is the most common approach. First, the standing volume is calculated using inventory data (Kurz 1993, Krankina and Harmon 1996, Başaran 2004). Afterwards, biomass (above ground and underground) calculation is performed using transformation coefficients from previously conducted studies and developed equations with calculated standing volume (Brown 1997, Yolasığmaz 2004, Keleş and Başkent 2006, Sivrikaya and Keleş 2007). After biomass calculation from the standing volume, the carbon storage capacity of forest areas can be estimated using biomass conversion coefficients (Sivrikaya and Bozali 2012).

In this study, we aimed at developing a forest plan with different strategies based on forest functions. It was intended to estimate which sub-compartments will be regenerated or thinned to optimize the amount of wood production, the quantity and quality of water and the amount of stored carbon. We used the allowable cut amounts from thinning and final harvests to develop long-term planning model. Shortly, the hypotheses tested in this study may be summarized as follows: 1) harvest scheduling changes with integration of different forest functions to planning process, 2) multiple use planning provides more revenues than single production, 3) water quality demands decreases the amount of wood production, 4) constraint on allowable cut obtained by regeneration cuttings effects the harvest scheduling.

METHODS

Study area. In this study, Çiçekli Forest Planning Unit (FPU) of Düzce Forest Enterprise works under Bolu Regional Directorate of Forestry, situated between 40º 37' 14'' - 40º 43' 34'' Northern Latitudes and between 31º 10' 27'' - 31º 15' 26'' Eastern longitudes in the Western Black Sea Region of Turkey, was selected as the study area (figure 1). Within the scope of the study, the stand map of the management plan, generated in 2000, was used. In this management plan, there are 64 compartments, 292 sub-compartments, and 85 different stand types in Çiçekli FPU. The total forest area covers 3,486 hectares (88 %), and the non-forest area is 455.2 hectares (12 %) in the FPU. Forests are dominated by pure stands of oriental beech (*Fagus orientalis* Lipsky.), fir (*Abies bornmülleriana* (Link) Spach.) and mixed stands of scotch pine (*Pinus sylvestris* L.), black pine (*Pinus nigra* Arnold) and

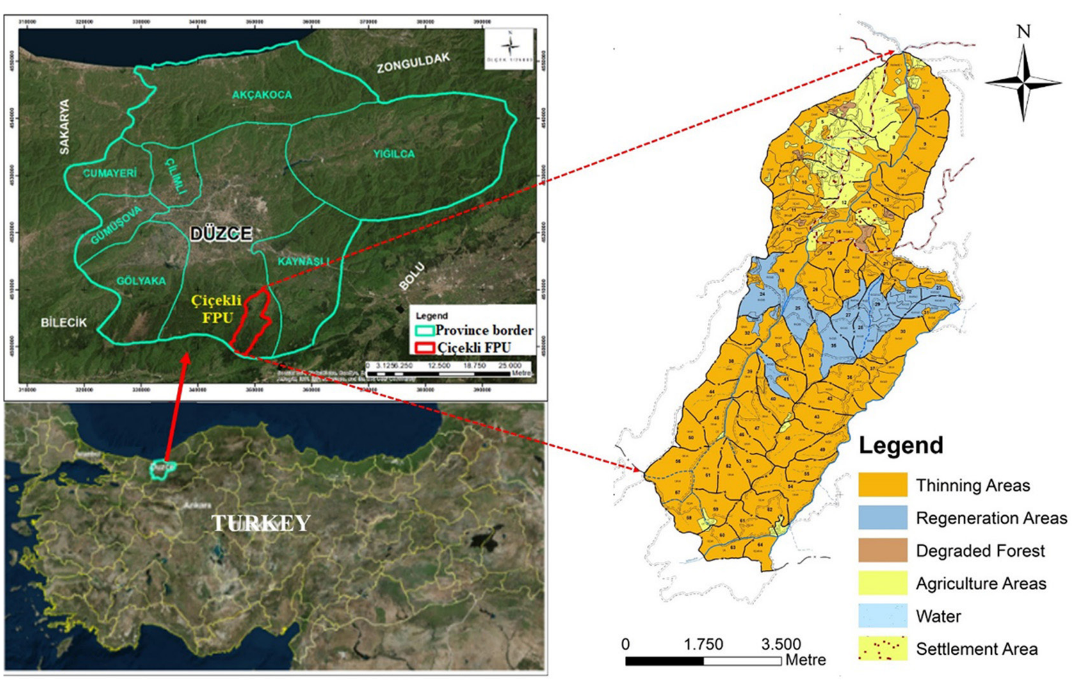


Figure 1. Geographic location of the study area.

Localización geográfica del área de estudio.

hornbeam (*Carpinus betulus* L.) trees. The elevation of the planning unit above sea level varies between 410-1,631 m.

To draw the creeks and roads in the planning unit and to determine the distance of each sub-compartment from the road and the forest store, 1:25,000 scale topographic maps were used. The slope group for each stand was also obtained by using the contour lines of the planning unit. Yield tables were used to achieve development trends of the various parameters related to the stands throughout the planning horizon. Data, such as mean slope, ground skidding distance and transportation distance, required for the calculation of production costs for each stand were determined using the ArcGIS 10.4™ software. The growth matrices for each stand type were performed using Microsoft Office programs according to the 100-year planning horizon within the scope of the mixed-integer programming model. General Algebraic Modelling System (GAMS 24.8.1) optimization program was used to create the optimal harvest scheduling for the 100-year planning horizon according to different scenarios. GAMS is a high-level modeling system for mathematical optimization problems. GAMS is designed for modeling and solving linear, nonlinear and mixed-integer optimization problems. The GAMS software is tailored for complex, large-scale modeling applications and allows the user to build large maintainable models that can be revised to new situations. The system is available for use on various computer platforms. Models are portable from one platform to another (GAMS 2020).

In this study, some basic data are needed to establish a planning model. In this context, some studies have been conducted as a preliminary preparation in 29 micro watersheds to reveal the relationships between basin characteristics and water yield, water quality and forest structure. As a result of these studies, the relationships between parameters were used to develop the following methods.

