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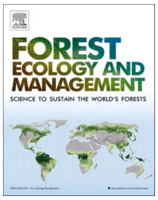

Exploring the effects of management intensification on multiple ecosystem services in an ecosystem management context

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ABSTRACT

Understanding forest dynamics under varying management intensification is a crucial step for designing and implementing sustainable forest management scenarios. One way to assess the sustainability is to evaluate the long-term supply of ecosystem services (ES) with some performance indicators. This research focuses on exploring the effects of management intensification on several ESs such as habitat for biodiversity conservation, wood production, carbon stock, cultural values, water provision and soil protection. Forest development was simulated over time with the ETCAP forest management decision support system (DSS) to investigate the effects of intensified forest management activities, representing different treatment rates, rotation periods and afforestation levels, on the selected ecosystem services. Hamidiye forest planning unit was used as a case study area with 19,009 ha forests in southeastern Turkey.

The management scenarios with intensified forest interventions such as high rate of thinning and afforestation areas with medium rotation ages led to increased harvest level, carbon storage, soil protection, deadwood and forest area, and reductions in largest stand volume, understory, basal area, ground water and cultural values. The same intensified scenarios with short rotation ages, however, resulted in again higher harvest levels, yet a more regulated forest structure due mainly to the increasing afforestation areas and productivity. Extension of rotation periods, however, appear to have marginal impact on carbon storage, positive effect on soil protection and significant effect on harvest level. Scenarios with low intensified interventions only resulted in high values of biodiversity conservation and cultural values. Intensive treatments and larger afforestation areas had significant impact on the overall results. Overall, the analysis of the modeling approach with varying management scenarios led to better and wider understanding of forest development over time by allowing the assessment of the impacts of management interventions on the sustainable supply of the ecosystem services that highly depend on the afforestation level, thinning rate and rotation period.

1. Introduction

Sustainable management of forest ecosystems (SFM) for multiple goods and services (i.e., ecosystem services (ES)) has been initiated to integrate economic, ecological, and social values, as delegated in Helsinki Conventions (Forest Europe, 2020). In compliance with the SFM initiative, an ecosystem based multiple use forest management approach has then become a necessity and part of management regulations in Turkey (Baskent et al., 2008), similar to most other countries (Nordström et al., 2016; Felton et al., 2016; Löf et al., 2016; Lindbladh et al., 2017; Lundhol et al., 2020; Mozgeris et al., 2021; Roces-Díaz et al., 2021). Ecosystem services, as benefits from the forests, are regarded to be the vital component of SFM to determine both the long-term performance of forest development and the level at which forests contribute to human well-being. However, characterizing ES and establishing the quantitative relationships between forest management interventions and ecosystem services and thus societal benefits are essential (Schwaiger et al., 2019; Baskent, 2020; Baskent et al., 2020; Morán-Ordóñez et al., 2020). Various approaches (e.g., regression models, measurement index) have been used to quantify ES and it is possible to analyze the interactions and trade-offs between them under different forest management scenarios (Nordström et al., 2016; Baskent et al.,

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2020; Lundhol et al., 2020; Mozgeris et al., 2021). Understanding both the dynamics of forest development and the trade-offs among ES is of a great challenge in designing and implementing appropriate management interventions.

Recently, forest management planning has expanded to accommodate multiple ecosystem services and attempted to address the impact of various management interventions on the sustainability of ES. Various ecosystem services such as 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), cultural values (Lundhol et al., 2020), soil erosion (Baskent, 2019; Rodrigues et al., 2020) and carbon sequestration (Backeus et al., 2006; Yousefpour and Hanewinkel, 2009; Dong et al., 2015; Yoshimoto et al., 2018) have been integrated into the forest planning framework. Among them, biodiversity conservation has often been treated with utmost importance due to its direct influence on the provision of other ecosystem services (Felton et al., 2016; Löf et al., 2016). Some researchers have indicated that increased management intensities often reduce indicators for biodiversity conservation such as reduction in species diversity and loss of habitat for target species (Verkerk et al., 2011; Duncker et al., 2012; Biber et al., 2015; Felton et al., 2016; Lindbladh et al., 2017). Among them, however, Biber et al. (2015) has asserted that depending on the forest region, biodiversity can also react positively to increased management intensity. Others also have indicated that more areas for habitat for biodiversity are closely related to other ES and ecosystem functions (Mace et al., 2012). While direct quantification of biodiversity is quite cumbersome, some proxy indicators have been used to characterize the habitat for biodiversity (Felton et al., 2016; Baskent, 2020).

Water provision, recreation and soil protection have long been considered to play a critical role in forest management planning (Forestry Commission, 2011), particularly in Turkey. Some indirect measures have been used to quantify and assess the flow of groundwater runoff over time (Bent, 2001; Bettinger et al., 2007; Hubbart et al., 2007; Maes et al., 2013; Baskent, 2019). The level of water provision is found to be highly dependent on forest composition (e.g., species mix, crown closure and development stages) and ecoregional characteristics (e.g., climate conditions) as well as management intensification (Anonymous, 2014; Baskent et al., 2020; Bentley and Coomes, 2020). Soil erosion, on the other hand, is largely related to the rate of forest cover change over time, topography and highly sensitive to the degree of felling, renewal and afforestation activities (Baskent, 2019; Rodrigues et al., 2020). Cultural values are often characterized by a set of combined index representing various features of recreational characteristics, the scenic quality and beauty of forests (Tveit et al., 2006; Edwards et al., 2012). Lundholm et al. (2020) have shown some variations in cultural indicators, which are greatly influenced by the extent of harvested areas. By and large, management interventions are to be carefully designed and implemented in a forest management plan to provide sustainable supply of multiple ES over time.

Closely related to forest cover and composition, carbon storage plays an important role in mitigating the climate change effects and has become a critical ES in forest management planning. (Yousefpour and Hanewinkel, 2009; Dong et al., 2015; Yoshimoto et al., 2018). In Turkey, the carbon density in above- and below-ground biomass, is around 41.66 Mg carbon ha^{-1} which is slightly lower than that in the forests of Europe (43.90 Mg ha^{-1}) (UN-ECE/FAO, 2006; Baskent and Keles, 2009; Tolunay, 2011). Great efforts of afforestation and rehabilitation activities have been employed towards mitigating climate change impacts and soil erosion, besides contributing to the future biomass accumulation and cultural values. Forest management policies and regulations are formulated basically for effective forest protection and rehabilitation of the degraded forests through increasing afforestation/reforestation activities and forest renewal, supported by the ecosystem based multiple use forest management initiative (Baskent et al., 2008; Creutzburg et al., 2017; Anonymous, 2015).

Accommodating several ES in a forest management planning context requires a sound decision support system (DSS) to analyze the level of ES trade-offs under various management scenarios (Nordström et al., 2011; Pukkala. 2014; Vacik et al., 2015; Borges et al., 2017; Nordström et al., 2019). Furthermore, assessing the dynamics of ecosystem services over time and understanding the long-term effects of different planning alternatives on the level of ecosystem services with the appropriate set of indicators and DSS are essential to design multifunctional forest planning and avoid adverse consequences on the forest composition, structure and the planning outcomes (von Gadow, 2004; Eriksson et al., 2014; Baskent 2020; Lundhol et al., 2020; Mozgeris et al., 2021; Roces-Díaz et al., 2021). In fact, decision support tools (i.e., models) have been widely used in forest management planning since the 1980s to forecast forest development, understand the forest dynamics and ensure the sustainability of forest ecosystems (Reynolds et al., 2008). The DSSs have now been improved to address spatio-temporal analysis of interactions among various ES such as biodiversity, carbon sequestration, water quality and cultural values under different management practices and assess the suitability of management alternatives for an optimal mixture of ESs (Bettinger et al., 2017).

