UDC 630.6/613

ANALYZING THE EFFECTS OF DIFFERENT MANAGEMENT STRATEGIES ON FOREST BIOMASS CARBON LOSS USING LINEAR PROGRAMMING

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Received 27.02.2018

The effect of greenhouse gases on climate change is of great importance. In this context, forest ecosystems are seen as a critical mechanism in reducing carbon emissions by storing large quantities of carbon in vegetation and soil. The aim of this study was to compare and monitor biomass carbon sequestered in a range of forest structures subject to different forest planning scenarios. To this end, many scenarios have been tried over a planning horizon of 100 years for 1000-ha hypothetic forests. Two forest sites (both high- and low-productivity) and two rotation ages (70 and 100 years) were studied to analyze the effects of site condition and logging rotation length on carbon stock. Some constraints were also included, such as set aside forest area and volume control. Then, 35 mathematical models were developed using a linear programming technique and solved in LINGO software. Among the models developed, S7 model appeared to be the best in terms of minimizing the carbon loss from forest biomass. With this scenario, only 6447 tons of carbon were lost over 100 years with an even-flow harvesting policy and a mature rotation age (u = 100). The worst model was S4, where there were no constraints and the rotation age was young (u = 70). Almost 215 000 tons carbon loss resulted with the use of S4 model for a 100-year planning horizon. The results showed that the carbon dynamics of forest ecosystem was influenced to a great extent by forest management strategies. Therefore, the application of the optimal strategy involving the use of modern planning techniques is very important for mitigating the effects of global climate change.

Keywords: *carbon management concept, forest planning, mathematical modeling, operation research techniques, Calabrian pine Pinus brutia Ten. stands, Turkey.*

How to cite: *Vatandaşlar C., Keleş C., Fosso L. C., Karahalil U.* Analyzing the effects of different management strategies on forest biomass carbon loss using linear programming // *Sibirskij Lesnoj Zurnal* (Sib. J. For. Sci.). 2019. N. 1: 65–72 (in English with Russian abstract).

DOI: 10.15372/SJFS20190106

INTRODUCTION

As population and deforestation have grown globally due to the industrial revolution, the amount of greenhouse gases in the atmosphere has increased rapidly (IPCC, 2007). This increase led to warming of the atmosphere towards the end of the 20th century and brought about big environmental problems, such as global warming and climate change. It was the time when research work began to focus on this subject and it was determined that carbon dioxide (CO_2) is the most dangerous among the greenhouse gases (carbon dioxide, methane, hydrofluorocarbons, perfluorocarbons, sulfuric anhydrides, and ozone) in terms of global warming (Nordhaus, 1991; Tolunay, Çömez, 2008). Besides it resulted in understanding of the importance of forest ecosystems in reducing CO_2 emissions and thus in mitigating global climate change effects due to that atmospheric CO_2 is only stored by terrestrial ecosystems (grassland, forest, agricultural lands etc.) and oceans. Among terrestrial ecosys-

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tems, forests sequester more CO_2 than other vegetation systems (Mısır et al., 2012; Zengin, Ünal, 2017). In fact, more than 80 % of the carbon stored in terrestrial ecosystems is in forest ecosystems depending on the amount of live biomass (Jandl et al., 2007; Tolunay, Çömez, 2008). Moreover, forest ecosystems have a carbon reduction potential of 5.38 Gt/year until 2050 (IPCC, 2007; Yolasığmaz et al., 2016). These findings triggered international awareness and events, such as the Protocol on Persistent Organic Pollutants (1998), Montreal Protocol (1987), and several international conventions were held on similar problems (United Nations…, 1992; Kyoto Protocol, 1998; Paris Agreement…, 2015). The signatories and contracting states have a number of goals and commitments. For example, «Paris Agreement» (2015), signed by Turkey among the other states, is aimed at keeping the increase in global temperatures below 1.5 °C (WWF, 2016). In order to achieve these goals, conservative forestry activities, such as deforestation prevention, reforestation enhancement, afforestation expansion, illegal logging prevention, degraded forestland rehabilitation, forestry practices accelerating forest growth, forest exploitation reduction, forest fire, and insect control are to be developed (Huston, Marland, 2003; Kurz et al., 2008). In this context, member-countries periodically prepare National Greenhouse Gas Inventories and report on annual carbon stock changes (Yolasığmaz et al., 2016). For example, Turkey has been reporting its carbon stocks since 2006 (Tolunay, Çömez, 2008; National Inventory…, 2007). As is clear from these reports, Turkey's forests sequestrated 14.5 million tons of carbon in 2004, which is equivalent to 53.1 million tons of CO_2 (Land Use…, 2006). Forest management administration plans constitute the basic data source for the above-mentioned inventories and reports (Karahalil et al., 2018).

