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Exploring the effects of various rotation lengths on the ecosystem services within a multiple-use management framework

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ABSTRACT

Addressing the spatio-temporal dynamics of forest development under different management scenarios with varying rotation lengths is a challenge in forest management planning. This research aims to forecast forest development and assess the relative consequences of varying rotation lengths on several ecosystem services such as wood production, habitat for biodiversity, carbon sequestration, water provision, soil protection and cultural values. Forest development is simulated with the ETCAP model to examine the long-term effects of various rotation lengths with silvicultural prescriptions on the ecosystem services. Bürücek forest planning unit is used as a case study area with 10,711 ha forests in upper Mediterranean region of Turkey. Shorter rotation lengths are considered one of the main mitigation measures to climate changes in forestry; however, lead to the increased harvest level, net present value, ground water and soil loss, and reductions in the largest stand volume, understory, basal area, carbon storage and the cultural values with less regulated forest structure. The management scenarios with longer rotation lengths, however, have highlighted improvements in the carbon storage, larger standing volume, mean stand age, basal area and cultural values, and reductions in the mean harvest volume, net present value, ground water and soil loss due to larger-even distribution of tree sizes and stand development stages. An aspiration for a higher level of provisioning services for economic motivations may need to be discarded for the sake of enhancing the capacity of forest ecosystems to sequester more carbon and provide better habitat condition for biodiversity conservation with a careful design and selection of rotation lengths. Overall, the choice of optimal rotation length is highly dependent on a desired set of management objectives and target forest structure driven mostly by management interventions with the appropriate type and level of ecosystem services, provided that a thorough understanding of forest dynamics is achieved by considering both risks and uncertainties associated with natural disturbances and socio-economic conditions.

1. Introduction

Holistic planning of forest ecosystems focusing on the smart integration of multiple ecosystem services (ES) has proliferated around the world (Nordström et al., 2016; Felton et al., 2016; Löf et al., 2016; Bettinger et al., 2017; Borges et al., 2017; Lindbladh et al., 2017; Lundholm et al., 2020; Mozgeris et al., 2021; Roces-Díaz et al., 2021) and triggered the revision of the national management policies and regulations as in Turkey (Baskent et al., 2008). The key components in a planning process are establishing the management goals and conservation targets based on the status of ecosystem services, exploring management alternatives and finding out the optimal set of actions to achieve the objectives. In the planning process the ecosystem services are crucial, representing the series of benefits from the forest ecosystems through the transformation of natural resources into the goods and services that have social, ecological and economical values for the people and contribute to their well-being (Aznar-Sánchez et al., 2018; Costanza et al., 2017; MEA, 2005; Forest Europe, 2020). However, characterizing and integrating them into the management planning process with a smart design of forest management interventions are essential for the smart conservation and sustainable management of forest resources (Schwaiger et al., 2019; Baskent, 2020; Morán-Ordóñez et al., 2020). Different methods, information technologies and decision making techniques have been widely used to help both the

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characterization of ES and assessment of the dynamic interactions (i.e., trade-offs) between ecosystem services under various forest management settings (Nordström et al., 2016; Baskent et al., 2020; Lundholm et al., 2020; Martes and Köhl, 2022; Mozgeris et al., 2021; Baskent and Kašpar, 2022). In this respect, rotation period, being the number of years between the establishment of an even-aged stand and the final harvest, is one of the crucial parameters of management strategies in optimizing the appropriate set of management goals (Bettinger et al., 2017). The length of rotation is very sensitive and directly affects the performances or achievement of ecosystem services for a given initial forest structure and other planning parameters. While, its dynamics (lengthening or shortening) or the effects on timber production has been widely studied, yet the long-term dynamics with the other ecosystem services are poorly studied. Therefore, developing sound management strategies with various rotation lengths based on through analysis of forest dynamics focusing on particularly the tradeoffs among the prevailing ESs is of a great challenge in sustainable management and conservation of forest ecosystems.

Several works have focused on the identification and quantification of the ecosystem services and their integration into the multi-objective forest management planning to address the impact of different management interventions on the sustainability of the ESs. The prevailing ecosystem services in forestry such as carbon sequestration (Backeus et al., 2006; Yousefpour and Hanewinkel, 2009; Dong et al., 2015; Yoshimoto et al., 2018), erosion prevention and maintenance of soil fertility (Baskent, 2019; Rodrigues et al., 2020), water provision (Feller, 2005; Baskent and Kucuker, 2010; Keles and Baskent, 2011; Cademus et al., 2014), habitat for biodiversity (Eriksson and Hammer, 2006; Ezquerro et al., 2016; Felton et al., 2016; Löf et al., 2016; Lindbladh et al., 2017) and cultural values (Lundholm et al., 2020) have been integrated into the forest management planning. Habitat for biodiversity conservation has commonly been considered as one of the primary ecosystem services due to several international conventions conducted on the crucial role of it and its direct influence on the delivery of other ecosystem services and ecosystem functions (Mace et al., 2012; Felton et al., 2016; Löf et al., 2016; Lovejoy, 2020, URL1, 2020). Some researchers have indicated that longer rotation lengths favor indicators for biodiversity conservation such as increase in species diversity and gain of habitat for target species (Verkerk et al., 2011; Duncker et al., 2012; Biber et al., 2015; Felton et al., 2016; Roberge et al., 2016; Lindbladh et al., 2017). On the other hand, Biber et al., (2015) has shown that biodiversity can also react positively to the increased management intensity, driven mostly by the short rotation lengths. Nevertheless, some proxy indicators are necessary to characterize habitat for biodiversity for better assessment of its trend or dynamics over time although there is not any unique or universal one to use in forest management planning (Felton et al., 2016; Baskent 2020).

Forest ecosystems have a critical role in mitigating climate changes and carbon cycling that has been increasingly realized in recent year (Yousefpour and Hanewinkel, 2009; Dong et al., 2015; Thom et al., 2017; Yoshimoto et al., 2018). Management strategies favoring afforestation, rehabilitation and protection activities with older forests driven mainly by the longer rotations have been recommended in offsetting and mitigating climate change effects and soil erosion, besides contributing to the cultural values (Lundholm et al., 2020; Baskent, 2019; Martes and Köhl, 2022; Baskent and Kašpar, 2022). Therefore, some jurisdictions around the world have developed new forest management policies and regulations for sound forest conservation and restoration of degraded forests with a set of management strategies with afforestation and forest renewal around the ecosystem management framework (Baskent et al. 2008; OGM, 2015; Creutzburg et al., 2017).

Other ecosystem services such as soil protection, water production and aesthetic-recreation are also of high relevance both locally and globally (Forestry Commission, 2011), specifically in Turkey. Some indicators have been developed and used to characterize the status of ground-water over time (Bent, 2001; Bettinger et al., 2007; Hubbart et al., 2007; Maes et al., 2013; Baskent, 2019). For example, a relatively good relationship between the amount of ground water and forest composition (e.g., basal area) has been found to estimate the level of ground water (OGM, 2014; Baskent et al., 2020; Bentley and Coomes, 2020). The similar relationship has also been found to exist between the amount of soil loss to erosion and the forest composition such as basal area, depending highly on the rate of forest cover change, renewal rate and afforestation activities given a specific eco-geo-climatic condition (Baskent, 2019; Rodrigues et al., 2020). Cultural values, however, have been characterized with a set of joint index that represents different characteristics of a landscape such as scenic quality and recreational capacities (Tveit et al., 2006; Edwards et al., 2012), influenced largely by the degree of harvesting area Lundholm et al., (2020). In essence, the management interventions with various rotation lengths have the ability to alter forest compositions affecting the sustainable provision of many ecosystem services over time.

Understanding the long-term forest dynamics focusing on the effects of different rotation lengths on the levels of ecosystem services with quantitative indicators and decision support systems (DSS) are indispensable to design and implement forest ecosystem management scenarios (von Gadow, 2004; Eriksson et al., 2014; Baskent 2020; Mozgeris et al., 2021; Roces-Díaz et al., 2021). In these regard, various types of DSS have been developed and used to explore the trade-offs between ecosystems services based on a number of management strategies (Reynolds et al., 2008; Nordström. et al., 2011; Pukkala. 2014; Vacik et al., 2015; Borges et al., 2017; Cristal et al., 2019; Nordström. et al., 2019). Nowadays, however, more versatile DSSs have been developed to conduct spatio-temporal analysis of forest dynamics and explore the trade-off analysis between various ES such as carbon sequestration, biodiversity conservation, soil protection and cultural values under management interventions (Bettinger et al., 2017, Borges et al., 2017: Nordström, et al., 2019; Sacchelli, and Bernetti, 2019; Knoke et al., 2020; Kolo et al., 2020).

Some studies have highlighted the effects of different rotation lengths on the performances of forest management planning targeting few ecosystem services. For example, Nghiem (2014) has indicated that considering biodiversity conservation in a simple planted tropical forest encourages a longer optimal rotation length compared to a shorter length that maximizes economic gain from the forests with wood production and carbon sequestration. A more recent work by Roberge et al. (2016) has evaluated the socio-ecological implications of modifying rotation lengths on a range of ecosystem services, yet without a real case study, and indicated that shortening rotations may have positive effects on the provisioning services, yet negative effects on the supporting (water, soil nutrients) and cultural (aesthetics, cultural heritage) ecosystem services. Similarly, Eggers et al., (2019) have indicated that a combination of management scenarios including longer rotation periods, a larger share of set-asides and a higher share of continuous cover forestry would be more appropriate to achieve the forest policy objective of a balance of production and environmental considerations. Longer rotation periods in forestry resulted in gradual changes in indicators without drastic short-term differences in indicator outcome. Sacchelli and Bernetti (2019) has highlighted a divergence between timber production/carbon storage, which is favored by shorter rotation age, and the touristic/recreational function that is favored by the longer rotation ages, with few differences resulted from commercial thinning. The study was conducted in a Natura 2000 site with a silver fir stand of 1 ha stand in Tuscany, Italy. While they have proposed optimal rotations in a spectrum of 50 to 72 years in a relatively uniform plantation forest with a single tree species, they have not incorporated various aspects of carbon pools (e.g., emissions, harvested wood products), biodiversity and cultural values as well as the other ecosystem services such as soil protection, water production to cover the comprehensive range of ecosystem services in a larger and real ecosystem with an ecosystem management perspective. On the other hand, however, the implementation of shorter rotation based management strategies has been suggested for reducing the future risk of storm damage (Olofsson, 2006). For example, Jönsson et al. (2015) have presented that successively shortened rotation periods generally result in a lower predisposition to damage compared to contemporary management practices, and this disparity tends to increase as the climate changes progress. Furthermore, Zimova et al. (2020) have indicated that the vulnerability to disturbances such as wind-throws and bark beetle infestations suggests that a reduced rotation length can be a powerful means for mitigating the impacts of such natural disturbances, yet severely affecting forest carbon and biodiversity.