Calculation of water yield, water quality and carbon storage amount. For this study, it is first necessary to determine the relationships among forest structure and land characteristics and various ecosystem characteristics. For this purpose, the forest inventory data of the project completed between 2013-2017 (Zengin *et al.* 2017) and the relationships determined in this context were used. The equations used for this purpose are given below.

$$\text{Flow} = 3{,}143.5 + 1.49A + 0.31V - 0.25Nug - 1{,}075.7HAu + 19.1BHu - 0.94Pu - 964.1HAa - 19.5STKa - 4.2Pa \quad (R^2 = 0.66;\ P < 0.01) \qquad [1]$$

Flow: flow from unit area (mm/m²), A: watershed area (ha), V: volume per hectare (m³/ha), Nug: number of long juveniles in hectares (number/ha) (dbh < 8 cm and h > 1.3 m), BHu: topsoil porosity (%), HAu: topsoil bulk density (g/cm³), HAa: subsoil bulk density (g/cm³), STKa: subsoil water holding capacity (%), Pu: topsoil permeability (mm/sa) and Pa: subsoil permeability (mm/sa).

Among the water quality parameters, nitrate, pH and suspended solids (SS) parameters, which are considered important for quality water, were used.

$$\text{Nitrate} = -1.885 + 0.004H - 0.005V + 0.0051STKu \quad (R^2 = 0.75;\ P < 0.01) \qquad [2]$$

$$pH = 8.62 - 1.431\,D + 0.606F - 0.0005H + 0.001V + 0.001BHu - 0.001Pu \quad (R^2 = 0.67;\ P < 0.01) \qquad [3]$$

$$SS = 0.116 + 0.004Ay - 0.0003Pa + 0.00009V \quad (R^2 = 0.58;\ P < 0.01) \qquad [4]$$

D: circularity ratio, F: form factor, H: elevation (m), V: volume per hectare (m³/ha), BHu: topsoil porosity (%), Pu: topsoil permeability (mm/sa), STKu: topsoil water holding capacity (%), Ay: ratio of non-forest areas in the watershed (%), Pa: subsoil permeability (mm/sa).

While determining the carbon amounts of the planning unit, only the amount of carbon stored in above-ground biomass (AGB) has been taken into account. For calculating the amount of the carbon stored in above-ground biomass, standing volume (SV) was used with a coefficient determined by the studies conducted by Asan (1995) and Tolunay (2011). The equations in table 1 show the

Table 1. Calculation of the amount of carbon stored in the planning unit.
Cálculo de la cantidad de carbono almacenado en la unidad de planificación

Categories		Biomass (Mg)	
		Productive forest	Degraded forest
Above ground biomass (AGB)	Coniferous	SV*0.446* 1.212	SV*0.446* 1.212
	Deciduous	SV*0.541* 1.310	SV*0.541* 1.310
Carbon in above ground biomass (C-AGB)	Coniferous	AGB*0.51	AGB*0.51
	Deciduous	AGB*0.48	AGB*0.48

calculation steps of the amount of the carbon stored in above-ground biomass (C-AGB) (Değermenci and Zengin 2016).

The planning periods in forestry are very long. Various goods and services are obtained in different periods and, in return, various expenditures are made. While comparing the expenditures and revenues in different periods, it is necessary to know their values at a certain time and for this purpose, net present value (NPV) was used (Türker 2000). The proposed interest rates in forestry were usually between 1-10 % (Bekiroğlu 2001). NPV rate was taken as 3 % in this study because interest-related works in forestry in Turkey are very limited, and they used the overall accepted NPV rate in forestry, which is 3 %.

General structure of the planning model. The mathematical expression of the model that will maximize wood, water and carbon income was created with different objective functions for the planning unit. To calculate the income from the amount of carbon and water in addition to wood production in the objective function, it is necessary to determine the numerical value of unit price for water and carbon. In the equations related to the amount of water used to run the planning model, the water prices of Düzce province were taken as the basis, and the unit price per m^3 was set as 2 TL (0.4 €) by the municipality. Assuming that 70 % of this unit price constitutes the general costs, the unit price of water obtained from the forest within the scope of this study has been considered as 0.6 TL (0.12 €). The unit price of the amount of carbon held in the above-ground biomass in the planning unit should also be determined. The pricing of carbon is distributed in a wide range of carbon prices with different pricing nationally, internationally or regionally (Huiyan *et al.* 2017). Generally, 75 % of the regions, where carbon prices are set, use a unit price inferior to 3 Euros (€) for carbon. However, the unit price of carbon may be ranged from 1 € to 35 € (World Bank 2017). Since the carbon unit price is below 3 € worldwide, it is taken as 5 TL, which corresponds to approximately 1 € in our study.

The basic expressions and some assumptions accepted to understand the main framework of the model are given below.

- Calculations were made for five periods with a planning horizon of 100 years and a period length of 20 years.
- In the 100-year planning horizon, only stands that reached rotation age can be regenerated.
- Stands that are not subject to regeneration will be subject to maintenance cuttings.
- Natural regeneration methods will be used for regeneration of the stand, and a successful regeneration is accepted in the future for the entire sub-compartments.
- The boundaries of the sub-compartments will not change, and clear-cut method will not be used throughout the planning horizon.
- Depending on the development class, a certain amount of volume was taken from the stands for thinning and only normal stocked stands will be intervened
- The developments of mixed stands will be made after their regeneration according to the dominant tree species, and the yield table of this tree species were used.
- For tree species that do not have a yield table, others similar to that tree species were used. The parameters of very old stands that are not included in the yield tables will be estimated by interpolation.
- The volume, basal area and mean-diameter development of the stands were determined according to the volume increment percentage simulation method (Eraslan 1981).
- The Age Classes Method was used as the management method, and the periodic final revenue will be calculated according to this method. The regeneration areas should not exceed the limits of Optimal Periodical Area (OPA) which is taken as 800 ha.
- Uneven-aged forests in the planning unit were considered as even-aged forest.
- Forest openings will be afforested in any period in line with the planning horizon, and beeches were used for afforestation.
- The effects of climate change and future demand to the wood type assortments were not taken into account.