Forest influence on the atmospheric CO_2 change is analyzed in biomass surveys and carbon sequestration studies (Mısır et al., 2013). The analysis involves the following steps: first, the amount of organic matter formed as a result of photosynthesis in forest ecosystems is determined. Then, the amount of carbon in this biomass is measured. The amount of CO_2 equivalent to the amount of carbon measured is finally calculated (IEA…, 2005). Carbon stocks and emissions can thereby be determined at a global, national, regional and even stand scale.

Numerous studies reported that carbon sequestration in forests depends on forest management strategy and ecosystem planning approach used (Diaz-Balteiro, Romero, 2003; Backeus et al., 2005; Keleş, Başkent, 2007; Hu, Wang, 2008; Karahalil, 2009; Swanson, 2009; Moreno-Fernandez et al., 2015; Kucuker, Baskent, 2015; Zengin, Ünal, 2017; Serengil, 2018). These studies show that the rotation ages (either short or long) and management strategies implemented (even-flow or non-declining harvesting policy, protected area constraints, carbon pricing etc.) considerably change the amount of carbon sequestrated. The initial forest structure (young or mature) and site conditions (high or low productivity) are also important factors accounting for carbon losses and CO_2 emissions. It is therefore vital to determine management alternatives most appropriate for different forest types specific in composition and configuration. Maximum carbon sequestration in a forest enterprise area can be achieved using an optimum long-term management strategy. This is the only way to effectively mitigate global climate change impacts at the landscape, national, and international levels.

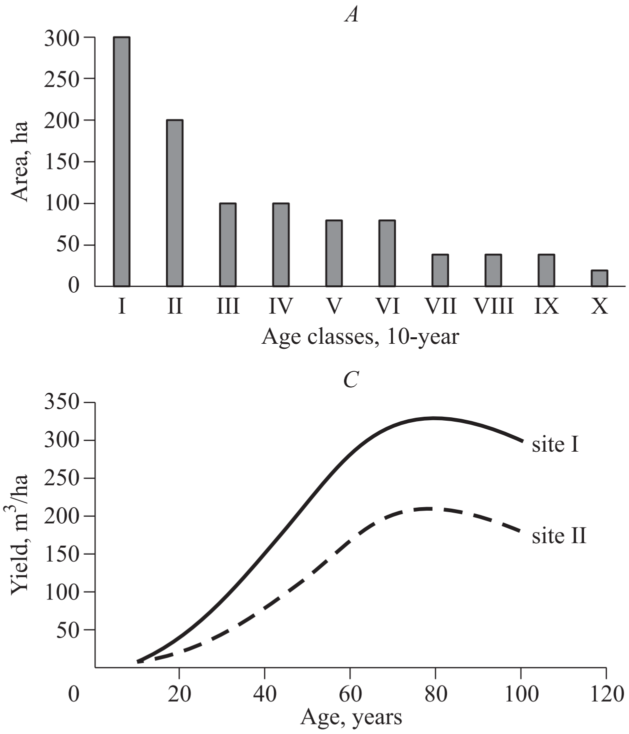
The aims of this study were (i) to implement various forest planning scenarios in hypothetical forest enterprise areas differing in forest structure, (ii) to quantify and compare carbon losses due to forest harvesting at the end of the planning horizon, and (iii) to determine the best planning scenario in terms of carbon loss minimization. With this methodology, optimum forest management strategy regarding carbon loss reduction can be identified for different forest types.

MATERIALS AND METHODS

Study area. The study area consisted of four hypothetically established forest enterprises. Let us assume that these enterprises had two initial age class distributions and two sites, 1000 ha each. The area and yield (i. e. timber volume) for each age class are shown in Figure.

The study area was a typical Mediterranean ecosystem of pure Calabrian pine *Pinus brutia* Ten. stands. Therefore, available growth and yield table data for Calabrian pine (Yeşil, 1992) were utilized and the forest yield curves built. The period intervals (i. e. time step) for Calabrian pine were taken to be 10 years, as is commonly done in Turkey.

Modeling approach and planning scenarios. Linear programming, one of the most common optimization techniques in forestry, was used for mathematical modeling (Ok, 1999; Bettinger et al., 2009; Baskent, 2010; Çağlayan et al., 2018). Many planning scenarios were developed for different rotation ages, management strategies, and forest structures. Then, a model matrix was built for each scenario.