One of the challenging issues in forest ecosystem management is the decision on the appropriate rotation lengths and determination of the appropriate level of the prevailing ecosystem services such as carbon storage, biodiversity conservation and wood production. Thus, it is essential to investigate the effects of varying rotation lengths on the output of prevailing ecosystem services to understand the causative basis of forest development over time in achieving the target levels of various ecosystem services within the framework of forest ecosystem management. While sustainable forest management has to simultaneously consider all ecosystem services, it may require trade-offs among conflicting objectives composed of various sets of ecosystem services with a better design of management strategies. For example, a desire for a higher level of wood production for economic motivations may need to be overlooked or relinquished for the sake of enhancing the capacity of forest ecosystems to sequester more carbon and provide better habitat condition for biodiversity conservation with a careful design and selection of rotation lengths, in addition to other forest interventions. Therefore, it is crucial to investigate the effects of various rotation lengths on the level of achievement of ecosystem services to better formulate the management strategies in a sustainable forest ecosystem management context.

This study aims to provide a comprehensive analysis of the effects of varying rotation lengths on a set of ecosystem services - timber production, water provision, carbon flow, biodiversity, soil loss and cultural values. Forest management strategies are developed by considering ecosystem based multiple use planning framework with different rotation lengths. The long-term forest dynamics is explored using the ETÇAP DSS (Ecosystem Based Multiuse Forest Planning Model - Keleş and Baskent, 2007) with various rotation lengths based on management scenarios implemented on a range of conservation versus utilization allocations of lands to management units in the Bürücek forest planning unit in Turkey. We hypothesize that the long-term impacts of longer rotation lengths compared to shorter ones on the provisioning of the ecosystem services, particularly carbon stock and habitat for biodiversity, are significant.

2. Material and methods

2.1. *Decision support system (DSS) for management planning*

The ETÇAP program was developed as a DSS for a long-term management planning to project the spatio-temporal development of forest resources and evaluate the impacts of various management strategies on the level and mix of ecosystem services (Keleş and Baskent, 2007; Keles 2008). While the concept and framework of the ETÇAP DSS are universal, it has been developed specifically in compliance with the state forest management regulations including the policies and the guidelines (OGM, 2008). The DSS accommodates various ES such as wood and non-wood forest production, carbon sequestration, soil erosion, water production and habitat for biodiversity. With the exception of The Recreation Aesthetics Forest Landscape (RAFL) index (Lundholm et al., 2020) and some measurements for the habitat for biodiversity conservation, all other ES indicators demonstrated in this study were generated as default outputs produced by the ETÇAP DSS. Some of the forest performance indicators were compiled from the DSS outputs to create the RAFL index post-simulation. Appropriate spatial analysis functions were then employed to estimate the geographic indicators such as patch size, largest patch size and patch density.

The ETÇAP model is a deterministic simulation based decision support tool with both the inherent empirical growth and yield tables developed to project various stand parameters on ideal stands after silvicultural treatments and an internal growth simulator developed to project the current stand development based on the relationship between the inventory data and the empirical yield tables. The DSS is based on an ecosystem management or multiple-use forest management forest planning approach with different management objectives and forest regulation or harvest policy strategies such as an area control, volume control and area-volume check. The model utilizes various management policies such as non-declining yield, increasing and even flow regulations with certain variation between periods, and cutting and thinning rules such as oldest first and volume lost first with user defined levels at specific time in the future. Notably, all stands are *a priory* stratified with the help of forest planning experts into the suitable management and analysis areas to design and implement a combined silvicultural regime with a user-defined level of silvicultural interventions. Stands which have similar species compositions and serve potential ecosystem services are allocated to the same management unit with the similar management objective. The planning prescriptions are designed and implemented on the same analysis areas, consisting of either a single stand or a group of homogeneous stands in each management unit. The forest management model then allocates the prescribed management interventions with the defined rules, levels and limits to the suitable stands and creates outcomes based on various management objectives. While pure or combinatorial optimization techniques may well be used to optimize multiple objectives simultaneously or minimize the trade-offs between the multiple objectives (Seppelth et al., 2013; Borges et al., 2014; Daniel et al., 2017; Gregor et al., 2022), we used a simulation technique (Yousefpour and Hanewinkel 2009; Baskent 2019; Friedrich et al., 2021; Baskent and Kašpar, 2022) to better understand forest dynamics with establishing the causative basis between various rotation lengths and the performances of various ecosystem services.

2.2. *The case study area*

The forestland of Turkey is geographically divided into forest administration areas with an independent forest management plan –called a forest planning unit (FPU). The Bürücek FPU, located in the Southeastern highland of Turkey (between 37°18′35″-37°26′01″ north latitudes and 34°43′30″-34°56′37″ east longitudes), is selected as a case study area which is a typical representative of 1,419 forest planning units. The case study area covers 10,711 ha, of which 9,830 ha are forested (6,040 ha productive, 1,791 ha degraded) (Table 1). There are 3,789 ha of treeless forest areas suitable for plantation (i.e., afforestation or reforestation) in addition to the degraded areas (e.g., crown closure less than 10%). The planning unit has eight primary tree species with three hardwood species (<1%) such as oak *(Quercus spp.),* walnut *(Juglans regia)* and plane (P*latanus orientalis)* and five softwood species such as Anatolian pine *(Pinus nigra)* (46.6%), Red pine *(Pinus brutia)* (40.5%), Fir *(Abies cilicica) (*0.5%), Cedar *(Cedrus libani)* (11.8%), and Junipers *(Junipers spp.)* (0.4%) (OGM, 2004). The elevation ranges from 812 m to 3,139 (Kızılgöltopu hill) m. and the mean slope is about 48%. The case study area has the typical Mediterranean drought climate conditions. Average annual temperature and total precipitation are nearly 13.5 °C and 450 mm, respectively (OGM, 2014). Majority of the forests in the case study area has been managed for dominatly wood production purpose with unregulated forest structure (i.e., age-class structure dominated by young and mature development stages of forest development, except Red pine mixed forest with almost regular age classes) (Başkent et al., 2005). However, the forest was established through natural development and natural regeneration after harvesting since 1960s with little changes by plantation. In general, the area is

Table 1
Characterization of the case study area based on the management units (OGM, 2014).

Management units* (working circles)	Productive forests (ha)**	Degraded areas*** (ha)	Bare forest lands*** (ha)	Total forest area (ha)	Other areas (ha)	Total area (ha)
A:Timber production (Turkish/Red Pine)	1,409	60	29	1,499	32	1,531
B:Round wood production (Anatolian Pine)	584	50	11	644	7	651
C:Afforestation (Walnut)	1	0	0	1	0	1
D:NWFP Production (Walnut)	73	0	14	87	4	91
E:Nature Conservation (Red pine, Anatolian pine, Cedar)	1,801	1,050	612	3,464	61	3,525
F:Nature protection (Anatolian Pine, Cedar)	784	230	1,227	2,241	0	2,241
G:Soil protection (Red Pine, Anatolian Pine)	277	30	6	313	0	313
H:Aesthetic (Anatolian Pine, Cedar)	617	211	98	927	17	944
I:Recreation (Red Pine, Anatolian Pine, Junipers)	495	159	0	654	757	1,411
Total	**6,041**	**1,792**	**1,998**	**9,831**	**880**	**10,711**

* Management units are formed by the spatially independent group of similar stands where the same ecosystem service (i.e., management objective) is provided by the dominant tree species.
** The stands over %10 of crown closure is classified as productive in terms of timber production.
*** The areas are appropriate for afforestation (crown closure less than 10% and bare forest areas).

similar to temperate forests which are simpler in structure than tropical forests and support a smaller number of tree species, whereas the forests in the area are more complex in structure than boreal forests and support large number of tree species with actively building carbon stores. The case study area is completely of a public forest owned and managed by the general directorate of forests in Turkey. Therefore, the General Directorate of Forestry on behalf of the state is the solo decision maker. The area is selected as it is a characteristic forest management planning unit in the upper Mediterranean region and sensitive to climate changes (FAO and Plan Bleu, 2018). Additionally, the area provides several ecosystem services and has the new spatial forest database covering the current forest inventory data and the coverages or maps (OGM, 2014).

Bürücek forest planning unit was stratified into nine management units (aka working circles), each representing the same management objectives, planning approach, set of ecosystem services and silvicultural regimes (Table 1). In addition to wood and non-wood forest products (NWFP) production, biodiversity conservation, nature protection, soil conservation and the provision of aesthetic and recreation are the primary forest ecosystem services, bundled in the form of management objectives and conservation targets. Management actions are cautiously designed and implemented on the special areas such as erosion sensitive forest lands, riparian buffer areas, recreational use areas and other stands that are subject to various conservation targets (OGM, 2014). The management units are determined with spatially independent forest stands with the similar appropriate silvicultural interventions, allowing to achieve the desired target of management planning. The forest in the case study area has multiple forest uses with complex ES interactions, making it an interesting research object for the analysis of the long-term sustainability impacts of rotation lengths on the changes in forest development and the anticipated performances of the key ecosystem services. Thus, the case study area was selected and designed to contribute to the appropriate provision of multiple ecosystem services, better understanding of forest dynamics and wide-ranging design of management strategies based on varying rotation lengths, thus making the results relevant for forest managers and policy makers in a wider area.

2.3. Management strategies

A total of six different management scenarios have been developed to analyze the long-term forest dynamics with six ESs including wood production, water provision, soil conservation, habitat for biodiversity, carbon sequestration and cultural values. The planning conditions indicated in the current forest management planning guidelines are observed with some modifications indicated as followings. The rotation periods in all management units are determined differently for all scenarios (Table 2). The forests of the Bürücek case study area under six management scenarios were forecasted over 100 years into the future with ten 10-year periods using the ETÇAP forest management model (Keleş and Baskent, 2007; Keles, 2008). The management planning approach used even-flow policy constraint referring basically to the volume control method to create even-flow wood production in each management unit with a 10% fluctuation between consecutive periods. The current forest management guidelines, however, satisfy with the single period-oriented management interventions with user defined allocation of stands to management actions such as harvesting, afforestation, tending and conservation. Such approach in determining management actions limits the users or managers to examine the consequences of different types, rules, levels and intensities of management actions in generating multiple ecosystem services in the forms of management objectives including various rotation lengths. Based on the multiple use-forest management planning concept, however, this study focuses primarily on developing management strategies to test and address the effects of various rotations lengths on planning output or the level of selected ecosystem services under the similar characteristics of management specifications (Table 2). The rotation lengths basically refer to the minimum harvest timing (i.e., minimum harvesting age) where the final felling will start and continue onwards until a maximum age (usually determined by a rate of natural mortality) is reached. Therefore, the rotation lengths are used to determine the width of operability window for final harvesting, not a specific harvest age at which the harvesting must occur.