Objective function:

$$maxZ = \sum_{j=0}^{N} \left(\left(\sum_k \sum_{u=1}^{npr} \left(P_u^w - C_{k,u} \right) m_{k,u,j}^c \right) + P^{wa} W_j + P^c m_j^c \right) (1+\propto)^{-n(j-1)} \quad [5]$$

(The objective function maximizing the NPV from wood, water and carbon net income)

Constraints:

$$m_{k,u,j}^c = \sum_i q_{k,i,u,j}^m X_{k,i,j}^m + q_{k,i,u}^r X_{k,i,j}^r \quad [6]$$

(amount of wood assortments)

$$X_j^p = \sum_{k,i} \left(X_{k,i,j}^r + X_{k,i,j}^m \right) \quad [7]$$

(periodic wood volume to be extracted)

$$V_{k,i,1} = V_k^0 A_k y_{k,i} \quad [8]$$

(actual wood volume of a stand)

$$V_{k,i,j+1} = V_{k,i,j}\left(1 + nr^{growth}_{k,i,j}\right) - X^{m}_{k,i,j}, \quad \forall k,i,j : i \neq j \qquad [9]$$

(growth balance between sequential periods)

$$V_{k,j,j+1} = V^{10}_{k} A_k y_{k,j}, \qquad \forall k,j \qquad [10]$$

(initial volume of a stand after regeneration)

$$X^{r}_{k,j,j} = V_{k,j,j}\left(1 + nr^{growth}_{k,j,j}/2\right), \quad \forall k,j \qquad [11]$$

(wood volume extracted by regeneration cuttings)

$$\underline{r}^{m} V_{k,i,j} \leq X^{m}_{k,i,j} \leq \overline{r}^{m} V_{k,i,j}, \qquad \forall k,i,j : i \neq j \qquad [12]$$

(limits of wood volume extracted by maintenance cuttings)

$$\left(1 - r^{p}\right) X^{p}_{j} \leq X^{p}_{j+1} \leq \left(1 + r^{p}\right) X^{p}_{j}, \qquad \forall j \qquad [13]$$

(constraint for periodical wood flow balance)

$$\sum_{i} y_{k,i} = 1, \qquad \forall k, \qquad [14]$$

(constraint for choosing only one scenario among the planning horizon)

$$\underline{A}^{p} \leq \sum_{k} A_k y_{k,i} \leq \overline{A}^{p}, \quad \forall i, \qquad [15]$$

(constraint for periodical regeneration area)

$$Mj^{c} = (V(k,i,j+1) - V(k,i,j))*0.541*1.31*0.48) \qquad [16]$$

(amount of carbon storage)

$$\sum_{k,i} X^{r}_{k,i,j} \leq \overline{R}, \quad \forall j, \qquad [17]$$

(amount of wood volume by periodical regeneration)

$$W_j = \frac{(3143.5 + 1.49\sum_{k} s_k A_k + 0.31 V^{w}_{j} + 0.25 Nu_j + const)}{\sum_{k} s_k A_k}, \qquad [18]$$

(amount of water)

$$Const = -1075.7\, HAu + 19.1\, BHu - 0.94\, Pu - 964.1\, HAa - 19.5\, STKa - 4.2\, Pa \qquad [19]$$

(characteristics of the watersheds)

The parameters:

N: the number of the periods,
n: the length of the periods,
P_u^{w}: the unit price of the wood product *u*,
S_k: Is stand k in the area reserved for water yield,
P^{wa}: the unit price of water,
P^{c}: the unit price of carbon,
$C_{k,u}$: the cost of transportation the required materials from stand k, for product u,
$\propto$: the interest rate,
A_k: the area of the stand k,
V_k^{0}: the actual volume of wood in stand k,in a unit area of land,
V_k^{10}: the wood volume of a new regenerated stand k,
$r^{growt}_{k,i,j}$: the growth rate of the volume of wood in stand k in period j, given that stand k is subject to regeneration in a different period i,
$\overline{r^{m}}, \underline{r^{m}}$: allowed upper and lower bounds on the ratio of the volume of the wood that is obtained by maintenance cuttings,
$\overline{A^{p}}, \underline{A^{p}}$: allowed upper and lower bounds on the total area that can be made regeneration cuts,
r^{p}: allowed change in the ratio of volumes of woods cut at consecutive periods,
$\overline{R}$: allowed upper bound on the amount of wood that can be obtained by regeneration cuts,
$q^{m}_{k,i,u,j}$: the ratio of wood product u, of the maintenance cuts in period j, in stand k, if it is regenated at period i,
$q^{r}_{k,i,u}$: the ratio of wood product u, of the regeneration cuts in period i, in stand k.
Nu_j: The number of juvenile trees per hectare in the watershed for period j,

The decision variables:

$y_{k,i}$: if the stand k is subject to regeneration cut at period *i*,
$X^{m}_{k,i,j}$: the wood volume obtained by maintenance cutting at period j from stand k, given that the stand k has a regeneration cutting at period i,
$X^{r}_{k,i,j}$: the wood volume obtained by regeneration cutting at period j from stand k, given that the stand k has a regeneration cutting at period i,
X_j^{p}: the total wood volume that is obtained in period j,
$V_{k,i,j}$: the growing stock of stand k in period j, given that the stand k has a regeneration cutting at period i,
V_j^{w}: the growing stock per ha in the watershed in period j.
$m^{c}_{k,u,j}$: the amount of wood product *u* from stand *k* in period *j*.
M_j^{c}: the amount of carbon storage in period *j*
W_j: the amount of water yield in period *j*

Determination of the planning strategies. To achieve specific goals within the scope of the study, seven different planning strategies have been developed to produce alternatives along the planning horizon and choose the best fit for the management goal among these strategies (table 2). It is possible to create various strategies by trying different alternatives and making changes to some levels of constraints affecting the objective function. However, certain objective functions were included not to expand the scope of this study, and the periodic change of outputs for objective functions was examined by taking the situations given in table 2 into consideration.

Table 2. Objective function and constraints related to planning strategies.