Initial age classes' distribution and growth pattern of the hypothetical forests (time step is 10 years): *A* – young forest; *B* – mature forest; *C* – yield curves.

The planning horizon was set to 100 years for all the models. Similarly, 70 (short) or 100 years (long) periods were taken as rotation ages. However, the 70-year period was the minimum harvesting age for regeneration and it could be extended to the planning horizon, if necessary. With this approach, we tried to increase the production capacity of the models by making them more flexible. However, the models had the following constraints: (i) 10 % of the total forestland should be under protection (i. e. no harvesting in these areas), (ii) old forests should be under protection, and (iii) even-flow, non-declining and changing flow harvesting rules should be followed. Finally, the maximum amount of timber (m^3) to be harvested over the planning horizon was introduced as the objective function. The mathematical equations for the models developed are:

$$z = \sum_{i=1}^{n} \sum_{j=1}^{m} (a_{ij} + x_{ij}), \tag{1}$$

$$\sum_{j=1}^{m} x_{ij} \le T_i, \tag{2}$$

$$(1 - y)\, H_j + H_{j+1} \ge 0, \tag{3}$$

$$(1 + y)\, H_j + H_{j+1} \le 0, \tag{4}$$

$$x_j \ge 0. \tag{5}$$

Eq. 1 is an objective function ($Z_{\max}$) maximizing allowable cut (AC) over the planning horizon (100 years). Eq. 2, 3, and 4 show area constraint and even-flow harvesting rules, respectively. Eq. 5 indicates the positivity condition in linear programming; *m* is period (from 1 to 10), *n* is age class (from 1 to 10), a_{ij} is timber volume in age class *i* over period *j*, x_{ij} is regeneration area in age class *i* over the period *j*, T_i is total area in age class *i*, and H_j is total AC over period *j*. Each model developed by combining these objectives and constraints is detailed in Table 1.

All models were then solved using LINGO software and the resulting total harvested timber volumes (AC, m^3) were converted into their carbon equivalent values (tons).

Carbon stock. The total timber volume (m^3) produced by each model during the planning horizon was converted into carbon values by a six-step procedure. The ratios and coefficients used in this method were chosen taking into consideration numerous studies (Asan, 1995; Good Practice…, 2003; Tolunay, Çömez, 2008; Global Forest…, 2010; Tolunay, 2011, Serengil, 2018). The steps of the method included calculation of:

i. living above- and below-ground biomass;
ii. living biomass carbon;
iii. deadwood carbon;
iv. litter layer carbon;
v. soil carbon; and
vi. total carbon by summing up the results of the above steps (Rescript N. 299, 2014).

Since there were no degraded stands in the hypothetical forests, all calculations were made using the coefficients for the productive forest. The values for harvested timber (m^3) were converted into car-

Table 1. Planning scenarios

Scenario	Initial age class distribution	Site conditions*	Management strategies		
			Rotation age, years	Protection constraints	Harvesting policy
S1	Mature	HP	70	+	Even-flow
S2	»	HP	70	+	–
S3	»	HP	70	–	Even-flow
S4	»	HP	70	–	–
S5	»	HP	100	+	Even-flow
S6	Young	LP	70	+	»
S7	»	LP	100	+	»
S8	»	HP	70	+	»
S9	»	HP	100	+	»
S10	Mature	HP	100	+	–
S11	»	HP	100	–	–
S12	Young	LP	100	–	–
S13	»	HP	70	–	Even-flow
S14	»	HP	100	+	–
S15	»	HP	100	–	–
S16	»	HP	100	–	Even-flow
S17	Mature	HP	100	–	»
S18	Young	LP	100	–	»
S19	»	LP	100	+	–
S20	»	HP	70	–	–
S21	»	HP	70	+	–
S22	»	LP	70	+	Even-flow
S23	»	LP	70	–	»
S24	Mature	LP	100	+	»
S25	»	LP	100	–	»
S26	»	LP	100	–	–
S27	»	LP	100	+	–
S28	»	LP	70	+	Even-flow
S29	»	LP	70	–	»
S30	»	HP	70	+	Changing at ± 15 %
S31	»	HP	70	+	Non-declining
S32	»	HP	70	–	»
S33	»	HP	70	–	Changing at ± 15 %
S34	Young	HP	70	+	Non-declining
S35	»	HP	70	+	Changing at ± 15 %

Note. * HP – high productivity; LP – low productivity.

bon values (tons). Then, the model with the lowest carbon loss was assumed to be the best in terms of maximum carbon stock. Finally, each model was analyzed and compared with other models for performance.