The management scenario S1, indicating the lowest age as an initial

Table 2
Various rotation lengths (years) used in six management strategies across nine management units.

	Management Strategies					
Management Units	**S1**	**S2**	**S3**	**S4**	**S5**	**S6**
A:Round wood production (Red Pine)	30	35	45	55	60	65
B:Round wood production (Anatolian Pine)	55	70	90	110	120	130
C:Afforestation (Walnut)	55	70	90	110	120	130
D:NWFP Production (Walnut)	55	70	90	110	120	130
E:Nature Conservation (Red Pine, Anatolian Pine, Cedar)	35	45	55	65	70	75
F:Nature protection (Anatolian Pine, Cedar)	70	90	110	130	140	150
G:Soil protection (Red Pine, Anatolian Pine)	35	45	55	65	70	75
H:Aesthetic (Anatolian Pine, Cedar)	70	90	110	130	140	150
I:Recreation (Red Pine, Anatolian Pine, Junipers)	35	45	55	65	70	75

rotation period, targeted to use the ages as rotation lengths where the mean volume increment per ha per year at a stand level is nearly the maximum for the primary species in each management unit. The minimum starting rotation ages in the scenario S1 were determined based on the empirical yield curve of the dominant tree species and site factor in each management unit. All other strategies, however, used nearly a 5–20-year rate of increase in rotation lengths between successive strategies, depending on the growth rate of each tree species. For example, 5–10 years of incremental increase in rotation lengths are used in the management units where Red pine (*Pinus brutia*) is the dominant tree species (Management units A, E, G, I). However, 10–20 years of incremental increase in rotation lengths are used in all other management units. The management units aiming at other than wood production (C through I), however, started with a bit longer rotation lengths to allow conservation oriented management strategies to prevail and represent ecosystem based planning or closer-to-nature forest management to a certain extent. Thus, various potential lengths of rotation periods have been considered in the study to highlight any incremental effects on the sustainability of key ecosystem services.

Aside from varying rotation lengths, the management strategies have the similar management characteristics to focus on and isolate the solo effects of rotation lengths. First of all, all of the six management scenarios used the same overall objective function of capitalizing on wood production over 100 years of simulation. The strategies targeted to afforest over 90% of all bare forest lands and degraded forests (3,410 ha with 300 ha per period) over time to experiment the full potential of the forest area in providing a variety of ecosystem services. Almost 40% of the bare forest lands is afforested with Red pine, 40% with Anatolian pine, 10% with Cedar, 4% with Junipers and 6% with Walnut. Such rates are used as they are quite consistent with the natural rate of these species dominant in the area. Furthermore, the case study area is *apriory* stratified into different management units with various rotation lengths to account for different management objectives determined based on the main ecosystem services rather than just focusing on wood production. Specifically, an ecosystem management or multi-objective planning concept is used as a basis for planning the area, referring to the sustainable management of forest ecosystems with multiple objectives and constraints (Baskent et al., 2008; Eriksson et al., 2014; Bettinger et al., 2017; Nordström et al., 2019). Similar other approaches such as Closer-to-nature forestry in Europe have emerged to primarily focus on the enhancement of the resistance, resilience and adaptive capacity of forest ecosystems (Larsen et al., 2022). The idea of identifying six management strategies based on nine management units with various objectives, rotation lengths and the associated interventions principally reflects the closer-to-nature forest management concept too.

As for the treatment intensities, on an average, nearly 6% of the standing volumes is subject to thinning at the suitable ages in all management units. The management interventions as well as the natural disturbances such as insects and forest fires are presumed to be under control. The stands are assumed to regenerate naturally right after final felling without any time lags. The silvicultural prescriptions, indicated in the current planning guidelines, are applied to the stands determined for the related treatments across all scenarios. All of the management scenarios used the "*oldest first*" intervention rule in implementing the final cutting and intermediate thinning over time. Finally, final felling is assumed to be carried out in a period length, regardless of what regeneration method such as clear felling or shelter wood harvesting used. However, since almost 98% of the area is covered with light-demanding tree species, clear felling can well be used as an appropriate regeneration method. Stands are identified to be appropriate for commercial thinning based on species mix, crown closure, forest site condition and stand development stages (i.e., age classes). Explicitly, the stands that are not scheduled for final harvesting and strict conservation and over 40% crown closure are potentially suitable for commercial thinning for all management units. Furthermore, all of the management strategies have not taken both the economic and biological risks as well as uncertainties into consideration during the simulation process, ending with some other assumptions that the model structure is deterministic and the natural disturbances such as wildfires and storms would not create any unexpected changes in future forest developments.

3. Forest ecosystem services

3.1. Timber production

The ETÇAP DSS has an internal stand simulation model which forecasts the development of current stands over time based on management prescriptions. The empirical yield tables, however, are incorporated into the DSS to project the growth and yield of future stands following the final harvesting and afforestation activities. The DSS assumes that no sooner is a particular stand regenerated or planted, then it will develop according to the empirical yield curve over time. The current stands will develop in relation to the internal growth and yield projection model, developed based on the relative growth adjustment between the current inventory data and empirical yield curve data (Keles and Baskent 2011). Therefore, the DSS estimates the necessary stand attributes for all stands including the standing volume, basal area, increment and number of stems over time. Furthermore, three percent discount rate, commonly used in Turkish Forestry, was used to calculate the Net Present Value (NPV) of wood production and the market value of a cubic meter wood assortment is taken from the state market sale prices in early 2022. The market sale prices include both the stumpage prices and the costs such as harvesting, hauling, transporting and rampage prices. The NPV in each period is then divided by the total harvest level in that period to arrive at a unit value for practical purposes to understand better and have opportunity for any comparisons with the other performance indicators.

3.2. Carbon sequestration

The DSS accommodates four categories of carbon pools: i) living carbon in above ground and below ground biomass, ii) deadwood carbon from harvesting and natural mortality including litterfall, iii) carbon stored in harvested wood products (HWP) and (iv) substitution of fossil fuels from using wood products. The soil carbon was not considered because of insufficient long term forest inventory in terms of stock changes resulting from the silvicultural interventions (IPCC, 2006). Living carbon was projected based on both above ground and below ground biomass growth using the IPCC guidelines and the specific parameters such as Biomass Expansion Factor (BEF), volume increment and C factor related to the major forest types in the country (IPCC, 2006; Baskent and Keles, 2009; Tolunay, 2011). Both harvested volume and the mortality losses were used in calculating the biomass losses. The deadwood carbon and HWP were subjected to a decay function to characterize decomposition of deadwood and decay of HWP (Baskent, 2019; Lundholm et al., 2020). The amount of deadwood was projected with the carbon flow model (Bond-Lamberty and Gower, 2008) using the forest inventory data projected by ETCAP model. The carbon stocks in deadwood include dead logs, stumps and roots that decompose over time with different rates. The carbon emissions from various forest timber assortments such as sawlog and pulpwood were estimated based on the half live of wood assortment in each stand (50 years for saw logs, 40 years for mining pole, 15 years for boards, and 10 years (i.e. a period) for firewood, bark and harvest residues) (Baskent and Keles, 2009; Black and Gallagher, 2010; Lippke et al., 2011; Baskent, 2019).

As known, carbon flow in HWP originates from both harvesting and the added potential of energy substitution of energy demanding products (e.g., steel, cement, fossil fuel energy production) (Sathre and O'Connor, 2010; Oliver et al., 2014). The management scenarios accepted the inflows of HWP and allocation between HWP storage, energy or product substitution common throughout all management scenarios (Skog, 2008; Smyth et al., 2016). For example, it is assumed that there is a similar allocation of saw logs and pulp to energy substitution (15%) and similar higher allocation of saw logs to wood based panels (WBP) in all management scenarios. It is also assumed that 20% of harvest residues are used for energy under all scenarios.

3.3. Water production

Amount of water resources is characterized with few indicators. They are described as the amount of rainfall, annual ground water, annual quick and base flow, annual sediment loss and total nutrient export, quantified by a number of practical parameters such as shrubs and litter percentage, species composition and vegetation removal (Maes et al., 2013). Here in this study ground water run-off is targeted. The ground water yield is commonly projected based on the relationship with stand parameters such as crown closure, tree species mix, mean stand diameter, basal area, number of stems, standing timber volume and leaf area index of trees. Among those stand parameters, however, ground water runoff is determined as a function of some stand characteristics particularly basal area, used as a legitimately good and practical indicator in estimating the amount of ground water runoff in forest areas (Tecle et al., 1998; Kucuker and Baskent, 2010; Keles and Baskent, 2011). The relationship between the ground water runoff and basal area is proportional to each other; high values of the indicator relate to the low values of the ground water runoff.

In this study, the statistical model developed by Mumcu (2007) and implemented by Kücüker and Baskent (2010) for similar other forest landscape with the similar climatic conditions such as temperature and precipitation and topographic features, was used as fairly good representation the relationship [1].

$$WP = 1797.97 * e^{-0.0196 * BA} \quad (R^2: 0.50. \mathrm{SE}: 0.19) \tag{1}$$

Where, BA is the residual stand basal area (m^2 ha^{-1}), WP is the annual water production (Mg ha^{-1} $year^{-1}$) and e is 2.71828.

3.4. Soil loss

Different methods such as Revised Universal Soil Loss Equation (RUSLE) with different parameters such as rainfall erosivity factor, soil erodibility factor, slope length factor, slope factor and cover management factor have been used to estimate the amount of soil loss to erosion (Wischmeier and Smith 1978; Renard et al., 1997). In general, stand characteristics such as species composition, basal area, mean diameter of stand, standing timber volume, and the number of stems are the most significant factors of soil erosion. Basal area, however, has been identified as a significant and practical parameter in estimating the amount of soil loss to soil erosion based on a given landscape with certain topography and climate conditions. The amount of soil loss to erosion was then estimated proportional to the stand basal area. The relationship between the soil loss and the basal area is typically negative; low values of the indicator mean high values of the ES. The model developed by Yolasığmaz (2004) for similar other planning units with the similar climatic and topographic conditions was used in this study as model indicated a fairly good relationship [2].

$$SL = 30.437 * e^{-0.0488 * BA} \quad (R^2: 0.55. \mathrm{SE}: 0.696) \tag{2}$$

Where, BA is the residual stand basal area (m^2 ha^{-1}), SL is the annual soil loss (Mg ha^{-1} $year^{-1}$) and e is 2.71828.