Current researches dealing with the integration of various ecosystem services such as biodiversity conservation, timber production and water provision have generally focused on the straightforward discrete incorporation of a few ES into the planning, often overlooking the trade-offs among them (Vacik et al., 2001; Gustafsson and Perhans, 2010; Angelstam et al., 2011; Ezquerro et al., 2016; Lindbladh et al., 2017; Baskent, 2019; Nordström et al., 2019). Some research initiatives, however, have presented the potential impacts of different planning alternatives on a variety of ecosystem services (Bettinger et al., 2007; Keles and Baskent, 2007; Keles and Baskent, 2011; Schwenk et al., 2012; Pukkala, 2014; Vacik et al., 2015; Irauschek et al., 2017; Mina et al., 2017, Blattert et al., 2020; Temperli et al. 2020). Most of the researches focused on a design and implementation of different set of management treatments at various intensities or rates. Conventionally though, conservation, less intensified management regimes and longer rotations have been theorized as attractive forest management strategies to better manage the forest ecosystem for a majority of the ecosystem services. For example, carbon sequestration and density can be manipulated with careful design of management interventions; i.e. treatment rates and rotation lengths (Jandl et al., 2007; Yousefpour et al., 2018). Blattert et al. (2020) showed a strong trade-off between biodiversity and carbon sequestration, indicating a combination of locally adapted management scenarios to guarantee a higher degree of multifunctionality and long-term timber supply. Mina et al. (2017) and Nordström et al. (2019) found that the impacts of climate change-related management scenarios on a few ecosystem services were highly heterogeneous depending on the region, site and future climate. They indicated a design of management regimes to be regionally adopted to the site conditions. Similarly, Irauschek et al. (2017) developed some management strategies with varying cutting pattern size, return interval and climate change options and found that no single management alternative performed best for all ES together, indicating that trade-offs among ES was substantial and site-specific. However, there are still limited initiatives regarding the long-term projection and exploration of the effects of high rates of management activities (e.g., afforestation and silvicultural treatments) on the sustainable supply of prevailing ecosystem services such as soil protection, timber production, carbon stock, cultural values, habitat for biodiversity and water provision (Nordström et al., 2016; Baskent, 2019; Nordström, et al., 2019). Such an observation is essential for the comprehensive assessment of forest management scenarios in terms of multiple-use or ecosystem based forest management planning. The challenging task is, therefore, to develop site specific forest management planning scenarios focusing on the understanding of spatio-temporal dynamics and exploring the impacts of increasing rates of afforestation and silvicultural treatment regimes on a bundle of ecosystem services with a sound DSS tool in a forest ecosystem management context.

The objectives of the study are to develop forest management scenarios incorporating various levels of management intensities such as increasing treatment levels, various rotation lengths and afforestation rates, and to explore the impacts of the management alternatives on the long-term provisioning of ecosystem services using the ETÇAP DSS (Ecosystem Based Multiuse Forest Planning Model - Keles and Baskent, 2007) in the Hamidiye forest planning unit in Turkey. Specifically, the study focuses on analyzing the long-term impacts that intensified forest management will have on forest ES such as timber production, carbon stock, habitat for biodiversity, soil loss, cultural values and water provision by examining and understanding long-term forest dynamics. We hypothesize that the long-term impacts of intensified management interventions such as high levels of afforestation and high rate of silvicultural treatments will affect the provision of all ecosystem services and forest development over time.

2. Material and methods

2.1. Development of a decision support system (DSS)

The ETÇAP DSS was developed and used as a core decision making tool/model to forecast future forest development and assess the effects of management alternatives on the ecosystem services (Keles, 2008; Keles and Baskent, 2007). The core model was developed specifically for Turkish forestry, compliant with the state forest management policy and guidelines. The DSS incorporates various ES such as timber production, carbon sequestration, soil erosion, non-wood forest products, water production and habitat for biodiversity. With the exception of The Recreation Aesthetics Forest Landscape (RAFL) index (Lundhol et al., 2020) and some biodiversity measures, all ES indicators presented in this study were generated as part of the outputs produced by the ETÇAP DSS; the cultural and biodiversity ES indicators were the DSS outputs that were integrated to create the RAFL-index post-simulation. Posterior GIS functions were then used to calculate spatially explicit indicators such as patch size, patch density and largest patch size.

The ETÇAP model is a deterministic simulation based decision support tool, incorporating empirical growth and yield tables to project stand development after regeneration and an internal growth simulator based on the relationship between the inventory data and the empirical yield table to project current stand development. The DSS is based on a multifunctional forest planning concept with an area-volume control forest regulation method. It uses several harvesting policies such as even flow and non-declining yield, and harvesting and tending rules such as "highest yield first" and "oldest first" with user defined levels at a specific time in the future; altogether comprises a management scenario. Importantly, all stands are *a priory* stratified into the appropriate management units and analysis areas in order to design and apply a common silvicultural regime with a certain level of management interventions. Stands having similar compositions and serving similar potential set of ES are allocated to a homogeneous management unit where a similar management target and output can be set. Management prescriptions are applied on the analysis area composed of either a single stand or a group of homogeneous stands within each management unit. The DSS allocates the management prescriptions with the defined rules, levels and limits to the appropriate forest stands and generates outputs based on multiple objectives (Keles and Baskent, 2007).

2.2. The case study area

Forest landscapes of Turkey are aggregated into geographically distinctive administrative regions with a unique forest management plan –called a forest planning unit (FPU). The case study area, one of the 1,419 FPUs, is in the Hamidiye FPU located in the Southeastern Plateau of Turkey (between $37^{0}29'40''$- 37^{0} $43'37''34^{0''}$ north latitudes and $34^{0}50'07''$- $35^{0}07'20''$ east longitudes). The area covers 40,433 ha, of which 19,009 ha are forested (9,713 ha productive, 9,296 ha degraded) (Table 1). There are 14,602 ha of bare forest land appropriate for afforestation actions in addition to degraded areas (e.g., crown closure less than 10%) that are subject to reforestation. The case study area is located in an upper Mediterranean region with a temperate forest type dominated primarily by Turkish red pine and Anatolian pine dominated coniferous forests with 4074 stands classified into 70 unique stand types. Specifically, the area has six primary tree species with two hardwood species (<1%) such as oak *(Quercus* spp.*)* and hornbean (*Carpinus* spp.) and five softwood species such as Anatolian pine *(Pinus nigra)* (19.9%), Red pine *(Pinus brutia)* (17.4%), fir *(Abies cilicica)* (6.4%), Cedar *(Cedrus libani)* (22.1%) and Junipers *(Junipers* spp.*)* (34.1%) (Anonymous, 2014). The elevation ranges from 880 m to 3,059 m a.s.l. and the average slope is about 44%. The area extents over the typical Mediterranean drought climate conditions. Mean annual temperature and total rainfall are about 13.5 °C and 587.2 mm, respectively (Anonymous, 2014). As overall management of forest resources in Turkey, the forests of the case study area have been historically managed for solo timber production, resulting in an unregulated forest structure due mainly to mismanagement of the area (Başkent et al., 2005). The forest structure (i.e., distribution of forest areas over age-classes) is dominated primarily by the mature and over-mature stages of forest development (>75%) with a very little area in young and immature stages of development in wood production oriented areas and vise-verse in conservation oriented areas. Such irregular initial forest structure provides difficult conditions for sustainable management of the forests at least in a short or medium term. Hamidiye FPU is a public forest managed exclusively by the state forest service in Turkey. The case study area is selected as the required up-to-date forest inventory data and spatial forest cover types are in place that represents a typical planning unit in the upper Mediterranean region and temperate forest type, which provides several ecosystem services and is sensitive to climate changes (FAO and Plan Bleu, 2018).