RESULTS AND DISCUSSION

The models based on the scenarios developed were solved using LINGO software (2007). The results of the modeling that involved different decision variables are given in Table 2.

The table presents the amount of timber for each model provided by harvesting operations in areas to be regenerated, as well as its carbon equivalent (C loss) throughout the entire planning horizon. As is clear from Table 2, scenario S4 yielded the highest timber volume (i. e. total allowable cut, AC) of about 600000 m^3 during all the periods. This scenario was applied to a mature forest located on a high-productivity site with a short rotation age (70 years), and its model had no constraints.

Unlike S4, planning scenario S7 yielded the lowest timber volume. With this scenario, only

Table 2. Model outputs based on different planning scenarios

Planning scenario	Total timber harvested over the planning period, m^3	Carbon equivalent of the timber harvested (C loss), tons
S1	377 647	135 262
S2	547 400	196 062
S3	412 020	147 573
S4	**599 400**	**214 689**
S5	237 671	85 127
S6	161 333	57 784
S7	**18 000**	**6447**
S8	257 333	92 169
S9	30 000	10 745
S10	270 000	96 706
S11	300 000	107 451
S12	180 000	64 471
S13	321 223	115 052
S14	270 000	96 706
S15	300 000	107 451
S16	60 000	21 490
S17	258 497	92 586
S18	36 000	12 984
S19	162 000	58 024
S20	425 200	152 294
S21	373 200	133 669
S22	161 333	57 785
S23	201 237	72 077
S24	127 189	45 555
S25	135 810	48 643
S26	180 000	64 471
S27	162 000	58 024
S28	224 234	80 314
S29	241 610	86 537
S30	420 032	150 443
S31	389 947	139 667
S32	427 251	153 028
S33	459 861	164 708
S34	386 475	138 424
S35	380 822	136 399

18 000 m^3 of timber were harvested over the planning horizon. S7 model was run for a young forest located on a low-productivity site with 100-year rotation age. Moreover, S7 had protection area constraints and even-flow harvesting policy among the periods.

Similarly, the highest and lowest carbon losses were achieved with scenarios S4 and S7. According to these scenarios, 214 689 and 6447 tons of carbon were lost, respectively as a result of forest harvesting over 100 years. S7 thus was found to be the best scenario as for achieving the maximum carbon stock.

The study showed AC, and carbon loss to decrease with long-rotation-age scenarios. Therefore, this type of planning scenarios provided the highest amount of carbon stored in the ecosystem. This may be attributed to Calabrian pine growth dynamics at older ages. Calabrian pine is known to be a fast-growing tree species, with the most intensive growth recorded at young and middle ages. Calabrian pine shows the highest timber volume at the age of 80, according to the yield curve (Yeşil, 1992) (see Figure). At any rotation age over 80 years tree increment slows down. The results of many similar studies agree with those of this study. Moreno-Fernandez et al. (2015), for example, conducted a study on Scots pine *Pinus sylvestris* L. in the Mediterranean region. They showed that the strategies with 120-year rotation age were the best for carbon sequestration. Malmsheimer et al. (2008) also reported that on-site carbon storage increases with increasing rotation age and sizes of trees for managing both even- and uneven-aged forest ecosystems.

Another common feature of planning scenarios aimed at maximum carbon stock is the implementation of the even-flow harvesting policy. In all the scenarios, e. g. S6, S7, S9, S16, S18, S22, S24, and S25 with the least carbon loss observed, the models were restricted by an even timber flow constraint for all the periods. This constraint requires that a forest AC be almost the same in any period within the planning horizon. It equates the periods of higher AC potential to those of the lowest AC, reducing thereby the total production. Therefore, forest biomass carbon losses also decrease and more carbon is stored.

When examining the low-carbon-stock planning scenarios, we found that short rotation ages and mature-forest initial statement dominated. Where these mature forests were managed using scenarios without harvesting policy constraints (e. g. S2, S4, and S20), they produced high quantities of raw wood. As a result, carbon losses have increased and carbon sequestration decreased. This might be due to that mature forests with large sites of older age classes offered many options to the model solver. For this reason, the model achieved the objective function more easily. On the other hand, for high-productivity sites wood yield was higher, as well as the amount of products to be harvested per unit area. Our results agree with those of some studies but sometimes differ. Kucuker, Baskent (2015), in their study conducted in a Scots pine forest, found that carbon storage increased with reducing rotation age. This may be due to afforestation of treeless areas in their model. In fact, live forest biomass gradually increased after the first period when these open areas covering more than 9000 ha of the total planning unit were afforested. On the contrary, we deliberately took a hypothetical forest that had no open areas in the present study to see the effect of actual forest sites. Another reason for that difference may be in growth characteristics of Scots pine and Calabrian pine. Calabrian pine is known to be a fast-growing species, while Scots pine grows at a normal growth rate. Moreover, period intervals of these species are absolutely different from one another (10 years vs 20 years).