Función objetivo y restricciones relacionadas con las estrategias de planificación

Strategy No	Constraints	Objective function
ST1	Consider the periodic allowable cut fluctuation (20 %), Consider the Optimal Periodic Area (OPA < 800 ha) constraints,	Maximizing Revenue from Wood Production,
ST2		Maximizing Revenue from Wood and Water yield
ST3		Maximizing Revenue from Wood Production and Carbon Storage
ST4		Maximizing Revenue from Wood, Water yield and Carbon Storage
ST5		Maximizing Revenue from Wood and Water yield, considering water quality parameters
ST6	No constraint	Maximizing Revenue from Wood, Water yield and Carbon Storage
ST7	Let the periodic total regeneration has an upper limit (100,000 m^3)	Maximizing Revenue from Wood, Water yield and Carbon Storage

RESULTS

When considering the objective function values of planning strategies, it is seen that the highest profit is obtained in ST6, where there are no OPA constraints, and the revenue obtained from wood production, water amount and carbon amount is taken into account. ST6, with an annual profit of 5,007,048 TL, is followed by ST4, which has the same objective function as ST6 with an annual profit of 4,329,677 TL, although with OPA and periodic allowable cutting fluctuation constraints. The profits obtained in ST2 (wood production and water yield) and ST5 (wood production, water yield and water quality) are also close to the profits obtained in ST4. The strategy with the lowest profit was ST1, aiming at maximizing the profit obtained from wood production alone with 2,041,697 TL per year. On the other hand, in the ST3 planning strategy, which aims at maximizing the profit obtained from wood production and carbon amount, an annual profit of 2,070,122 TL was achieved. Unlike ST1, ST3, which also calculates the revenue obtained from carbon, could not increase its revenue too much because carbon revenues did not affect the objective function value much. Unlike the ST6 planning strategy, which has the highest objective function value, an annual profit of 2,813,607 TL was achieved in the ST7 planning strategy, which has a periodic regeneration constraint of 100,000 m^3 only. Although the revenue obtained from wood production in the ST7 planning strategy is lower than the revenue obtained from all other strategies, more profit was obtained in terms of objective function value due to the monetary value of the increased growing stock and consequently the increased amount of water compared to ST1 and ST3. According to these results, it is clearly seen that especially the objective functions not including water yield have low revenues.

When considering the distribution of profits obtained from wood production, water amount and carbon amounts in each strategy throughout the planning horizon, it is seen that the strategy that makes the most profit from wood production is ST6. Considering the profit obtained from carbon and water yield, ST6 takes the last place. However, ST6 is the strategy where the most profit is obtained as the objective function. In obtaining this profit, it was effective to regenerate a very high amount of forest area, especially in the first two periods, and to generate a very high amount of revenue from forest products obtained from it. The lowest amounts were obtained, especially for the NPV, since the monetary values after the first period were drawn. However, ST6 generated a high revenue in the first period, and this revenue was reflected in the objective function. The strategy with the lowest profit obtained from wood production is ST7. Since there is a periodic regeneration constraint, the allowable cut amount of final revenue is very low compared to other strategies. The ST7 planning strategy is the strategy in which the most profits are made in terms of water and carbon revenues, as it builds up a wealth of growing stock. Even though revenues are close to each other in the first five strategies with OPA constraints, the lowest revenue from wood production is obtained in the ST2 planning strategy. The carbon revenues and water revenues of these five strategies are close to each other. The values with asterisk in the revenue distributions given in table 3 are those that do not impact the objective function value of that strategy. For example, the profit from wood production in ST1 is equal to the objective function value. The ST3 planning strategy used the profits obtained from carbon and wood production in the objective function. Although other revenues are not included in the objective function, they show the revenues that can be achieved by changes in the objective function in the planning model (table 3).

The amount of growing stock in the planning unit has decreased by almost the same amounts in all periods in the first five planning strategies. These first strategies with OPA constraints made the logging scheme very similar to each other, and they tried to optimize their profit. The ST6 planning strategy with no OPA constraints decreased significantly in the first 3 periods, increased in the last two periods, and at the end of the plan horizon, it had a growing stock amount close to the first five strategies. ST7 was the only planning strategy that increased the amount of growing stock in all periods. Since there is a periodic regeneration constraint in ST7, the amount of cutting taken from the forest remained below the increase of the forest and accumulation of growing stock was observed. The first five strategies have lost about 42.5 % of their growing stock compared to the initial amount of their growing stock. The ST6 planning strategy lost 43.2 % of its growing stock, while the ST7 planning strategy achieved 57.3 % growing stock accumulation. At the end of the planning horizon, the lowest amount of growing stock was observed in the ST6 planning strategy with 803,440 m^3, whereas the highest amount of growing stock was observed in the ST7 planning strategy with 2,227,009 m^3. The ST6 planning strategy has regenerated areas above OPA to increase wood production, and this has caused the ST6 planning strategy to have the lowest growing stock values in all periods. The changes in the amount of growing stock are given in figure 2.

When considering the amount of allowable cut obtained from all planning strategies, it is observed that the strategy with the highest thinning yield is ST7 (908,161 m^3), and the lowest strategy is ST6 (226,732 m^3), respectively. Since there were no OPA constraints in ST6, the cuttings were mostly taken as regeneration cut, and the allowable cutting amount of thinning yield remained low compared to other strategies. In the ST7 planning strategy, very small forest areas were subject to regeneration due to the periodic regeneration constraints, and the allowable cut were taken as thinning yield. Therefore, in the ST7 planning strategy, thinning yield was found to be very high. In terms of thinning yield, ST1, ST2, ST3, ST4 and ST5 planning strategies have received similar allowable cut. It is seen that the ST7 planning strategy, which has a periodic regeneration constraint, regenerated small amounts of forest area in all periods and therefore the final yield was very low considering the periodic distribution of planning strategies in terms of allowable cut amount of final harvest. ST6 with no OPA, periodic allowable cut fluctuation and periodic allowable cut constraints received more allowable cut than did all planning strategies in the first two periods in terms of the final harvest. In contrast, it received a lower amount of allowable cut than that received by the first five strategies in the next three periods. The ST2 planning strategy produced the most wood in terms of total final harvests. Although other planning strategies (ST1, ST3, ST4 and