The Hamidiye forest planning unit is stratified into seven management units (aka working circles, Table 1, A-G), each representing a different set of management objective, ecosystem services, planning

Table 1

Classification of the case study area into various management units (Anonymous, 2014).

Management units (working circles)	Productive forests (ha) (*)	Degraded areas(**) (ha)	Total forest area (ha)	Bare forest lands(**) (ha)	Other areas (ha)	Total area (ha)
A:Max. round wood production (Red Pine)	258.9	16.4	275.3	0.0	47.9	323.2
B:Max. round wood production (Black Pine)	424.5	43.4	467.9	43.1	2.2	513.2
C:Nature protection	44.8	292.4	337.2	2,161.0	257.8	2,756.0
D:Wildlife protection	1,864.1	976.5	2,831.6	5.4	8.3	2,845.3
E:Wildlife development	5,281.5	4,852.7	10,134.2	7,026.0	3,426.3	20,586.5
F:Soil Protection	1,839.7	3,117.1	4,956.8	5,367.1	3,021.2	13,345.1
G:Recreation	0.0	6.7	6.7	0.0	57.6	64.3
Total	**9,713.5**	**9,296.2**	**19,009.7**	**14,602.6**	**6,821.3**	**40,433.6**

(*) Forest stands over %10 of crown closure is defined as productive primarily in terms of wood production ES.

(**) These areas are potential for afforestation (crown closure less than 10% and bare forest areas).

approach, silvicultural regimes and product types. In addition to timber production; nature protection, biodiversity conservation, soil protection and the provision of ecotourism and recreation are the primary forest management objectives and conservation targets. The management actions designed for wood production are restricted on erosion sensitive areas, riparian buffers, recreation areas and other areas subject to conservation targets (Anonymous, 2014). Unlike zoning approach, the management units are not spatially contiguous with strict bordering, and are designed to describe the most appropriate silvicultural prescriptions, paving way to achieve an overall objective of management planning. The case study area is selected and designed to contribute to appropriate provision of multiple ecosystem services, better understanding of forest dynamics and future design of management planning.

2.3. Management scenarios

A baseline and three other management scenarios are developed to analyze forest dynamics with six ecosystem services such as timber production, soil protection, water provision, habitat for biodiversity conservation, cultural values and carbon sequestration. The forest management specifications (i.e., policy, levels and rates) identified in the current management guidelines are followed with the differences indicated below. The rotation periods in conservation based management units (C through G) stay constant for all scenarios (Table 1). The forests of the Hamidiye case study area (CSA) under the four management scenarios are projected over 100 years with ten 10-year periods using the ETÇAP simulation DSS (Keles, 2008; Keles and Baskent, 2007). The management planning approach has employed the volume control method to generate even-flow production of harvested volume in each management unit with a 10% flexibility. The current forest management guidelines, however, restrict management actions into the first 10-year period with a user defined allocation of stands to management interventions and conservation. This confines one to explore the effects of various types, rules, levels and intensities of management interventions on the achievement of multiple objectives including management intensification. Compared to the current forest management guidelines in Turkey, this study focuses primarily on developing management scenarios to explore the consequences of various afforestation rates, treatment intensities and rotation lengths on the achievement level or amount of selected ecosystem services.

The characteristics used in the modeled management scenarios are;

- **BASE** (Current management scenario): The traditionally accepted rotation periods were replicated for all management units; 60 years in Red pine and 120 years in Black pine working circles (A and B) which are totally available for economic function. Around 9% of all suitable stands (200 ha period^{-1}) was subject to afforestation. On average, nearly 15% of standing volume is subject to commercial thinning at the available ranges of ages in economic based management units and 10% in conservation based management units.
- **LMI (**Low management intensity scenario); Rotation periods increased by 30% (80 years in Red pine and 160 years in Black pine working circles). Nearly 30% of all suitable stands (700 ha period^{-1}) was subject to afforestation. Stand tending stayed the same as the BASE scenario.
- **MMI (**Medium management intensity); Rotation periods increased by 20% (70 years in Red pine and 140 years in Black pine working circles). Almost 60% of all available stands (1,300 ha period^{-1}) was subject to afforestation. On average, almost 25% of total yield is subject to commercial thinning at the available ranges of ages in economic based management units and 15% in conservation based management units.
- **HMI (**High management intensity scenario): Rotation periods indicative of maximum yield (50 years in Red pine and 100 years in Black pine working circles) were used in this scenario. Almost all available stands (2,300 ha period^{-1}) were subject to afforestation. On average, almost 45% of total yield is subject to commercial thinning at the available ranges of ages in economic based management units and 25% in conservation based management units.

All scenarios have the same overall objective function of maximizing timber production over the simulation time horizon. Both the management interventions and natural disturbances such as wildfires and insects are assumed to be under control as there is a strict national forest policy to safeguard the forest ecosystems. All of the bare forest lands and the degraded areas are targeted to be forested in the HMI scenario over time to test the full potential of the case study area and create forest conditions for a variety of ecosystem services. Red pine, Anatolian pine, Junipers and Cedar are the natural tree species of the case study area and used in planting to maintain natural biodiversity and persist to the low precipitation condition (587.2 mm year^{-1}). Almost 35% of the afforested areas is afforested with Red pine, 35% with Anatolian pine, 20% with Junipers and 10% with Cedar. These rates are consistent with the natural rate of these species in the case study area. Normal stands are assumed to regenerate naturally after final harvesting without any lags. Across all scenarios, the silvicultural treatment regimens, indicated in the management guidelines, are applied to the appropriate stands. The management scenarios used the "*oldest first*" intervention rule in applying both harvesting and thinning interventions over time. Stands are determined to be available for thinning based on tree species, crown closure, site and development stages (i.e., forest age-classes). Specifically, the stands over 40% crown closure and not scheduled for final felling and conservation are potentially available for thinning across all management units.

3. Ecosystem services

3.1. Wood production

An internal growth and yield projection system within ETÇAP DSS was used to project the development of current stands over time, with and without interventions. However, empirical yield tables were used to estimate the growth and yield of future stands after regeneration or afforestation. Specifically, it was assumed that when a stand is regenerated or planted, it will follow the empirical yield curve pattern developed for all commercial species across the country. However, we assume all other stands to develop according to the in-house growth and yield projection system, developed by Keles and Baskent (2011) and adapted (i.e., calibrated) for the trees in the case study area based on the relative growth adjustment between the actual inventory data and empirical yield curve values. The DSS was able to estimate the necessary dendrometric attributes of all stands such as standing volume, basal area, increment and number of stems projected over time. Additionally, the net present value (NPV) was calculated based on the present value of all revenues from wood production minus the present value of all costs of silvicultural operations and transportation at different periods in the future, all discounted to the present by using the common discount rate in Turkish Forestry.

3.2. Carbon sequestration

Carbon pools considered in the DSS include four categories: i) living carbon both in above and below-ground biomass, ii) deadwood carbon from harvesting and natural mortality, iii) carbon stored in harvested wood products (HWP) and (iv) substitution of fossil fuels from using wood products. The carbon stored in litterfall and soil was not included due to both insufficient data and ambiguity in stock changes as a result of management activities (IPCC, 2006). Living carbon was estimated using the above and below-ground biomass growth based on IPCC guidelines and the country-specific parameters such as Biomass Expansion Factor (BEF), volume increment and C factor related to the major forest types (URL1, 2006; IPCC, 2006; Baskent and Keles, 2009;

Tolunay, 2011). Harvesting and mortality losses were used in calculating the biomass losses. The deadwood carbon and HWP were subjected to a decay function to represent decomposition of deadwood and degradation of HWP (Masera et al., 2003; Lundhol et al., 2020). Emissions from each wood assortment such as sawlog and pulpwood were estimated using half-lives of each wood product type regardless of species type (50 years for saw logs, 40 years for mining pole, 15 years for boards, and 10 years for firewood, bark and harvest residues) (Baskent et al., 2008; Baskent and Keles, 2009; Black and Gallagher, 2010; Lippke et al., 2011; Baskent, 2019; Lundhol et al., 2020).