3.5. Habitat for biodiversity conservation

Representation of habitat for biodiversity is quite dispersed without any unique (recognized) set of direct indicators. In fact, there are a variety of quantification methods to represent the composition and configuration of habitats, such as richness, abundance, evenness, and distribution of habitats (Baskent 2020). Therefore, a combination of some proxy measures in the form of indexes relating to the structural and qualitative changes in habitats have been used. In this study, the habitat for biodiversity conservation was determined based on a number of forest attributes such as volume of larger and native tree species, coarse woody debris, average stand age, regeneration rate, species composition, plant diversity, and the rate of old forest (Felton et al., 2016; Baskent, 2019; Lundholm et al., 2020). Additionally, some forest fragmentation measures including patch density, mean patch size and largest patch index were also used to determine the spatial representation of biodiversity ES (Başkent and Jordan, 1995; McGarigal and Marks, 1995). To interpret the meaning of such indicators, lower values of patch density and higher values of both mean patch size and largest patch index indicate un-fragmented forest landscape in terms of forest connectivity and habitat integrity, representing the forest habitat condition for biodiversity conservation. These indicators were characterized and assessed at landscape level using some spatial analysis functions on the output of the DSS results.

3.6. Cultural services

Similar to the biodiversity indicators, the cultural services are represented with a diverse spectrum of attributes such as spiritual enrichment, cognitive development, reflection, recreation, and aesthetic experiences, all are in fact intangible attributes (Tveit et al., 2006; Ode et al., 2008; Edwards et al., 2012; Giergiczny et al., 2015; Torralba et al., 2020; Velasco-Muñoz et al., 2022). Therefore, developing a common indicator for the cultural values is quite challenging. In this study, however, the commonly prevailing aspect of cultural services such as aesthetic-recreation was taken into account as a proxy measure. The Recreation Aesthetics Forest Landscape (RAFL) index developed based on four abstraction levels such as concept, dimension, attribute and indicator (Tveit et al., 2006), was used as the cultural ES indicator (Lundholm et al., 2020). As the RAFL index is composed of different sub-indicators with different influences, they were scaled down and averaged at landscape level to create a harmonized impact of the sub-indicators on the RAFL index with the limits of the indicators as suggested by Lundholm et al. (2020) (Table 3). The percent merchantable volume of each species in the landscape was used to calculate Shannon diversity index. The Shannon Diversity and Evenness Indices were calculated using landscape level average values (Mouillot and Leprêtre, 1999). As such, the evenness of tree sizes at the landscape level was calculated by the percentage logarithmic estimate of each diameter class, summed and divided by the natural logarithm of the number of diameter classes.

4. Results

4.1. Forest development

The forests apparently develop towards mature and over-mature stages as the rotation periods get longer particularly in strategies from S3 to S6 (Fig. 1). On the contrary, the regenerated areas gradually decrease from the S1 scenario to the S6 scenario, starting from 30% to 10% at the end of simulation, respectively. Naturally, older forests diminish primarily as the rotation lengths get shorter. Another general observation is related to the gradual regulation of forest structure with respect to the initial age-class structure, almost apparent in all strategies due mainly to the even-flow management policy applied across all strategies. The sharp decreases of mature and over-mature forests in the first 30 years result from the fact that oldest-first rule are applied in all strategies.

4.2. Habitat for biodiversity conservation

Over 100 years of simulation, the total growing stock increased by 17% (S1) in strategies with shorter rotations strategy up to 44% (S6) in

Table 3
The indicators with their primary characteristics by all dimensions and concepts with the specific value functions including the upper and lower limits in averaging the score to create the RAFL-index (Modified from Lundholm et al., 2020).

Concepts	Dimensions	Attribute (following template)	Indicator (units)	Direction of attribute	Value-function (Linear)
Stewardship	Sense of care	Harvest residues	m^3 ha^{-1}	–	0 m^3 = 0, >=10 m^3 = 1
Naturalness / disturbances	Alteration or impact	Final felling areas	% of forest area harvested	–	0% =0, 9% = 1,
	Wilderness	Mortality volume	m^3 ha-1	+	0 m^3 ha-1 = 0, 5 m^3 ha-1 = 1,
	Intrusion	Naturalness (Hemeroby index)	0 = natural, non-disturbed forest, 0.33 = close to natural, 0.66 = semi-natural, 1 = far from natural (monocultures, plantation)	–	linear
Complexity	Diversity	Shannon index (Species, standing volume)	0 – 2	+	0.5 = 0 2 = 1,
	Variety	Evenness of tree sizes on landscape level (dbh)	0–1	+	linear
	Spatial structure	Patch (stand) size variation	% of total forest landscape occupied by largest forested stand	–	0.001%=0, 5%=1,
Visual scale	Openness	Mean tree number	Stems ha^{-1}	–	900 = 0, 1600 = 1,
	Visibility	Understory	% of forest stands with understory	–	linear
Historicity / imageability	Historical richness	Mean stand age	Years	+	20 yr = 0, 80 yr = 1,
	Historical continuity	Change in forest location (afforestation, deforestation)	% of forest area that changed location (afforestation and deforestation)	–	0% = 0, 10% =1,
Ephemera	Seasonal change	Broadleaves share	% broadleaf volume of total	+	0% = 0, 6%=1,

strategies with longer rotations (Fig. 2a). The apparent increase is mainly associated with early recovery of poor growing stands with regeneration and afforestation of bare and degraded forest stands with the natural tree species, all growing in nearly optimal conditions. The obvious decrease in regenerated areas towards the end of simulation (Fig. 2b) is an evidence for improved forest conditions given the same or sustainable level of harvesting volume (i.e., allowable cut) over time (Fig. 9a). As expected, however, the regenerated areas are higher in strategies with shorter rotation lengths than that of the strategies with longer rotation lengths. Such increase in growing stock and decrease in regenerated areas have the potential to provide better habitat conditions for biodiversity conservation.

The volume of large diameter trees (over 50 and 60 cm) per hectare increased in the scenarios from S3 towards S6 without any large trees (>60 cm) in the S1 and S2 strategies, yet more apparent in the S6 scenario compared to the other scenarios (Table 4). However, the volume of small diameter trees (>30 and 40 cm) per hectare substantially decreased in the scenarios from S1 towards S6; yet the decrease is more apparent in the scenarios with shorter rotation lengths (the S1, S2 and S3 scenarios) and less apparent in scenarios with longer rotation lengths (the S4, S5 and S6 scenarios). While the scenario S6 maintained the volume of trees with DBH > 40 towards the end of the planning horizon, the strategies with shorter rotations (S1 and S2) left no volume over 40 cm DBH (Fig. 3a).

The total deadwood volume declined in the first half of the simulation due to natural mortality, yet it increased substantially in all scenarios over the second half of the simulation towards the end (Fig. 3b) with apparent decrease in the scenarios with shorter rotation lengths (the S1, S2 and S3 scenarios) and increases in other scenarios with longer rotation lengths at the end of the simulation (S4, S5, S6). The coarse deadwood constantly increased over time; however, with a slight increase in the scenarios with shorter rotation lengths (S1, S2 and S3) and higher increase in other scenarios with longer rotation lengths (S4, S5, S6). The pattern indicates clear responses of rotation lengths on the amount of deadwood volume, an indicator for biodiversity conservation, where higher deadwood volume created with long rotation lengths provides better conditions for biodiversity conservation than the shorter rotation periods.

The share of the broadleaved species such as oak and walnut, which are rather low within the overall forest composition, experienced a substantial increase in the first half of the simulation and leveling off towards the end of time in all scenarios (Fig. 4a) due mainly to some afforestation with walnut as NWFP and promotion of hardwood species. The differences between the strategies with short rotation lengths and long rotation lengths are apparent over time. The average stand age decreased in the first half of the simulation, while it recovered from then on in all scenarios (from 60 years to 30–55 years) (Fig. 4b). As mature and over mature stands are quickly harvested first, it recovered towards the end of simulation time as both naturally regenerated areas and planted stands improved conditions towards the end of simulation. The area of forests older than 80 years decreased in all planning scenarios with fluctuating levels at the end of the planning horizon; however, the area decreased substantially in the scenarios with shorter rotation lengths (the S2, S2, S3 scenarios) yet slowly in the scenarios with longer rotation lengths (the S4, S5, S6 scenarios) (Table 4). However, the areas with ages between 60 and 70 years have improved in all scenarios over time.

There are other proxy indicators for evaluating the status of habitat for biodiversity. Among them, the Shannon diversity index and Evenness index stayed almost the same over the planning horizon with a little decrease in shorter rotations and a gradual improvement in longer rotations. Patch density, used as a legitimate parameter for habitat for biodiversity conservation, decreased (from 20 to 19.1), the mean patch size increased (from 4.8 ha to 5.2 ha) and the largest patch index increased (from 0.007 to 0.011) almost the for all the scenarios over time. The results show a slight enhancement in habitat conditions for all the scenarios in terms of a spatial aspect of biodiversity.

4.3. Water production

The forested areas improved steadily (Fig. 5a) with the plantation of bare forest areas in all scenarios with different rates, showing a promising condition for provisioning of higher quality of water towards the production of fresh water. However, regeneration of the degraded areas with the coniferous trees such as Anatolian pine, Taurus cedar and Calabrian pine and replacement of the understory vegetation (Fig. 5b) create some concerns and pose risks against fresh water production and forest fires in the planning unit.