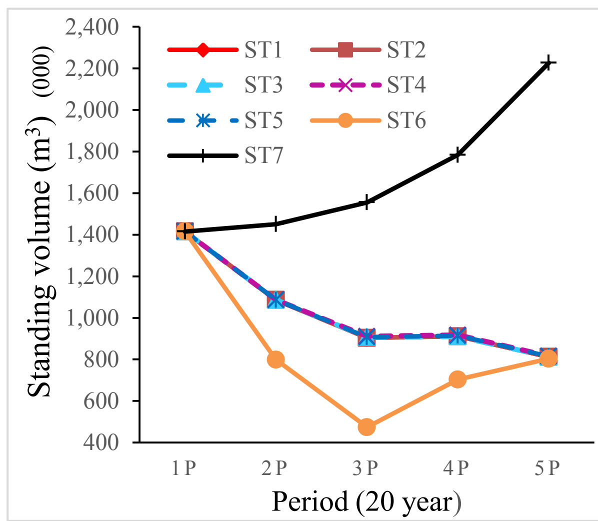


Figure 2. Variation of the standing volume according to different strategies throughout the planning horizon.

Variación del volumen en pie según las distintas estrategias a lo largo del horizonte de planificación.

Table 3. Revenues based on planning strategies.

Ingresos basados en las estrategias de planificación

Strategy	Income from planning horizon			Object function (TL)
	Wood (TL)	Carbon (TL)	Water (TL)	
ST1	204,169,655	3,116,463*	225,856,252*	204,169,655
ST2	189,478,238	3,116,330*	225,858,946	415,337,184
ST3	203,889,108	3,123,051	225,857,110*	207,012,159
ST4	203,980,095	3,123,558	225,864,064	432,967,717
ST5	204,004,613	3,122,283*	225,861,068	429,865,681
ST6	272,683,605	2,644,512	225,376,730	500,704,847
ST7	49,225,245	5,316,284	226,819,130	281,360,659

* Without impact on the objective function value of that strategy.

ST5) with OPA constraints were close to ST2 in terms of final harvests, they have taken at least 3,000 m^3 less wood than ST2 (figure 3).

When considering the areas regenerated in the planning unit after final harvests, it is seen that similar harvest scheduling occurred in the first five strategies with OPA constraints. The area of forest subject to regeneration is almost equal to the OPA value in the first three periods and below the OPA value in the last two periods, respectively. The ST6 planning strategy, which has no OPA and periodic regeneration constraints, regenerates nearly twice the amount of OPA in the first two periods while regenerating forest areas were well below the OPA in the next three periods. The ST7 planning strategy with no OPA constraints, but periodic regeneration constraints, regenerated areas well below the amount of OPA in all periods (figure 4).

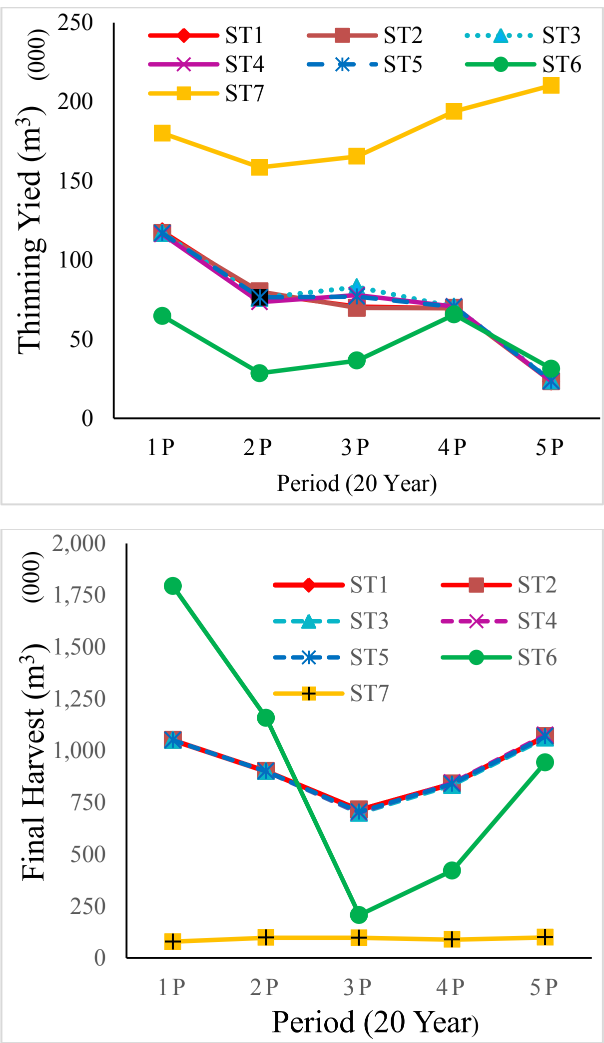


Figure 3. The thinning (above) and final (below) harvest distributions of all strategies by periods.

Las distribuciones de entresaca (arriba) y de corta final (abajo) de todas las estrategias por períodos.

As a result of the purpose-oriented cutting plan determined by the planning strategies and wood products, each planning strategy has different age classes distribution. With the addition of regenerated areas and non-intervened areas, the age class distributions related to planning strategies were determined at the end of the planning horizon. In the planning strategies of ST1, ST2, ST3, ST4 and ST5 with OPA constraints, the area distribution occurred below the amount of OPA in the first two age classes and above the OPA amount in the next three age classes, respectively. In the ST6 planning strategy, there were areas well below the OPA in the first three age classes, while there were forest areas in the IV. and V. age classes much above the amount of OPA. The ST7 planning strategy included very few scheduled regeneration harvests and left the forest to grow. As a result, while the regenerated forest area was below the OPA amount in the first four years of age, it is observed that more than four times the amount of OPA was accumulated in the last age class of the forests when the stands are not regenerated (figure 5).