Carbon flow in HWP comes from harvesting and the added potential of energy substitution of energy demanding products such as steel or cement or fossil fuel energy production (Sathre and O'Connor, 2010; Oliver et al., 2014). The management scenarios accept the inflows of HWP and allocation between HWP storage, energy or product substitution differently (Skog, 2008; Smyth et al., 2016). Various levels of allocation of HWP product to energy substitution are considered in the management scenarios. It is assumed that there is a higher allocation of saw logs and pulpwood to energy substitution and similar higher allocation of saw logs to wood based panels (WBP) in the MMI and HMI scenarios. It is also assumed that the 20%, 20%, 30% and 40% of harvest residues are used for energy under the BASE, LMI, MMI and HMI scenarios, respectively. Above all, the equations suggested by Lundholm et al. (2020) are used to calculate four main carbon pools in total carbon stock.

3.3. Water production

Water provision is generally represented by a number of indicators. They include annual surface water run-off, precipitation, annual quick and base flow, annual sediment loss and total nutrient export that are ideally measured by some practical parameters such as the percentage of shrubs and litter, vegetation removal and species composition to measure the water yield and flow (Maes et al., 2013). However, water yield (i.e., ground water runoff) is practically estimated based on the relationship with some stand parameters such as basal area which has been used as a fairly good indicator in determining the amount of surface water flow in forest ecosystems (Tecle et al., 1998; Kucuker and Baskent 2010; Keles and Baskent, 2011). The relationship is positive; high values of the indicator mean high values of ground water runoff.

The water yield model developed by Mumcu (2007) and used by Kucuker and Baskent (2010) for similar forest ecosystems with similar climate (i.e., temperature and precipitation) and topographic condions, indicated a fairly good relationship and is used in this study (1).

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

where WP: annual water production (Mg ha^{-1}).BA: residual stand basal area (m^2 ha^{-1}). And e:2.71828.

3.4. Soil loss

Soil loss by erosion is generally estimated by various approaches such as Revised Universal Soil Loss Equation (RUSLE) which includes some important parameters such as rainfall erosivity factor, soil erodibility factor, slope length factor, slope factor and cover management factor (Wischmeier and Smith 1978; Renard et al., 1997). Forest vegetation represented by tree species, basal area, mean diameter of stand, standing timber volume and the number of stems is the most influential factors of soil erosion. Among them, basal area has been found a significant and practical parameter in estimating soil erosion in a certain topography and climate conditions. Thus, the amount of soil loss by erosion is estimated in relation to stand basal area. The relationship is negative; low values of the indicator mean high values of the ES. Soil loss model developed by Yolasığmaz (2004) for similar forest ecosystems with the similar climate (i.e., temperature and precipitation) and topographic conditions indicates a fairly good relationship and is used in this study (2).

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

where SL: annual soil loss (Mg ha^{-1} year^{-1}).BA: residual stand basal area (m^2 ha^{-1}). and e:2.71828.

3.5. Biodiversity conservation

The provisioning of habitat for biodiversity conservation is assessed based on numerous forest attributes. They include volume of larger trees, coarse woody debris, volume of native tree species, mean stand age, forest renewal rate, species composition such as broadleaf tree species, tree species diversity, and proportion of older forest (Felton et al., 2016; Baskent, 2019; Lundhol et al., 2020). Furthermore, some measures related to the spatial configuration of stands defined by some landscape fragmentation metrics such as patch density, mean patch size and largest patch index have been used to contribute to the quantification of biodiversity ES (Baskent and Jordan, 1995; McGarigal and Marks, 1995;). For example, lower values of patch density and higher values of both mean patch size and largest patch index indicate less disintegration of landscape in terms of forest connectivity and habitat integrity, contributing better condition for biodiversity conservation. All these attributes are quantified and assessed at forest planning unit level using geo-processing functions of GIS, posterior to the simulation results.

3.6. Cultural values

The cultural services contributing directly to the social relations are represented by a diverse spectrum of attributes such as spiritual enrichment, cognitive development, reflection, recreation, and aesthetic experiences, all are non-quantifiable attributes (Tveit et al., 2006; Ode et al., 2008; Edwards et al., 2012; Giergiczny et al., 2015; Torralba et al., 2020). Thus it is quite cumbersome to develop a direct quantitative indicator for the cultural values. Here, the most commonly perceived aspect of the cultural ES such as the aesthetic value of forest for recreation is taken into account and a proxy index of Recreation Aesthetics Forest Landscape (RAFL), developed based on four abstraction levels such as concept, dimension, attribute and indicator (Tveit et al., 2006), is used as the cultural ES indicator (Lundhol et al., 2020). Since the composing attributes of RAFL index are different with different influences, they are scaled and averaged landscape-wise to have harmonized impact on the RAFL index, by determining the upper and lower limits of the indicator as suggested by Lundholm et al. (2020) (Table 2). In calculating the Shannon index, the percentage merchantable volume of each species in the landscape is used. Both the Shannon Index and evenness of tree size at landscape level are calculated using landscape average values (Mouillot and Leprêtre, 1999). The evenness of tree sizes at the landscape level is calculated by the percentage logarithmic estimate of each DBH class, summed and divided by the natural logarithm of the number of diameter classes.

4. Results

4.1. Forest structure

The apparent change in forest development stages over the planning horizon was the replacement of regenerated areas with other developmental stages, highly pronounced in the MMI and HMI scenarios (Fig. 1). The area of regenerated forests decreased from around 58.0% in 2020 to 42.0, 24.0, 18.0, and 10.0% of the forest area by 2110 for the BASE, LM1, MMI and HMI scenarios, respectively. A similar trend was observed in old forests across all scenarios. Another observation towards the end of the planning horizon was that there was a gradual even

Table 2

List of indicators and attributes for all dimensions and concepts with the specific value functions including the upper and lower limits in averaging the score to create the RAFL-index (Adopted from Lundhol et al., 2020).

Concepts	Dimensions	Attribute (following template)	Indicator (units)	Direction of attribute	Value-function (Linear)
Stewardship	Sense of care / upkeep	Harvest residues	m^3 ha^{-1}	–	0 m^3 = 0, >=6 m^3 = 1
Naturalness / disturbances	Alteration/ impact	Area harvested (final felling area)	% of forest area harvested	–	0% =0, 5% = 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)		+	0.5 = 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 forest stand	–	0.001%=0, 5%=1,
Visual scale	Openness	Mean tree number	Stems ha^{-1}	–	800 = 0, 1500 = 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	Share broadleaves	% broadleaf volume of total	+	0% = 0, 6%=1,