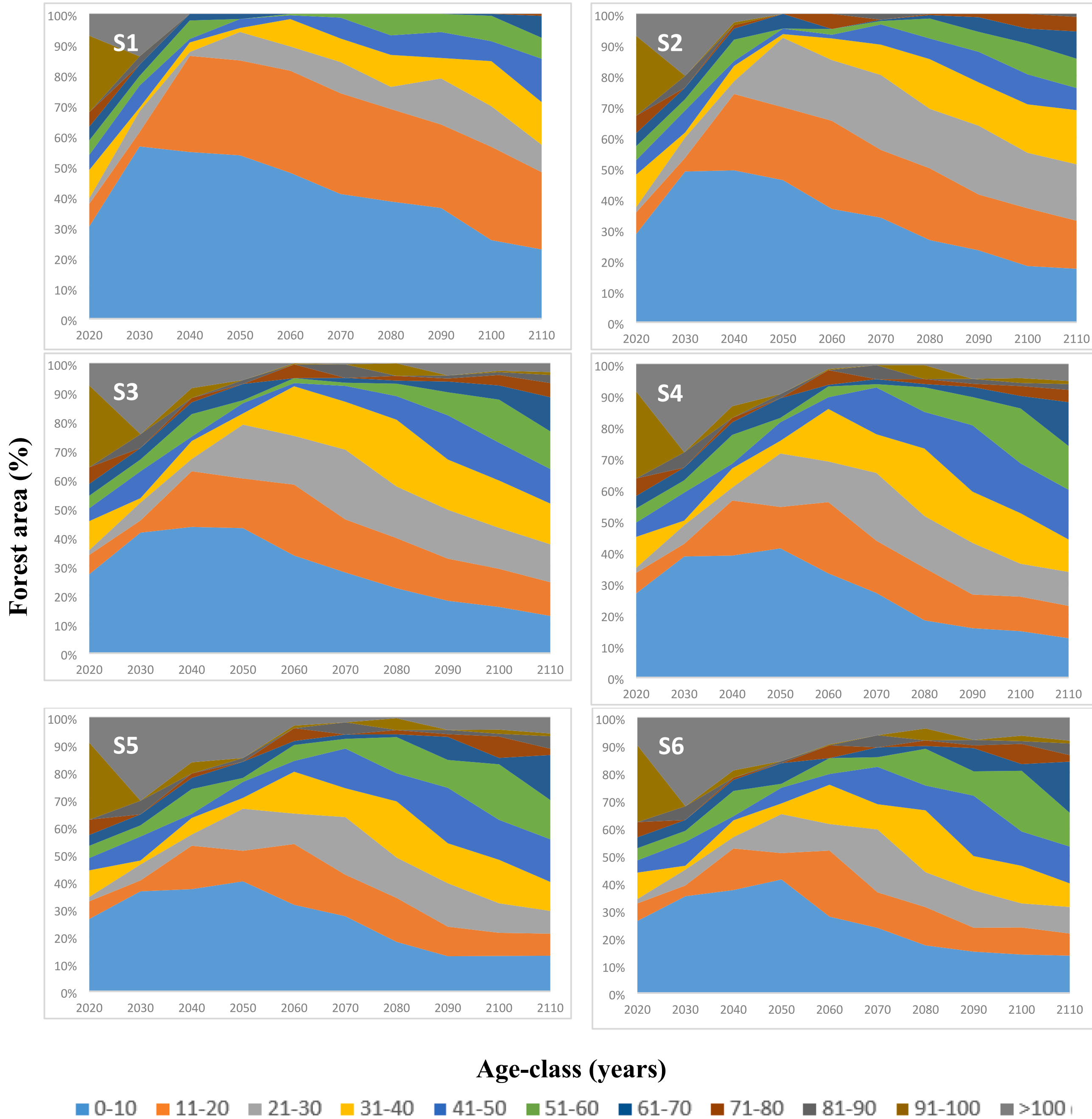


Fig. 1. The development of forest area (ha) by age-class over 100 years of simulation for six management scenarios.

On the other hand, the amount of ground run-off water decreased continuously (Fig. 6a) with respect to the gradual improvement of basal area (Fig. 6b), particularly in the second half of simulation, due to afforestation and recovery of degraded stands. These results may also be associated with the certain level of commercial thinning in all scenarios. However, the higher production of surface runoff water in the management scenarios with short rotations (S1 and S2) compared to the others, is also related to the relatively higher regeneration areas or final felling areas and harvest levels (Figs. 2b and 9a).

4.4. Carbon sequestration

The cumulative carbon storage stayed almost regular until 2050 and started to increase rapidly over the rest of time, reaching up to 3 and 6 carbon Mg ha^{-1} year^{-1} for all scenarios, with less apparent increase in S1 scenario (Fig. 7a). While the C balance was negative in 2040 in all scenarios, this was quickly recovered and improved in the later periods of the simulation, levelling off towards the end of simulation (Fig. 7b). This is mainly related strongly to the gradual increase both in growing stock (from 100 m^3 ha^{-1} to 221 m^3 ha^{-1}) and increment (1.0 m^3 ha^{-1} year^{-1} to 6 m^3 ha^{-1} year^{-1}) over the planning horizon. The increase in growing stock and increment is mainly driven by a shift in age class structure towards mature stands (Fig. 1), increase of productive forest areas (Fig. 5) by plantation of degraded stands and bare forest lands and future stands growing according to the empirical yield curves. Furthermore, the simulation was extended over 300 years to evaluate the sensitivity of the results, specifically the longer term dynamics of carbon storage and balance in order to eliminate any potential effects of initial unregulated forest structure on C dynamics. The results indicate that the cumulative carbon are nearly stabilized and maintained after

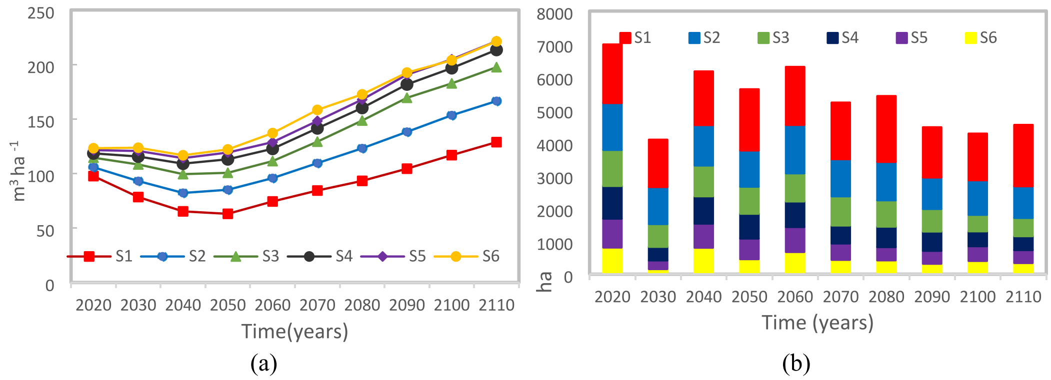


Fig. 2. The development of growing stock (a) and final felling area (b) over time. The initial growing stock is 102 m^3 ha^{-1}.

100 years of simulation towards 300 years in future, interestingly with the similar trend or differences among the management scenarios (Fig. 7c). The carbon balance also leveled off and maintained around “0” values right after 200 years in simulation, indicating almost a carbon–neutral situation provided that the same set up and assumptions continue towards 300 years of simulation (Fig. 7d).

4.5. Cultural attributes

While the overall trend in RAFL-index over the planning horizon is relatively stable in the scenarios with short rotation lengths (S1 and S2), the cultural values gradually increased in all other scenarios. For example, the RAFL-index increased from 0.48 and 0.50 in 2020 to 0.53 to 0.62 in 2110 for the scenarios S3 and S6, respectively (Fig. 8a). The progressive improvement of RAFL-index is primarily due to a joint impacts of changes in forest composition, regenerated areas, and the volumes of harvest residue in forest landscape. While the S1 and S2 scenarios scored a relatively stable RAFL index value compared to the others, all other scenarios experienced similar changes in forest structure and the tree species composition. For example, the final felling areas are constantly higher throughout the planning horizon in the scenarios with shorter rotation lengths (the S1, S2, S3 scenarios) that that in the scenarios with longer rotations lengths (S4, S5, S6).

4.6. Soil loss

The prevailing outcome regarding the amount of soil loss to erosion relates to the fact that the scenarios with short rotation lengths (S1 and S2) experienced the highest soil losses per ha per year over the simulation (Fig. 8b). For example, the amount of soil loss gradually decreased from 7.5 and 6.2 in 2020 to 4.8 and 2.8 Mg ha^{-1} $year^{-1}$ in 2110 in the scenarios S1 and S6, respectively. The changes in soil loss over the planning horizon are about 36% and 55%, respectively, which the latter one is quite significant. In all scenarios, the overall gradual decrease in soil loss over time is mostly related to the improvement in basal area (Fig. 6a).

4.7. Timber production

Fig. 9a indicates that harvested volumes over the planning horizon are regulated in all strategies due mainly to the fact that volume control or even flow harvest policy is used as part of contemporary management guidelines and policies. Interestingly though, similar pattern in harvested areas is observed while the harvested area is not totally regulated over time (Fig. 2b). This mainly relates to the fact that the share of unproductive forests such as degraded and loosely covered stands is not substantial in the case study area compared to the similar other studies (OGM, 2014; Baskent and Kašpar, 2022). The overall trend in Net Present Value (NPV) shows the general pattern of interest in all strategies, a sharp decrease is observed in the first half of the simulation and levelling off towards the end of planning horizon (Fig. 9b). However, the fact that the S1 scenario generated the highest harvested volume and thus the highest NPV per m^3 over time is more apparent than the other strategies as the annual allowable cut is substantially higher in the S1 scenario compared to the others.

The overall performance of all management scenarios was analyzed with the mean provision of ecosystem services over time to assess and compare the success levels of each ES. As ETÇAP DSS targeted to generate maximum even flow of harvest volume over time, the indicators of various ESs such as carbon storage, soil loss to erosion, surface run-off water, RAFL-index and Shannon diversity index would best be compared to the amount of harvest and its NPV (Table 5). The average NPV per m^3 is generally higher in short rotation scenarios and lower in long rotation periods, similar to the trend in average harvest levels across all scenarios. Similarly, carbon storage increased parallel to RAFL-index and Shannon diversity index, and inversely proportional to the amount of soil loss to erosion and water production, in the order of S1 towards S6. Such trend is quite logical as more areas are harvested, water production and the amount of soil removed by erosion (soil loss) are expected to increase. However, both the cultural and biodiversity values are anticipated to decrease in scenarios with shorter rotation lengths. Similar trend was also observed such that as the amount of harvested volume decreased the cumulative amount of carbon increased from 1.28 to 2.88 Mg ha^{-1} $year^{-1}$ in the order of S1 towards S6.