When the planning strategies are evaluated in terms of the amount of product variety achieved at the end of the 100-year planning horizon, it is seen that the largest amount of forest goods were produced in the ST2 planning strategy with 4,938,568 m^3. On the other hand, the lowest amount of forest goods was produced in the ST7 planning strategy with 1,370,970 m^3. Other planning strategies (ST1, ST3, ST4 and ST5) with OPA constraints have also produced amounts of wood close to the ST2 planning strategy. The ST6 planning strategy, which has no OPA constraints, produced wood products in lower amounts than those produced by the planning strategies with OPA

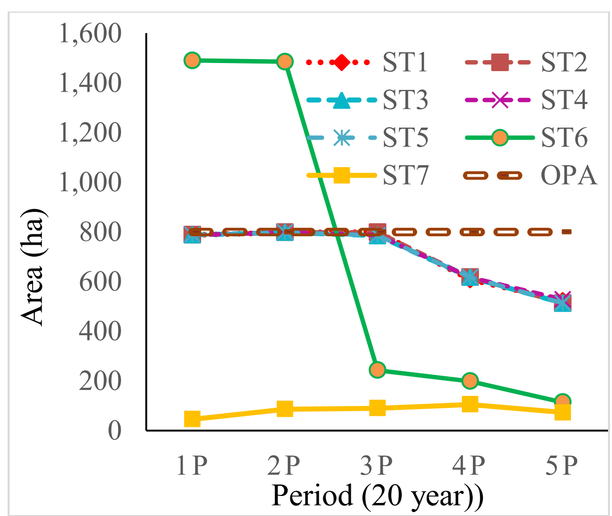


Figure 4. Amount of regenerated areas according to planning strategies.

Cantidad de áreas regeneradas según las estrategias de planificación.

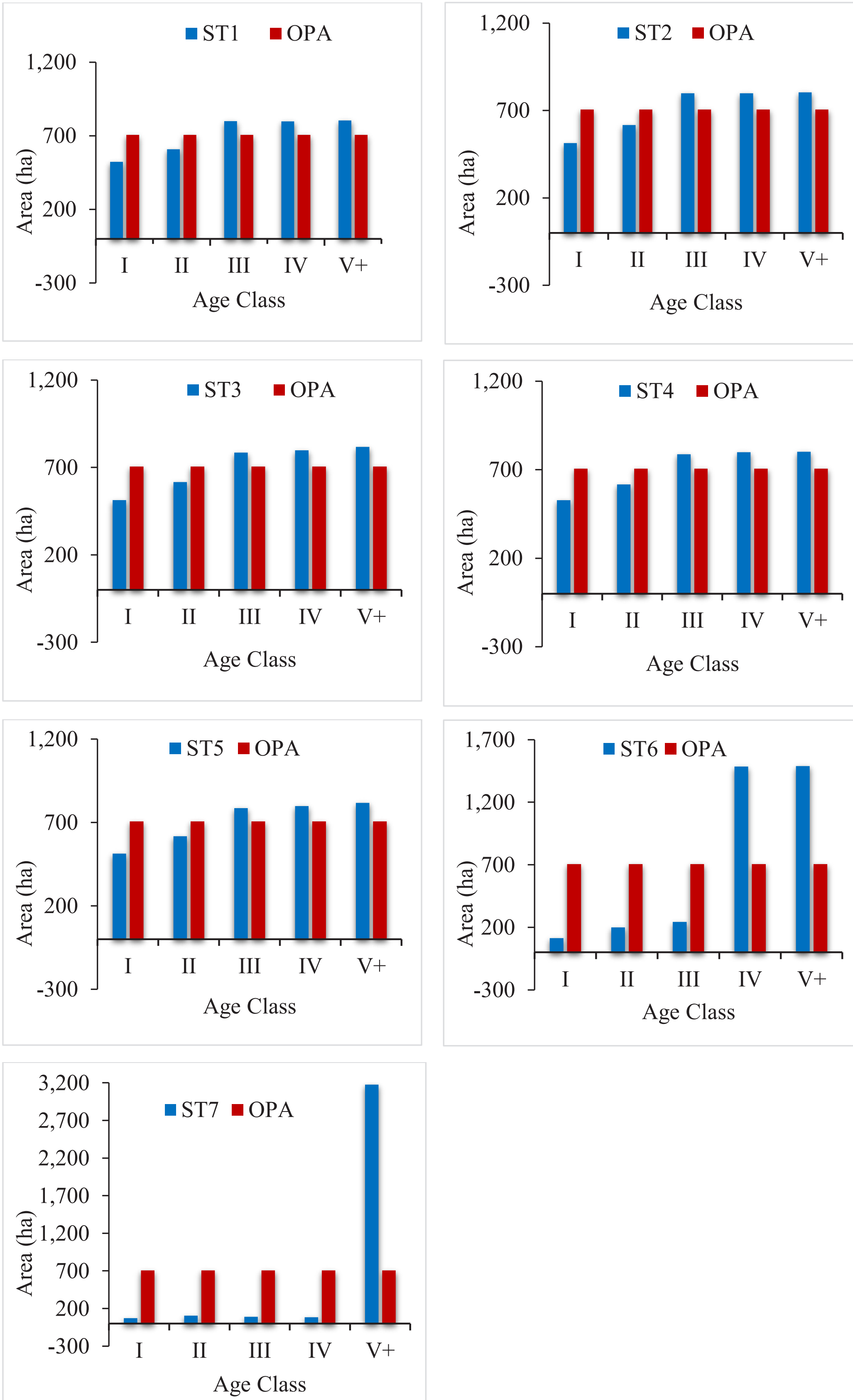
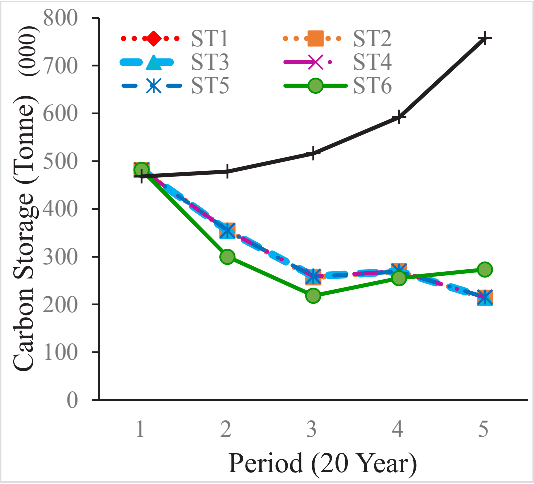


Figure 5. Planning strategies age classes distribution at the end of the planning horizon.