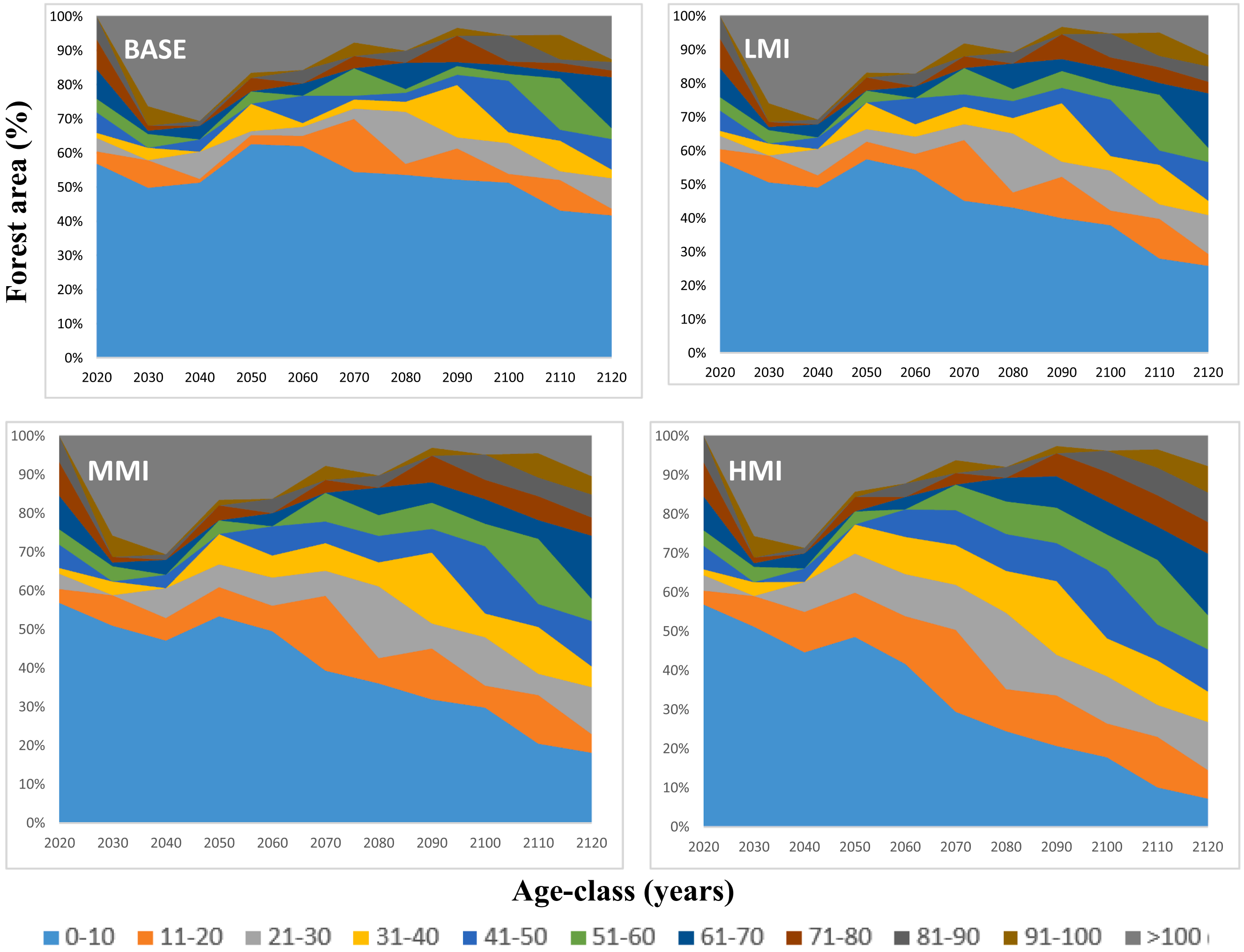


Fig. 1. Percent forest area (ha) by age-class over 100 years of simulation for four scenarios.

distribution of the age classes, particularly in the HMI scenario.

4.2. Biodiversity conservation

The management scenarios indicated a dramatic increase in growing stock (55 m^3 ha^{-1} current and 128–204 m^3 ha^{-1} in 100 years (Fig. 2a). The increase was mostly associated with both the regeneration activities and afforestation of degraded and bare forest stands with the primary species such as Calabrian pine, Anatolian pine, Junipers and Taurus cedar (i.e., 200 ha in the BAU scenario, 700 ha in the LIM scenario, 1,300 ha in the HMI scenario and 2,300 ha in the MMI scenario), providing better habitat conditions for biodiversity conservation. The rate of planting of these pioneer tree species proportional to their natural areas was necessary to maintain the natural forest composition and structure for biodiversity. Focusing on maintaining tree species composition consistent with the biodiversity goals of the country, the disturbance or turnover rate of forest renewal was not even throughout the scenarios and time periods considered. This allowed the user to control the volume to be harvested through regeneration activities from the desired species in each management unit (Fig. 2b).

The volume of large diameter trees (over 40, 50 and 60 cm, except 30 cm) per hectare increased in all scenarios, yet more apparent in the BASE scenario compared to the other scenarios where intensive management impacts were implemented (Table 3). The LMI and MMI scenarios resulted in a greater volume per ha for trees with DBH > 30 cm than the other scenarios by the end of the planning horizon. All scenarios resulted in a volume of trees with DBH > 40 cm between 3 and 7 m^3 ha^{-1} at the end of the planning horizon, with a sharp recovery from 2050 to the end of the planning horizon (Fig. 3a). Exceptionally, the volume of diameter trees DBH > 40 cm decreased in the HMI scenario (from 2020 to 2110). Towards the end of simulation, all scenarios resulted in a volume of trees with DBH > 50 cm between 1 and 4 m^3 ha^{-1}, the volume of trees with DBH > 40 and 50 cm increased by at least a factor of two in the BASE and LMI scenarios and very few large trees (>60 cm) were maintained in all scenarios.

The total volume of coarse deadwood volume due to natural mortality gradually increased (nearly doubled) in all scenarios (except the HMI scenario) over the planning horizon (i.e., from 0.47 to 1.23–1.64 m^3 ha^{-1}, Table 3). The coarse deadwood volume (DBH > 30) from natural mortality also marginally increased in all scenarios, except the HMI scenario with a slight decrease from 1.52 to 0.74 m^3 ha^{-1} (Fig. 3b). The increase indicated a moderately high levels of deadwood in the forest landscape, according to the model. Nevertheless, the development of deadwood over 30 cm was more or less stable for all scenarios except the HMI scenario.

The rate of broadleaved species (i.e., oak), which was quite low within the overall forest composition, experienced a gradual decrease over time in all scenarios (Fig. 4a). The average stand age decreased from 80 years to 60–70 years (Fig. 4b). Although the decreasing trend continues by 2080, as the old stands were harvested first, it recovered towards the end of simulation as regenerated areas and afforested areas improved the conditions later in the simulation. Specifically, the area of forests older than 80 years increased in all scenarios with varying levels at the end of the planning horizon; the total area increased from 1,285 ha in 2020, to 4,072 ha, 4,692 ha, 5,132 ha, and 5,708 ha in 2110 for the BASE, LMI, MMI and HMI scenarios, respectively (Table 3). More forest area entered this older age-class in the first half of the planning horizon (i.e., year 2020– 2060) than in the second half.

Patch density, as another parameter for biodiversity, decreased (from 16 to 11.81) and the mean patch size increased (from 6.25 ha to 8.46 ha) while the largest patch index remained the same for all scenarios over time. Such outcome indicated a moderate improvement in biodiversity conservation conditions for all the scenarios in terms of a spatial aspect of biodiversity (Table 3).

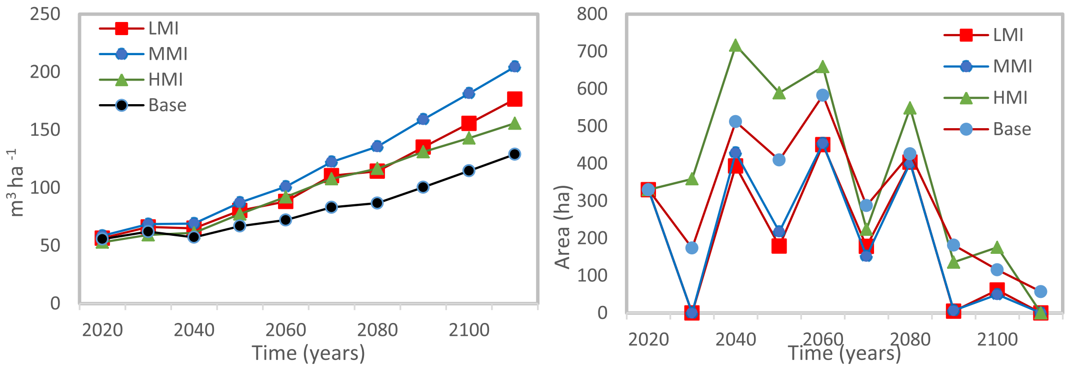
4.3. Water production

The forested areas increased gradually (Fig. 5a) with the afforestation of bare forest lands in all scenarios with varying rates, indicating a better condition for fresh (drinking) water production. While afforestation caused the average age to drop by 2080 (Fig. 4b), it was able to recover or increase from 2080 to the end of simulation as the existing forests became older. However, rehabilitation or regeneration of large degraded areas with commercial tree species such as Calabrian pine and Anatolian pine replacing understory vegetation (Fig. 5b) poses some concerns and risks of natural disturbances (i.e., wildfires) in the area.