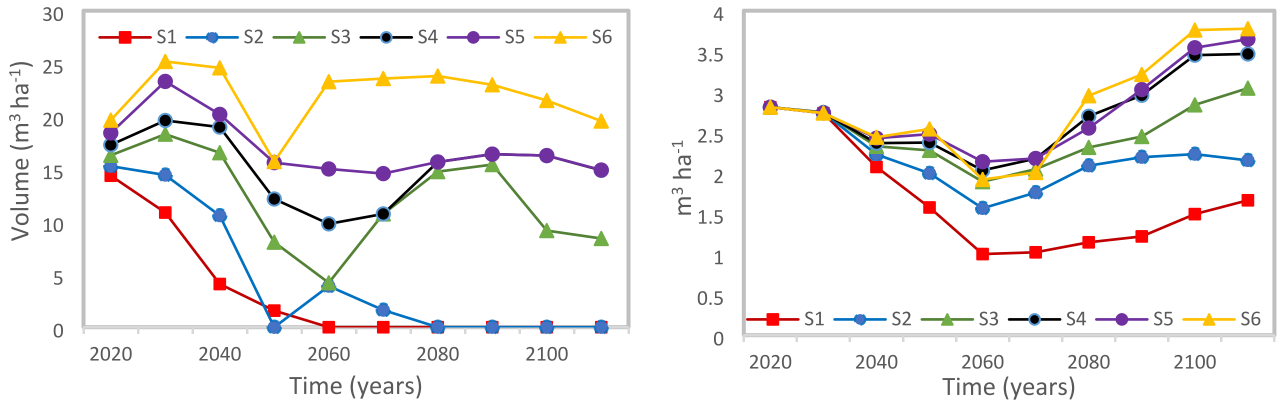
5. Discussion

This study has investigated the impacts of six different management strategies on the levels of various ESs such as carbon sequestration, soil loss, water provision, cultural values, habitat for biodiversity and timber production in a typical case study area with a forest ecosystem management approach. The ETÇAP model is used as a decision making tool to incorporate the ESs and evaluate the trade-offs among the management alternatives. The potential trade-offs between the strategies are that higher diversity of age classes with much older forests and less amount of harvesting areas, obtained in strategies with longer rotation lengths, results in less vulnerable forest ecosystems; i.e., better conditions for biodiversity conservation, soil protection, carbon sequestration and recreation; yet poor conditions for economic gain and ground water production.

A number of biodiversity indicators are used to evaluate the habitat conditions for biodiversity conservation under six different planning scenarios. The overall results are promising given the fact that the habitat conditions are gradually improved in strategies with long rotation ages based on the indicators such as old forests, the amount of dead wood and Shannon diversity and evenness index due mainly to lower harvesting level and the opportunities for the stands to mature enough for harvesting. However, the similar trend has not been observed in

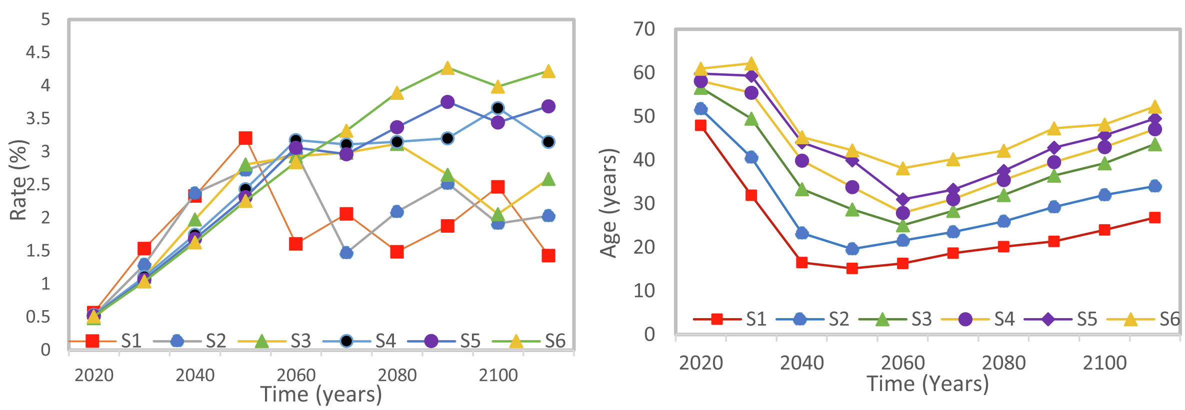
Table 4
The summary values of biodiversity indicators for the six scenarios at three time points in time: 2020, 2060, and 2110.

	S1			S2			S3			S4			S5			S6		
Biodiversity Indicators	**2020**	**2060**	**2110**	**2020**	**2060**	**2110**	**2020**	**2060**	**2110**	**2020**	**2060**	**2110**	**2020**	**2060**	**2110**	**2020**	**2060**	**2110**
Volume (m^3 ha^{-1}) DBH > 30 cm	57,69	0,00	1,16	61,77	13,29	4,02	67,45	14,42	23,20	71,27	21,65	27,61	73,92	29,34	29,19	75,25	41,12	35,99
Volume (m^3 ha^{-1}) DBH > 40 cm	14,36	0,00	0,00	15,26	3,90	0,00	16,29	4,21	8,41	17,28	9,80	14,87	18,41	15,00	14,90	19,63	23,27	19,54
Volume (m^3 ha^{-1}) DBH > 50 cm	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	8,01	0,00	2,17	14,33	0,00	5,66	14,33	0,00	9,32	17,89
Volume (m^3 ha^{-1}) DBH > 60 cm	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	6,21	0,00	2,12	10,62	0,00	4,92	10,62	0,00	4,92	11,16
Coarse deadwood volume (m^3 ha^{-1})	2,81	1,00	1,66	2,81	1,56	2,15	2,810	1,89	3,04	2,81	2,03	3,46	2,810	2,13	3,64	2,81	1,90	3,77
Coarse deadwood volume (m^3 ha^{-1}) DBH > 30	0,00	0,00	0,08	0,00	0,55	0,33	0,00	1,60	0,90	0,00	1,16	0,56	0,00	1,52	0,61	0,00	2,19	0,69
Broadleaves volume share (%)	0,57	1,61	1,43	0,53	2,98	2,03	0,49	2,93	2,59	0,53	3,18	3,15	0,52	3,06	3,69	0,51	2,84	4,22
Volume (m^3 ha^{-1}) *Pinus brutia*	39,87	43,39	53,69	41,79	26,04	55,82	42,93	33,00	62,79	42,91	39,80	63,30	43,51	48,51	63,85	60,85	46,38	64,49
Volume (m^3 ha^{-1}) *Pinus nigra*	40,92	0,52	59,31	46,88	54,59	86,27	53,09	62,47	101,03	57,21	65,20	111,82	59,07	62,32	117,41	0,81	66,66	116,44
Volume (m^3 ha^{-1}) *Abies cilicica*	0,81	8,32	1,41	0,81	0,50	1,96	0,81	0,23	1,85	0,81	0,50	1,96	0,81	0,09	1,78	16,78	0,00	1,62
Volume (m^3 ha^{-1}) *Cedrus libani*	15,08	0,18	12,42	15,24	11,56	18,93	16,48	12,19	26,64	16,30	13,05	29,52	16,78	13,71	30,06	0,59	19,68	29,22
Volume (m^3 ha^{-1}) *Juniperus sp*	0,36	0,04	0,07	0,45	0,19	0,08	0,59	0,20	0,08	0,59	0,20	0,07	0,59	0,19	0,09	0,12	0,43	0,09
Volume (m^3 ha^{-1}) *Quercus* sp.	0,05	0,93	0,04	0,05	0,01	0,01	0,05	0,09	0,15	0,12	0,05	0,09	0,12	0,09	0,06	0,33	0,05	0,28
Volume (m^3 ha^{-1}) *Juglans sp*	0,33	0,07	1,58	0,33	2,73	3,33	0,33	3,10	4,48	0,33	3,11	6,28	0,33	3,11	7,75	0,08	3,11	7,75
Volume (m^3 ha^{-1}) *Platanus* sp.	0,08	0,16	0,22	0,08	0,07	0,04	0,08	0,07	0,49	0,08	0,07	0,35	0,08	0,07	0,35	0,10	0,07	1,31
Volume (m^3 ha^{-1}) *Maquis*	0,10	43,39	0,00	0,10	0,04	0,00	0,10	0,00	0,00	0,10	0,67	0,00	0,10	48,51	0,00	60,85	0,67	0,00
Areas of forest aged 61–80 years (ha)	565,35	0,00	564,35	638,72	346,35	1098,70	667,8	364,45	1419,1	659,3	404,22	1550,69	670,33	475,82	1623,94	670,33	364,45	1828,64
Areas older than 80 years (ha)	1972,81	0,00	0,00	2135,88	346,35	78,23	2436,34	391,63	578,87	2516,72	513,20	709,84	2617,60	671,96	993,78	2685,19	1154,68	1186,64
Alteration –final felling areas (%)	22,50	19,71	20,52	18,06	12,99	10,62	13,89	10,19	6,12	12,57	6,27	4,65	11,15	5,72	4,34	10,30	5,04	3,78
Hemoroby index (0–1)	0,39	0,42	0,64	0,39	0,45	0,63	0,38	0,49	0,72	0,38	0,66	0,76	0,38	0,69	0,76	0,38	0,62	0,78
Mean patch size	4,89	5,14	5,24	4,89	5,14	5,24	4,89	5,14	5,24	4,89	5,14	5,24	4,89	5,14	5,24	4,89	5,14	5,24
Patch density	20,44	19,42	19,09	20,44	19,44	19,09	20,44	19,44	19,09	20,44	19,44	19,09	20,44	19,44	19,09	20,44	19,44	19,09
Largest patch index	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01
Shannon species diversity (0–2)	1,08	0,97	1,00	1,07	0,97	1,01	1,07	0,96	1,03	1,06	0,98	1,02	1,06	0,98	1,01	1,05	1,02	1,01
DBH evenness index (0–1)	0,67	0,34	0,56	0,67	0,58	0,58	0,66	0,58	0,72	0,66	0,69	0,72	0,66	0,75	0,72	0,66	0,82	0,76



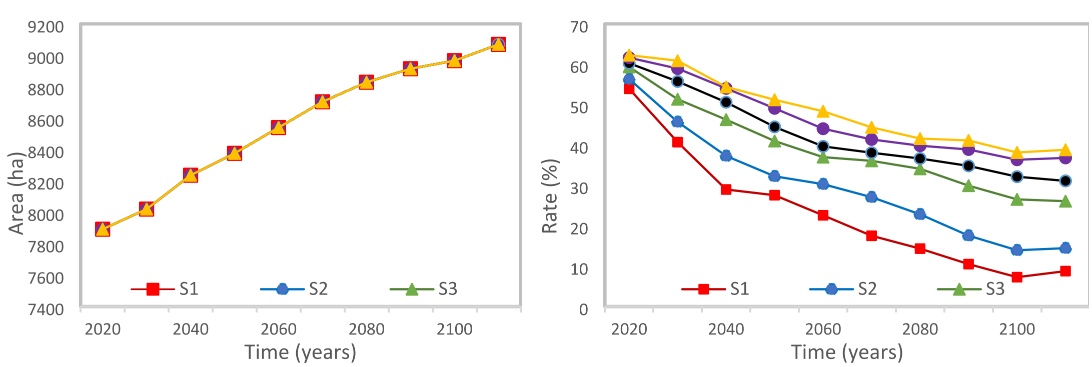
(a) (b)

Fig. 3. Largest stand volume over 40 cm DBH (a) and the total deadwood volume (b) over 100 years.



(a) (b)

Fig. 4. The rate (%) of broadleaved species (a) and the average stand age (b) over 100 years.