One more point in common with the low-carbon-stock planning forestry is that they have no protected area constraints. In this study, we used a protected area constraint in some planning scenarios. The constraint was that at least 10 % of the entire planning area was designated to no-harvesting old forests. With these scenarios (e. g., S6, S7, S9, S22, and S24), the amount of carbon stored in forest biomass was high, while it was low with other scenarios (e. g. S3, S4, S20, S32, S33), which had no constraints. The reason for this was a decrease in the carbon sequestration, because wood production was higher with the management strategies having no production constraints.

CONCLUSION

In this study, we used a linear programming technique to model the total biomass carbon losses for different forest structures subject to different forest management strategies over 100 years. This technique allowed us to determine the management strategy best in terms of maximizing carbon storage. Based on the results of the study, we would make the following suggestions.

1. Management of forests designated for maximum carbon stock should involve long rotation ages. However, one should keep in mind that this may not necessarily guarantee maximum carbon sequestration concurrently, as they have considerably different dynamics.
2. Even-flow harvesting policy should be applied over periods.
3. Protected areas, such as old forests and national parks, should be increased in the planning unit.

In conclusion, all types of forests, managed and unmanaged, store carbon. However, in the forests under long-rotation management, not only are carbon stocks maximized, but also biodiversity and timber quality increase. Today, forest managers should, therefore, consider a multiple-use management concept and try to incorporate many non-timber ecosystem services (e. g. climate regulation) into their management plans. It should be noted, however, that with too long rotation ages, fast-growing tree species risk to become prone to biotic and abiotic disturbances.

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УДК 630.6/613

АНАЛИЗ ВОЗДЕЙСТВИЯ РАЗЛИЧНЫХ СТРАТЕГИЙ УПРАВЛЕНИЯ НА ПОТЕРИ УГЛЕРОДА БИОМАССЫ ЛЕСОВ С ИСПОЛЬЗОВАНИЕМ ЛИНЕЙНОГО ПРОГРАММИРОВАНИЯ

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Поступила в редакцию 27.02.2018 г.

Поскольку влияние парниковых газов на изменение климата имеет большое значение, лесные экосистемы считаются критическим механизмом сокращения выбросов углерода путем консервации большого его количества в растительности и почве. Целью данного исследования явились сопоставление и анализ механизмов поглощения углерода биомассой лесных насаждений различной структуры при различных сценариях лесоустройства и лесопользования. Многие сценарии лесопользования были апробированы с горизонтом планирования в 100 лет для гипотетических насаждений на площади в 1000 га. Рассмотрены два вида насаждений (высоко- и низкопродуктивные) и два возрастных интервала оборота рубки (70 и 100 лет) с целью анализа влияния состояния лесного участка и длительности оборота рубки на запас углерода. Были также включены некоторые ограничения, такие как выделение примыкающих лесных участков и контроль запасов древесины. В последующем были рассчитаны 35 математических моделей с использованием метода линейного программирования и программного обеспечения LINGO. Модель S7 оказалась лучшей среди разработанных с точки зрения минимизирующего содержания углерода в лесной биомассе. При таком сценарии потери углерода составили 6447 т в течение 100 лет при равномерных сплошных рубках спелых насаждений с оборотом рубки 100 лет (u = 100). Худшей по результатам оказалась модель S4, где не вводилось никаких ограничений, а оборот рубки устанавливался для средневозрастных насаждений (u = 70). Почти 215 тыс. т составили потери углерода при использовании модели S4 на 100-летнем горизонте планирования основного пользования лесом. Исследование показало, что динамика углерода в лесных экосистемах в значительной степени зависит от стратегии ведения лесного хозяйства. В связи с этим применение стратегий управления лесами с использованием современных методов планирования очень важно для смягчения последствий глобального изменения климата.

Ключевые слова: *концепция управления углеродом, лесоустройство, математическое моделирование, операционные методы исследований, сосна калабрийская Pinus brutia Ten., Турция.*