The amount of ground water constantly decreased in relation to the gradual increase of basal area due to afforestation and quick recovery of underproductive stands, developing according to the empirical yield tables (Fig. 6). The outcome was also related to the steadily increasing rates of afforestation in the LMI, MMI and HMI scenarios. The higher production level of ground water in the BASE scenario, compared to the others, was also related to the lower harvesting amount yet higher final felling area and lower afforestation level (Fig. 2b and Fig. 9a).

4.4. Carbon sequestration

The net cumulative carbon storage (the added amount of carbon accumulation over time) in all carbon pools increased rapidly over the planning horizon reaching between 2 and 4.2 Mg ha^{-1} $year^{-1}$ for all scenarios, with less apparent increase in the BASE scenario (Fig. 7). The increase was greatly pronounced in the MMI scenario with a lower increase in the other scenarios. While the carbon balance (the net change of carbon storage in consecutive periods) was negative in 2050 in all scenarios, except the HMI scenario, it was recovered and improved in the later periods of the simulation. This would appear to be associated

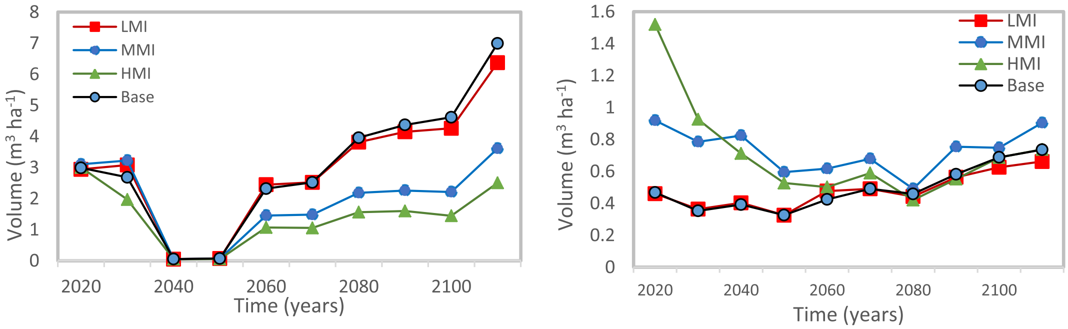


(a) (b)

Fig. 2. The development of total standing volume (a) and final harvesting area (b) over 100 years.

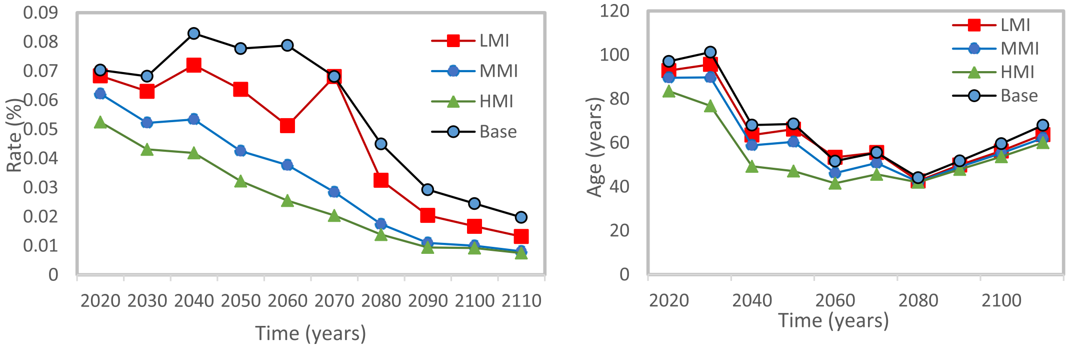
Table 3
The summary values of biodiversity indicators for the four scenarios; BASE, LMI, MMI and HMI, at three time points: 2020, 2060, and 2110.

Biodiversity indicators	Base			LMI			MMI			HMI		
	2020	2060	2110	2020	2060	2110	2020	2060	2110	2020	2060	2110
Volume (m^3 ha^{-1}) DBH > 30 cm	18.81	10.27	18.19	18.66	12.60	24.59	19.48	8.49	24.81	18.18	5.79	11.34
Volume (m^3 ha^{-1}) DBH > 40 cm	2.99	2.32	6.99	2.91	2.35	6.28	3.10	1.37	3.54	3.00	1.00	2.45
Volume (m^3 ha^{-1}) DBH > 50 cm	0.00	0.01	3.49	0	0.01	3.11	0.00	0.01	1.40	0	0.01	0.98
Volume (m^3 ha^{-1}) DBH > 60 cm	0	0	0,14	0	0.01	0.12	0	0	0.6	0	0	0.04
Coarse deadwood volume (m^3 ha^{-1})	0.47	0.75	1.35	0.48	0.77	1.23	0.93	0.97	1.64	1.54	0.80	1.27
Coarse deadwood volume (m^3 ha^{-1}) DBH > 30	0.46	0.42	0.74	0.47	0.48	0.66	0.92	0.62	0.90	1.52	0.68	0.74
Broadleaves volume share (%)	0.07	0.08	0.02	0.07	0.05	0.01	0.06	0.04	0.01	0.05	0.03	0.01
Volume (m^3 ha^{-1}) *Pinus brutia*	11.06	16.92	23.41	11.05	26.35	36.75	11.54	26.24	47.62	11.37	48.82	92.15
Volume (m^3 ha^{-1}) *Pinus nigra*	21.04	22.18	49.42	21.77	41.07	82.61	22.86	42.51	109.11	18.96	11.73	15.16
Volume (m^3 ha^{-1}) *Abies cilicica*	6.31	5.49	10.77	6.48	6.34	9.85	6.68	5.40	7.94	5.94	4.16	4.26
Volume (m^3 ha^{-1}) *Cedrus libani*	9.87	21.60	40.50	9.87	27.60	43.83	9.85	21.76	37.18	9.34	23.57	40.71
Volume (m^3 ha^{-1}) *Juniperus sp*	7.40	4.26	2.47	7.25	3.78	1.29	7.59	3.47	0.77	7.34	2.38	0.29
Volume (m^3 ha^{-1}) *Quercus* sp.	0.04	0.06	0.03	0.04	0.05	0.02	0.04	0.04	0.02	0.03	0.02	0.01
Areas of forest aged 61–80 years (ha)	3304	677	879	3304	677	1719	3304	677	2578	3304	677	4733
Areas older than 80 years (ha)	1285	3734	4072	1285	4083	4692	1285	4009	5132	1285	3350	5708
Alteration –final felling areas (%)	1.73	1.47	0.29	1.70	2.23	0.00	1.69	2.17	0.00	1.68	2.81	0.00
Hemoroby index (0–1)	0.45	0.48	0.74	0.44	0.52	0.75	0.56	0.63	0.79	0.65	0.61	0.81
Mean patch size	6.25	6.33	6.33	6.34	6.34	6.57	6.33	6.46	7.03	6.34	6.91	8.46
Patch density	15.99	12.66	15.79	15.79	15.79	15.22	15.79	15.48	14.22	15.78	14.48	11.81
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
Shannon species diversity (0–2)	1.52	1.41	1.33	1.51	1.35	1.23	1.51	1.33	1.13	1.53	1.18	0.99
DBH evenness index (0–1)	0.69	0.65	0.73	0.69	0.67	0.74	0.69	0.60	0.71	0.69	0.46	0.61



(a) (b)

Fig. 3. Largest stand volume over 40 cm dbh (a) and the deadwood over 30 cm dbh (b) over 100 years.