(a) (b)

Fig. 5. The change of forest land with afforestation (a) and the rate (%) of understory (b) over 100 years.

other strategies with shorter rotations due mainly to early harvesting of stands with higher level of harvesting. Thus, creating better habitat conditions for biodiversity conservation such as mature-over mature forests with large tree sizes highly depends on the rotation lengths where higher rotation lengths have the opportunity to create or maintain older forests while the shorter rotation lengths create relatively immature forests which are unfavorable for biodiversity conservation. On an average, 85% of the total small diameter volume (DBH< 30) in strategies with short rotation ages is reduced to 65% in the scenarios with longer rotation lengths, and inversely 11% of the total larger diameter volume (DBH > 30) in strategies with short rotation ages is improved to 33% in the scenarios with longer rotation lengths. Such results indicate a significant improvement in habitat conditions particularly with longer rotations, providing far better habitat conditions for biodiversity conservation. Improvements in biodiversity indicators are also viewed to contribute to the improvements for the provision of habitat for biodiversity as well as most of the other ESs (Lefcheck et al., 2015; Baskent and Kašpar, 2022). Consequently, sacrificing certain amount of harvested volume with longer rotation lengths can lead to increased biodiversity and realization of multifunctionality of forests.

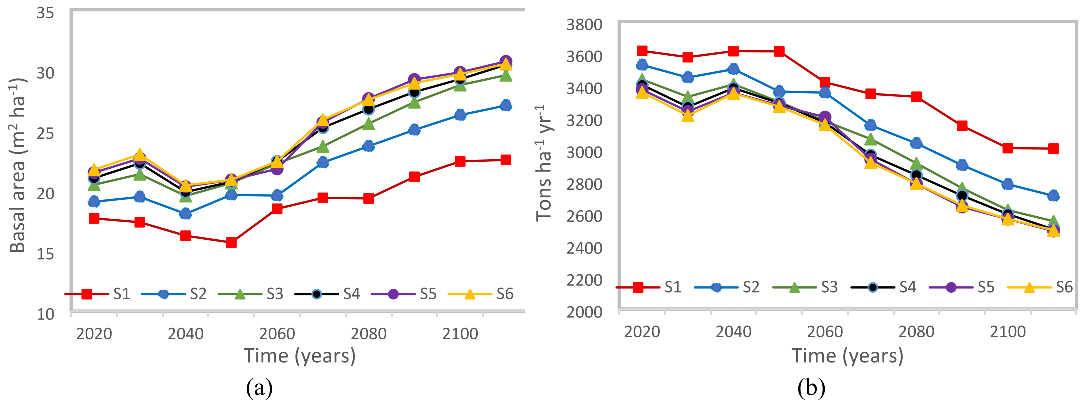


Fig. 6. The temporal change in basal area (a) and surface water (b) over 100 years.

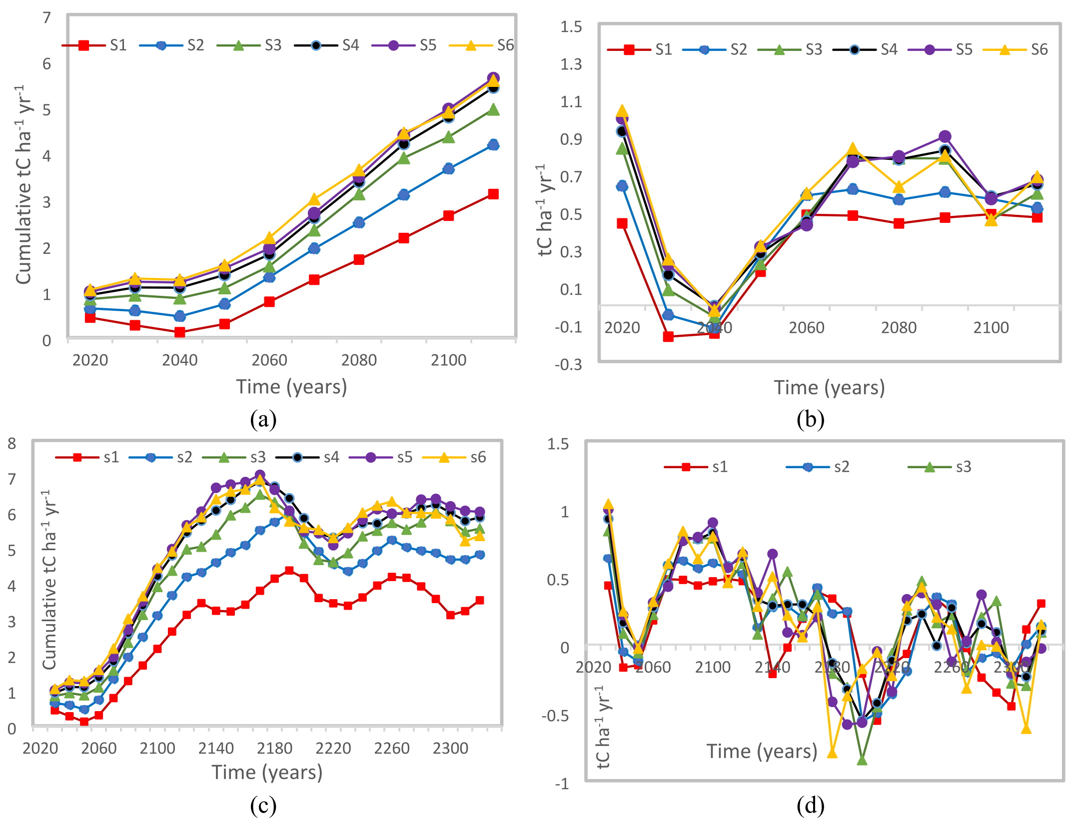
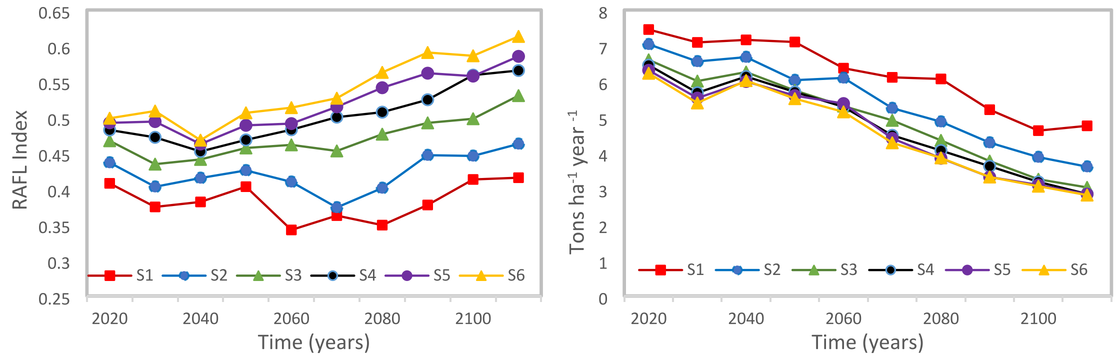


Fig. 7. Cumulative stored carbon in tons ha^{-1} year^{-1} (a) and carbon balance in tons ha^{-1} year^{-1} (b) over 100 years. Similarly, the cumulative stored carbon in tons ha^{-1} year^{-1} (c) and carbon balance in tons ha^{-1} year^{-1} (d) over 300 years.

Furthermore, any rare or sparsely distributed species and ground vegetation are maintained during management activities, small forest openings are left out and the natural composition of stands is preserved for biodiversity conservation (Barbier et al., 2008), as also highlighted by the current planning guidelines.

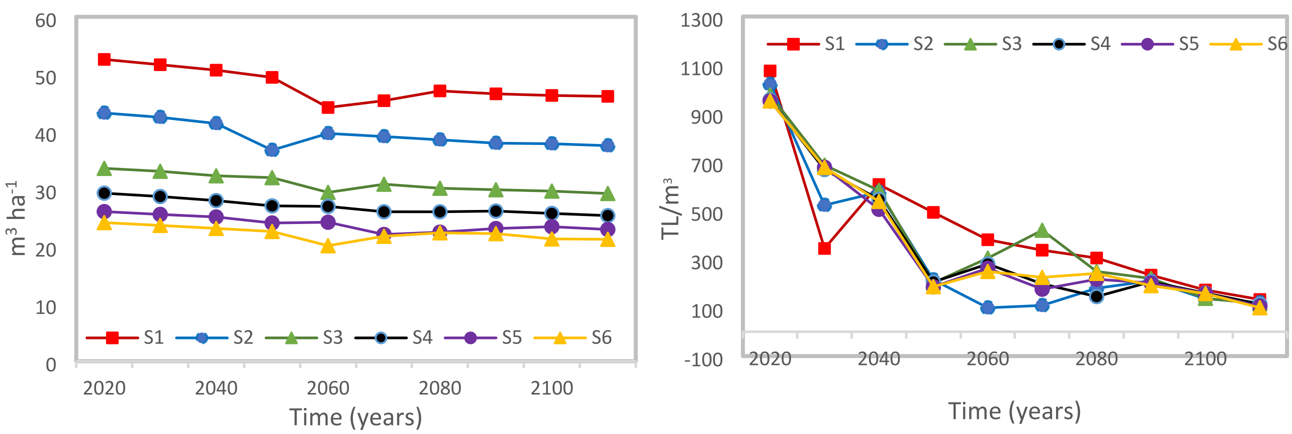
Aside from the S1 and S2 scenarios in 2030 and 2040, all scenarios have generated positive carbon balance over 100 years, showing a total carbon sink in the Bürücek FPU. Such general trend appears to be associated with the age class shifts towards the mature and over-mature development stages, afforested areas and improvement in the forest productivity (i.e., growing stock) due to increase in volume increment over time. Such results are reasonably consistent with the national GHG projections for managed forest in Turkey (Tolunay, 2011) and the findings by Böttcher et al., (2008). Specifically, the positive trend is consistent with national projected forest C stock (from a net sink 2.2 Tg year $^{-1}$ of carbon to a net gain of 6.8 Mt Tg year^{-1} (Tolunay. 2011). In general, the Carbon sequestration capacity of Turkey's forests has been increasing with the gradual increase in forest areas and their productivity over the last three decades, with the shift of forest policy towards the forest ecosystem management philosophy (Baskent, 2019).

The differences in the total C balance and the cumulative amount of carbon among the scenarios, however, are mainly related to the apparent increase in the growing stock and increment in the strategies with longer rotation lengths (S4, S5 and S6). Carbon stored in the harvested wood products as well as emission savings from the energy and product substitution particularly in strategies with short rotations and higher harvest levels is unable to compensate or recover carbon balance in the long run due mainly to small sized harvests which did not endure carbon in the long run. We caution that steadily increasing harvesting level with shorter rotation lengths may well cause certain shortages in



(a) (b)

Fig. 8. The trend of RAFL-index (a) for cultural values and per ha soil loss (b) over 100 years of simulation across six scenarios.