Distribución de las clases de edad de las estrategias de planificación al final del horizonte de planificación.

constraints and higher amounts than those produced in the ST7 planning strategy (table 4). In all strategies, the most produced wood product type was log, while the least produced wood product was firewood.

When considering the planning strategies in terms of the amount of carbon stored periodically in aboveground biomass, it is seen that the ST7 planning strategy increased the amount of carbon storage in all periods. The periodic regeneration constraints limited the amount of regenerated area in the ST7 planning strategy and prevented the amount of allowable cut extracted from the forest. This situation led to an increase in the ST7 planning strategy growing stock and an increase in the amount of carbon storage in all periods. Even though the amount of carbon stored in the ST6 planning strategy decreased in the first 3 periods, it increased slightly due to the increase in the amount of grown stock in the last two periods. In the first five strategies with OPA and periodic allowable cut fluctuation constraints, the amount of carbon stored by periods increased only in the 4th period compared to the previous period, while it decreased in all other periods. While the lowest carbon storage amount was seen in the ST1 planning strategy, a similar amount of carbon was connected in ST2, ST3, ST4 and ST5 planning strategies. The amount of carbon was decreased by 56 % compared to the initial carbon amount of the planning unit at the end of the planning horizon while the amount of carbon was increased by about 57 % in the ST7 planning strategy with the highest carbon storage. When planning strategies are evaluated in terms of the amount of water produced by periods, the ST7 planning strategy produced more water in all periods compared to other strategies in parallel to the changes in the grown stock. While the amount of water yield of the ST6 planning strategy decreased in the first three periods, it increased in the last two periods. Although the amount of water produced in the first five strategies, which have OPA constraints, is close to each other, it decreased in general. A slight increase was observed in the 4th period compared to the previous period (figure 6).



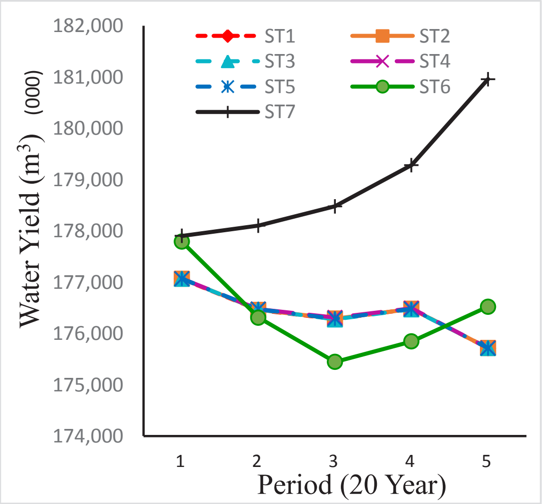


Figure 6. The amount of carbon stored (above) and the amount of water yield (below) along the planning horizon according to planning strategies.

La cantidad de carbono almacenado (arriba) y la cantidad de rendimiento hídrico (abajo) a lo largo del horizonte de planificación según las estrategias de planificación.

Table 4. Wood assortment types produced over a 100-year planning horizon.

Tipos de surtidos de madera producidos en un horizonte de planificación de 100 años.

	Strategies						
Range of product	ST1	ST2	ST3	ST4	ST5	ST6	ST7
	m^3	m^3	m^3	m^3	m^3	m^3	m^3
Log	1,480,049	1,481,174	1,479,029	1,481,635	1,480,632	1,390,973	452,841
Mine timber	1,394,503	1,395,612	1,385,846	1,393,976	1,391,538	1,356,866	382,982
Industrial timber	628,499	628,840	625,144	628,264	627,268	624,506	180,185
Wood fuel	1,431,435	1,432,942	1,425,274	1,432,087	1,429,974	1,376,791	354,962
Total	4,934,485	4,938,568	4,915,293	4,935,961	4,929,966	4,749,136	1,370,970

In the ST5 planning strategy, the periodic changes in water quality parameters in the planning unit were also examined in addition to water yield (table 5). Conditions such as forest form, type of tree, regeneration order of stands and type of intervention affect water quality. In this context, the pH parameters, which are among the quality parameters, were observed to be acidic in all periods in the ST5 planning strategy that aims at maximizing the revenue obtained from wood and water yield. The pH value varies between 0-14, and it is between 4-9 in natural waters. Suspended solids formed by solid substances that can or cannot settle in water may be transported with water depending on the flow rate of water and the size of the particles. Water pollution control regulation emphasizes that the total amount of dissolved suspended solids for 1st class waters should not exceed 0.5 g/L. During the planning horizon, it is seen that SS value is among the values that should be in 20-year periods. Nitrate is an effective factor in the growth of plants. It does not have a toxic effect unless it is in high concentration in natural waters; thus, it can be used by plants. The average value of nitrate in water should be inferior to 10 mg/L. In the planning unit, the nitrate amounts throughout the planning horizon were determined in the desired range and varied in the range of 2.4-2.9 mg/L.

Within the scope of different objective functions, all planning strategies may differ from each other in terms of the periods in which the stands are subject to regeneration or care. In this context, especially in the first five planning strategies, similar logging schemes were formed. It is seen that the ST6 planning strategy rejuvenated the majority of the stands in the planning unit in the first two periods. On the other hand, the ST7 planning strategy subjected the majority of stands to the care and never regenerated them due to the periodic regeneration constraints. The cutting plan map of ST1 for the first five strategies with similar distribution is shown below. Furthermore, ST6 and ST7, which have cutting plans different from those of these five strategies, are given below (figure 7).

Table 5. Water quality parameters along the planning horizon according to the ST5 planning strategy.

Parámetros de calidad del agua a lo largo del horizonte de planificación según la estrategia de planificación ST5.

Periods	Water quality parameters		
	pH	SS	Nitrate $(NO_3)^-$
		g/L	mg/L
1P	4.901	0.186	2.432
2P	4.848	0.182	2.700
3P	4.900	0.181	2.746
4P	4.920	0.178	2.896
5P	5.010	0.177	2.975

CONCLUSIONS

In this study, which was conducted by using the mixed integer programming technique, the most important advantage may be that a whole stand can be treated as a processing unit in any period. In modelling studies using linear programming techniques instead of integer programming, it is possible to process small pieces of stands rather than the whole stands during periods. This is not a desirable situation for practitioners, and the practitioners may have problems in terms of determination of the period and the part of the stand they will intervene. With the mixed integer programming technique, it is possible to regenerate a stand only in one period, which significantly increases the applicability of the plan. A disadvantage that we may encounter in this plan is the negativities that may occur when a whole stand with a large area is cut within a period. To eliminate these disadvantages, assessments should be made according to the purpose of the operation and necessary measures should be taken, or the stands should be divided into smaller pieces before initiating the planning.