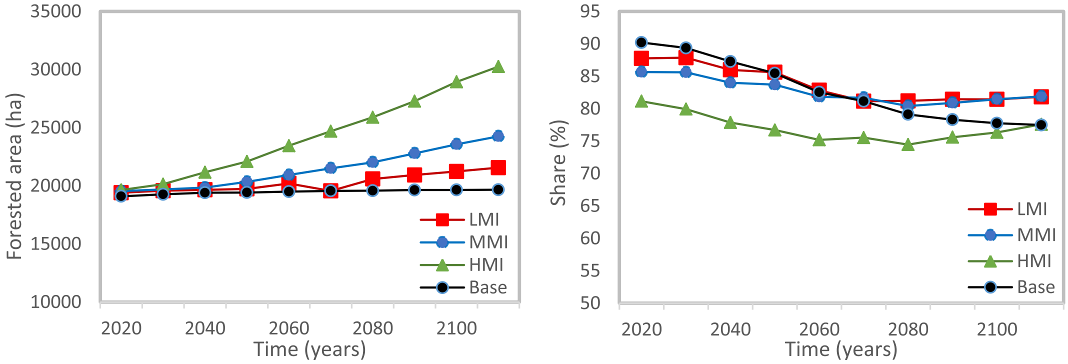
(a) (b)

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

strongly with a consistent increase in growing stock (from 50 m^3 ha^{-1} to 204 m^3 ha^{-1}) and increment (1.0 m^3 ha^{-1} year^{-1} to 3.7 m^3 ha^{-1} year^{-1}) over the planning horizon. Additionally, one of the reasons for the negative peak of carbon balance in 2050 might well be related to the decrease in volume of diameter trees DBH > 40 cm between 2040 and 2050 (Fig. 3a).

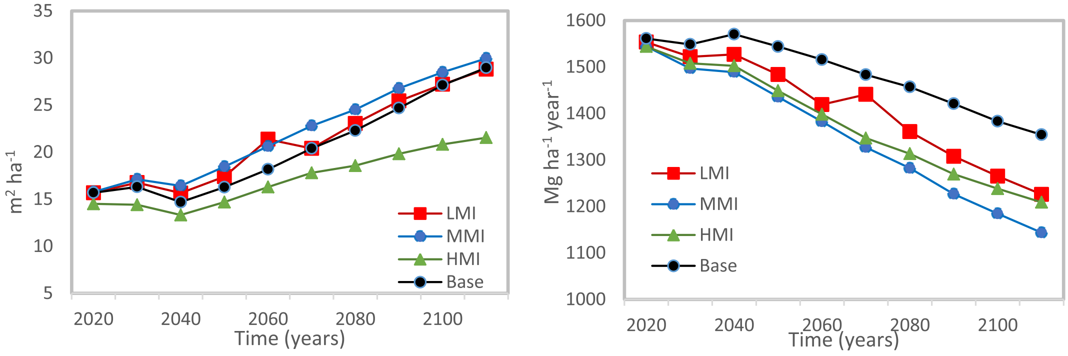
4.5. *Cultural attributes*

All scenarios resulted in a slight decrease in the RAFL-index over the planning horizon and there were no large differences in the final index values between the scenarios. The RAFL-index decreased from 0.56 in 2020 to 0.53, 0.51, 0.49, and 0.46 for the BASE, LMI, MMI and HMI scenarios, respectively (Fig. 8a). The changes of RAFL-index were



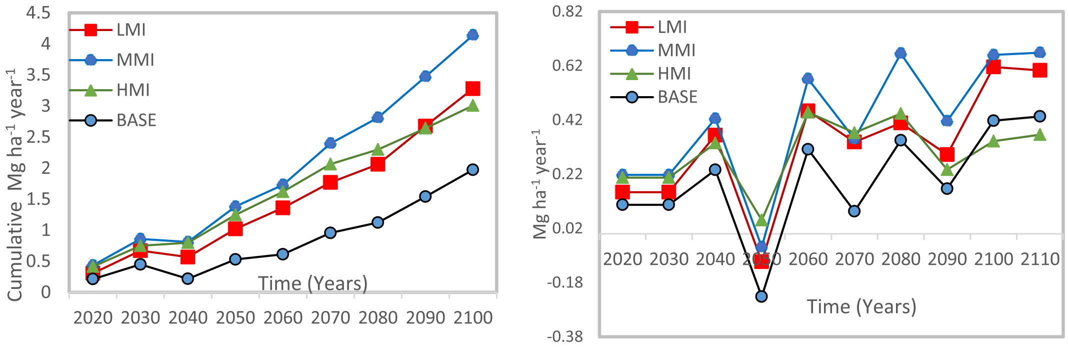
(a) (b)

Fig. 5. Temporal evolution of forest area (a) and the share (%) of understory (b) over 100 years.



(a) (b)

Fig. 6. Temporal evolution of basal area (a) and ground runoff/water production (b) over time.



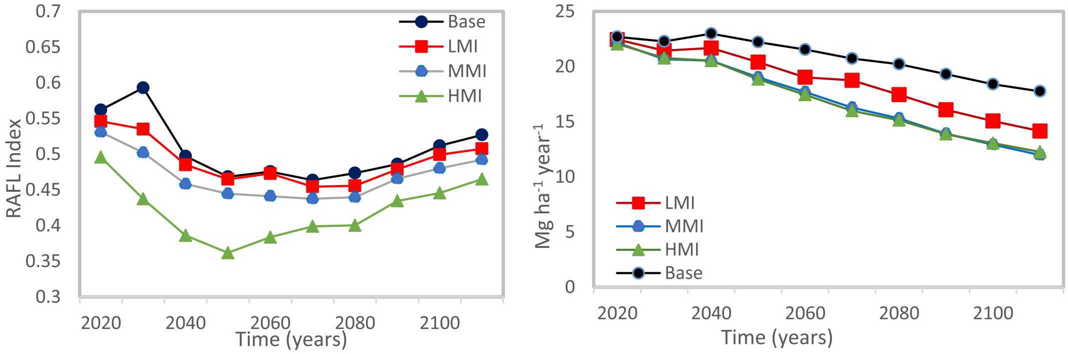
(a) (b)

Fig. 7. Cumulative stored carbon in Mg ha^{-1} year^{-1}, (a) and carbon balance in Mg ha^{-1} year^{-1} (b) over time. Dashed lines indicate the mean value for each of the four scenarios with the same color code.

mainly due to a combined effects of changes in forest composition, harvesting areas, and the volumes of harvest residue in the forest ecosystems. While the HMI scenario scored a consistently lower RAFL index value compared to the other, all scenarios experienced very similar changes in forest composition. However, total harvested area differed greatly between the management scenarios, - the HMI scenario experienced 21, 86, and 83% more total harvesting areas than the BASE, LMI and MMI scenarios, respectively.