(a) (b)

Fig. 9. Mean harvested volume per ha (a) and NPV (b) over 100 years for the six scenarios.

Table 5
The average values of ES indicators for the six scenarios over time: cumulative carbon storage change, soil loss to erosion, surface water, RAFL index and Shannon diversity index, and some performance indicators such as harvested areas, harvest volume and the NPV.

Scenarios	NPV (TLm^{-3})	Harvest volume (m^3 ha^{-1})	Area Harvested (%)	Cumulative Carbon storage (Mg ha^{-1} year^{-1})	Soil loss (Mg ha^{-1} year^{-1})	Water Prod (Mg ha^{-1} year^{-1})	RAFL-Index	Shannon diversity index
S1	407.89	48.01	19.86	1.28	6.20	3367.63	0.383	0.998
S2	318.89	39.47	13.67	1.91	5.43	3177.30	0.422	1.006
S3	389.40	31.01	9.24	2.39	4.93	3054.88	0.471	1.013
S4	347.98	26.93	7.55	2.66	4.75	3011.36	0.501	1.017
S5	343.94	23.91	6.38	2.80	4.64	2985.23	0.519	1.018
S6	351.50	22.26	5.72	2.88	4.57	2974.77	0.537	1.019

cumulative carbon storage and balance in the longer time (Fig. 7cd) as also indicated by Trivino et al., (2017), Lundholm et al., (2020) and Mozgeris et al., (2021). Furthermore, short rotation lengths have been shown to be less effective in carbon sequestration than the long ones because they reduce the biomass carbon stock and the litter input to soil (Akujärvi et al., 2019). Similarly, Liski et al., (2001) have indicated that longer rotation lengths at the sites of tree species they studied would be favorable to carbon sequestration. Knoke et al. (2020) indicated that silvicultural strategies that consider multiple criteria stored up to 47% more carbon than the clear-cutting system, yet, in the expenses of 39% lower soil expectation values, while Kolo et al. (2020) showed that including carbon storage lead to small changes in harvest schedule and species composition. Thus, it is critical to consider the potential trade-offs between the temporal stability and the level of ecosystem service provisioning in forest ecosystems as indicated by Albrich et al., (2018). Furthermore, based on the additional simulations over 300 years, we postulate that when forest development is forecasted further into the future for a given initial age class structure and management policies, there may well be an optimal rotation length for a carbon–neutral conditions as the forests get regulated.

The gradual decreasing trend in ground water production and soil loss over time is mainly due to the steady increase of the basal area as a result of both afforestation and the replacement of unproductive stands with more productive stands after regeneration. The improvement in development as well as forest area indicates lower levels of ground water as indicated in other studies such as Bentley and Coomes (2020), Roces-Díaz et al. (2021) and Baskent and Kašpar (2022). Therefore, the management strategies have provided great opportunities to minimize the risk of soil erosion and manage the amount of surface water, to a greater extent. It is obvious that the management scenarios with longer rotation lengths (S3 – S6) save higher amount of soil to erosion than that of the scenarios with shorter rotation lengths (S1, S2), as they have regenerated lesser areas and allowed stands to develop towards mature and over mature stages of development. The differences among the outcome of the management scenarios are almost stable with a slight increase towards the end of simulation. Aside from management policies, the temporal changes of soil loss and water provision are mainly determined by the renewal rate and forest development performance, all are related to the development of forest structure over time as also indicated by Baskent (2019), Roces-Díaz et al. (2021) and Baskent and Kašpar (2022).

The cultural values, represented by a combine RAFL-index, have maintained the aesthetic and recreational characteristics of forests over time in strategies with short rotation lengths, while gradual improvement are observed in other strategies. The slight initial decrease and overall maintenance of RAFL-index values in the S1 and S2 strategies are mainly due to higher harvesting rate and rapid replacement of older forests with much young stands, resulting in increased number of trees per hectare, reduced average stand age and increased volume of harvest residues. However, the gradual relative progression of RAFL-Index in the scenarios with higher rotation lengths (S3 – S6) over time can well be attributed to the lower harvesting rate (Fig. 9a), relatively less number of trees per ha, higher mean stand age (Fig. 4b) and lower harvest residues as a result of high rotation lengths used in the management units. Specifically, older Anatolian pine and Red pine stands have larger natural mortality volume causing the wilderness score to increase in the related management scenarios.

There are few limitations of the study to consider in exploring and extending the results to other areas of planning. First of all, there is no pro-active spatial planning mechanism to assess and control forest landscape structure or landscape fragmentation with spatial metrics. The results do not guarantee optimal solutions as inexact models or heuristic simulations are used in planning. Disturbance regimes and their potential impacts on the ecosystem services particularly water production and soil loss are not specifically included in the study. Low level of representation of those ES needs some attention too. As cautioned by both Helmedag (2018) and Moog (2020), attention should be directed to the relevance and particularly the assumptions such as stable natural disturbances and market conditions as used in our modeling exercise and the model outcomes with different rotation lengths should be interpreted very carefully in order to retain creditability. The RAFL-index is a combination of some stand attributes whose contribution to the index is subjectively determined. Adjusting some parameters of Carbon stock such as energy substitution of wood products, estimating of total biomass and inclusion of other carbon pools such as litter fall and soil carbon may well be needed for a more accurate calculation of carbon stocks. Nonetheless, an adaptive management approach based on a wide spectrum of forest management scenarios including the risks and uncertainties (Daniel et al., 2017; Friedrich et al., 2021; Gregor et al., 2022) needs to be developed to locate the best possible combination of ES provision levels using exact techniques such as mixed-integer programming, combinatorial optimization, pareto frontier and MCDA techniques (Kangas and Kangas, 2005; Seppelt et al., 2013; Borges et al., 2014; Nordström et al., 2019; Sacchelli and Bernetti, 2019). In fact, Pareto-frontiers coupled with both optimization techniques and scenario analysis can well provide better alternatives for assessing the tradeoffs for sustainable management of forest ecosystems from global to local scales (Seppelt et al., 2013; Borges et al., 2014). However, the methodology and analysis developed and used in this study regarding various rotation lengths can well be up-scaled in any other jurisdictions with the similar ecological conditions using the nationally relevant indicators of ES and parameter settings under national management guidelines.

6. Conclusion

Six different forest planning scenarios were designed and applied with the ETÇAP DSS to simulate forest developments under different rotation lengths in a forest planning unit demonstrative of mid Anatolian and greater Mediterranean forest ecosystem conditions in Turkey. In general, all of the management scenarios presented almost similar temporal trends due primarily to the same objective function (i.e., maximizing wood production) and planning parameters, aside from the rotation lengths. However, the values of selected ecosystem services varied greatly between the scenarios, primarily due to harvesting levels and the rotation lengths. The largest differences in terms of ecosystem services between scenarios were observed in timber production, carbon storage and cultural values with smaller differences of ground water runoff, soil loss, and biodiversity indicators. Some apparent conclusions could be highlighted as followings;

- Forest management strategies driven by the gradual increase of rotation lengths over time generated different and critical planning outputs for forest dynamics, effecting the level of all ES over the planning horizon. Strong and systematic effects of longer rotation lengths were observed almost proportional to the level of ES, due mainly to the areas harvested and forest structure generated in addition to the near regular initial age class structure.
- Significant effects of the long rotation lengths on the carbon storage were observed (e.g., nearly 70% difference between the short and long rotation lengths) as the relatively produced large materials had long term endurance of carbon in harvested wood products. Longer term simulation, did not offset the carbon balance among the strategies; the cumulative carbon storage was nearly stabilized resulting in an almost carbon–neutral situation over longer time (i.e., 300 years into the future). Thus, we postulate that when forest development is forecasted further into the future for a given initial age class structure and management policies, there may well be an optimal rotation length for a carbon sink or carbon-balanced conditions as the forests get regulated.
- The total amount of sustainable harvest was the highest in the management scenario with the shortest rotation length, as expected, due to early harvesting opportunities and initial age-class structure allowing more stands available for sustainable harvest level.
- Rapid and constant replacement or renewal of unproductive current stands (e.g., degraded and sparse crown closure) led to more productive forest areas over time, resulting in a better forest performance or development indicated by the basal area, growing stock and volume increment to help improve all ES, except cultural values and biodiversity conservation, over time in all scenarios.
- Rotation lengths had profound effects of the product assortments produced. Average large size harvest product strikingly increased nearly from 40% to 50% in the management scenario with the longest rotation length and from 35% to 95% in the shortest rotation length in the end of the planning horizon as smaller material was harvested.
- Various levels of trade-offs between the strategies regarding the output of the ESs were experienced over time. There are clear synergies between carbon sequestration and biodiversity conservation while wood production displayed trade-offs with both carbon sequestration, recreation and biodiversity conservation as also indicated by Augustynczik and Yousefpour (2021), concluding that forest conditions, planning policies and the socio-economic conditions may facilitate the trade-offs and synergies among ecosystem services. Higher diversity of age classes with much older forests and less amount of harvesting areas obtained in strategies with longer rotation lengths could result in less vulnerable forest ecosystems; i.e., better conditions for biodiversity conservation, soil protection, carbon sequestration and recreation; yet poor conditions for economic gain and ground water production. Aside from the effects of rotation lengths, the harvesting rule and management policy applied in the strategies were the other important causes of forest dynamics and the level of ESs over time.

Overall, the forest management interventions with varying rotation lengths have profound effects on the provision of ES. Therefore, the hypothesis relating to the fact that longer rotation lengths have substantial effects on the forest development and the level of ecosystem services, primarily carbon stock, timber production and cultural services is substantiated, to a greater extent. An aspiration for a higher level of provisioning services for economic motivations may need to be discarded for the sake of enhancing the capacity of forest ecosystems to sequester more carbon and provide better habitat condition for biodiversity conservation with a careful design and selection of rotation lengths, in addition to other forest interventions. The DSS has provided a great opportunity to grasp forest ecosystem dynamics with different ES services such as wood production, ground water production, carbon sequestration, soil loss, cultural values and biodiversity conservation. The capacity of forest ecosystems to be a net carbon sink is undeniably associated with the longer rotation lengths in addition to the increasing rate of both productive forests and mature-over mature stands. Consequently, a well-suited instrument such as a versatile DSS is critical in testing the postulation and exploring a wide range of planning opportunities to find out the appropriate set of management actions and break-away from the prevailing production legacy.

Author contributions

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Emin Zeki Başkent: Conceptualization, Methodology, Software, Validation, Formal analysis, Writing – original draft, Writing – review & editing. **Jan Kašpar:** Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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