This study aimed at using the data produced by different disciplines (forest management, forestry yield, watershed management, soil science and forest economy) under one framework and create a long-term planning model for different objective functions. Especially in Turkey, there is no study that takes into account the integration of water quality parameters, such as pH, SS and nitrate values, into the forest planning process. While there are many assumptions in forest optimization studies, we intended to decrease these as much as possible and used the real data generated for Çiçekli FPU in terms of forest services considered in this study. The developed planning model was designed by taking multiple services of the forest and functional planning criteria into consideration. By organizing the harvest scheduling in the planning unit, it is possible to determine where and when to regenerate, the interventions for each stand in terms of time and place, and how much allowable cut will be taken as thinning and final yield. Different objective functions may be created and plans may be prepared for different management goals by utilizing the equations expressing the ecological, economical and socio-cultural functions that can be integrated to the planning model. In this study, seven different planning strategies have been developed to test four hypotheses, and information has been obtained regarding planning and harvest scheduling that was created by the planning model according to different constraints and objective functions throughout the planning horizon.

When examining the hypotheses of the study, it is observed that different objective functions under the

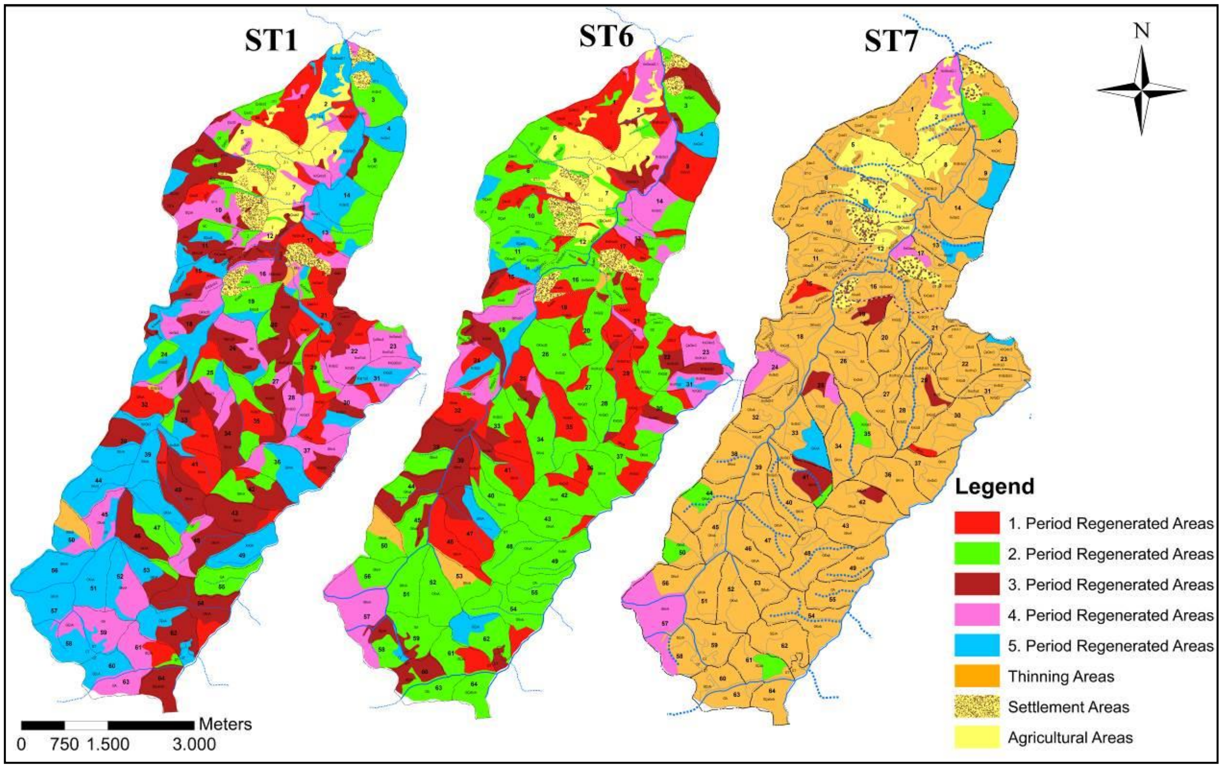


Figure 7. Planning strategies harvest scheduling maps.

Mapas de programación de la cosecha de las estrategias de planificación.

same constraints have very limited effects on the model to change the harvest scheduling. The model has created nearly the same harvest scheduling, even if the objective function changes. This is especially apparent in the first five strategies where different objective functions showes the same constraints. Only the regeneration period of few stands changed in the fifth period. However in some studies it is vice verse, for this planning unit situation there are not many changes observed in the harvest scheduling regarding the first hypothesis. Because the unit prices entered into the model, especially for water and carbon, are not attractive enough for the model to reduce wood production and increase water and carbon by changing the harvest schedule. The least total revenue was obtained at the first strategy which has an objective function with only wood production. The total revenue was increased as the carbon and water production entered to the model. However the revenues increased by the integration of water yield and carbon storage objectives to the model, and water quality demands decreased the amount of wood produced along the planning horizon. While there is not too much decrease, generally, to meet the water quality demand, the model avoided harvesting trees. The constraint related to allowable cut obtained by regeneration cuttings was very effective on harvest scheduling. When this constraint was added to the model, harvest scheduling and activities related to this, revenues and production amounts were completely changed.

The number of strategies can be increased by adding different constraints. In particular, the unit carbon and unit water prices used in the study can be changed to observe how the model will behave after making these changes. An increase in the unit price of carbon and water could allow the model to tend to increase the amount of water and the amount of carbon stored instead of wood production. In this way, different strategies may be tried to achieve the desired goal under different constraints, and different cutting plans may be obtained.

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