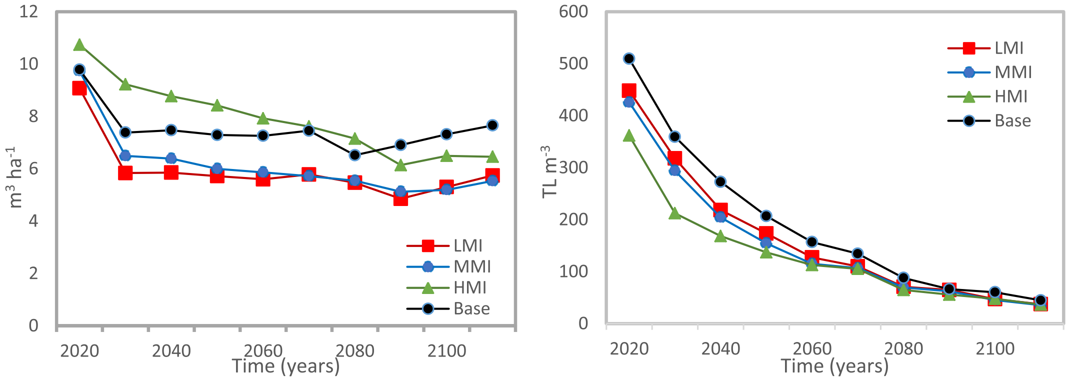
4.6. Soil loss

Among the forest management scenarios, the BASE scenario experienced the highest soil losses per ha per year throughout the planning horizon (Fig. 8b). Overall, however, the soil loss decreased from 23.1 in 2020 to 17.75 Mg ha^{-1} year^{-1}, 14.14, 12.25, and 12.25 for the BASE, LMI, MMI and HMI scenarios, respectively. Compared with the BASE scenario, soil losses in the LMI, MMI and HMI scenarios decreased by about 20.34, 30.98 and 30.98%, respectively. In all scenarios, however, soil loss continuously decreased over time in close relation to the improvement in basal area (Fig. 6a), although the amount was generally high due to high share of degraded and loosely covered forest composition in the case study area (Anonymous, 2014)).



(a) (b)

Fig. 8. Ten-year average RAFL-index, (a) and soil loss (b) over time.



(a) (b)

Fig. 9. Average harvested volume per ha (a) and net present value (b) over the planning horizon for the four scenarios. *Note: The unit value of a m^3 wood assortment is taken from the state prices in 2021.*

4.7. *Timber production*

All scenarios used current management guidelines and policies, referring to the volume control method. Thus, while the harvested areas were not regulated (Fig. 2b), the flow of harvested volume (Fig. 9a) was relatively stable over time in all scenarios due to even-flow harvest policy imposed in all scenarios. The trend in NPV, with 3% interest rate commonly used in Turkish Forestry, followed the general law of interest rate over time. However, the HMI scenario produced more timber volume, yet less NPV per m^3 as small size trees were mostly harvested due to intensive thinning rates.

4.8. *Summary of results*

The overall performance of all management scenarios was analyzed with the average supply of the ES over the planning horizon to evaluate and compare the achievement levels of ESs. Since all management scenarios aimed to maximize even flow of harvest volume over time with its NPV as objective functions, the indicators of various ecosystem services such as carbon storage, soil loss, water run-off, RAFL-index and Shannon diversity index might be compared to the harvest level and its NPV (Table 4). The NPV followed the trend parallel to the amount of soil loss and water production, RAFL-index and Shannon diversity index, in the order of the BASE, LMI, MMI and HMI scenarios. Such trend was quite logical as more areas were harvested, water production and the amount of soil removed by erosion (soil loss) were expected to increase, yet the recreational and biodiversity values were anticipated to decrease. Similar trend was also observed in other ES in such that as the harvested volume decreased, the cumulative carbon amount increased in the order of the BASE, LMI, HMI and MMI scenarios.

5. Discussions

This study integrated the effects of four different management scenarios on ES, including carbon sequestration, recreation, soil loss, water provision, habitat for biodiversity and timber production in a real case study area using an ecosystem based multifunctional forest management planning approach. ETÇAP DSS was used as forecasting and decision

Table 4
The mean values of various indicators of ecosystem services for the four scenarios over 100 years of simulation: cumulative carbon storage change, soil loss, ground water run-off, RAFL index and Shannon diversity index, in addition to some performance indicators such as NPV, harvest volume and harvested area.

Scenario	NPV (TL m^{-3})	Harvest volume (m^3 ha^{-1})	Area harvested (%)	Cumulative carbon storage (Mg year^{-1})	Soil loss (Mg ha^{-1} year^{-1})	Water prod (Mg ha^{-1} year^{-1})	RAFL-Index	Shannon diversity index
Base	189.88	7.50	1.58	1.60	20.81	1483.85	0.51	1.42
LMI	161.49	5.92	1.00	2.45	18.65	1410.55	0.49	1.36
MMI	151.27	6.15	0.99	3.03	17.04	1351.13	0.47	1.30
HMI	130.21	7.89	1.65	2.82	16.99	1377.74	0.42	1.22

making tool in this study to integrate ES and assess the performance of various management alternatives (Keleş, 2008; Borges et al., 2017; Baskent et al., 2020). While the planning approach developed with the DSS was applied to a CSA in Turkey, the basic methodology could well be applied in any other countries or regions with similar ecological conditions. However, the locally relevant indicators of ecosystem services and parameter settings under national political and legislative guidelines might need to be calibrated.

Several indicators could be used to assess the status of habitat for biodiversity conservation (Schwenk et al., 2012; Maes et al., 2013; Baskent, 2020). In our study, the majority of biodiversity indicators such as the largest stand volume, the basal area, the older areas, and the DBH evenness index increased over time in all planning scenarios, except the high intensity modelled scenario. On the contrary, the deadwood, the share of broadleaved species, as well as the mean stand age slightly decreased due to the management interventions, resulting in a less favorable condition for biodiversity conservation. Overall, the biodiversity indicators were not greatly affected by the intensive management scenario as it was not directly influenced by the objective function of maximizing total harvested volume. The increases in biodiversity indicators resulted generally from increasing afforested areas and the large diameter trees in older stands, either due to setting more areas in conservation oriented management units or replacing the poor yielding stands with the high yielding stands (thus lower clear-felling areas) by regeneration activity. This outcome would be quite promising given the fact that the old forests were at least maintained and gradually improved. In fact, lower clear-felling rate and higher conservation areas also caused the area of older forest to increase in all scenarios. Interestingly, nearly 84% of the total large diameter volume was deposited in trees with DBH 30–40 cm across all scenarios, similar to the results by Lundholm et al. (2020).

As in other forest management settings, forest management planning in Turkey focuses on developing management scenarios to protect target species and habitats and to generate less fragmented forest structure (Anonymous, 2004). Although the share of broadleaved species is minimal, there are few other broadleaf species such as hornbeam, maple, plane and poplar in the database that are opted out in the forest projection system as they are sporadically distributed over the area and the forest management guidelines do not show tree species contribution less than 10% (Anonymous, 2008). However, current planning guidelines also promote the conservation of old forests, natural species composition including the rare broadleaved species, important bird and plant areas, alpine forest zones, riparian buffers in addition to the legally identified protected areas to improve the status of biodiversity in the region.

Natural mortality volumes increased in all scenarios, as the volume in all commercial trees increased over time except Junipers and Oak. Increases in biodiversity indicators were also considered to contribute to the improvements in the provision of most of other ESs (Lefcheck et al., 2015). Thus, sacrificing a small amount of harvested volume by implementing relatively low intensive management scenario could lead to increased biodiversity and multifunctionality of forests. Furthermore, the individual tree species and understory vegetation were maintained during management activities, small forest openings were left out, natural composition of forest stands was saved to circumvent any concern for biodiversity conservation (Barbier et al., 2008), promoted also by the current management guidelines. In terms of spatial configuration, a consistent increase in mean patch size and a gradual decrease in patch density in all scenarios led to unfragmented forest landscape pattern, indicating a promising future condition for biodiversity conservation. The intensified management actions as well as afforestation of bare forest lands had the potential effects on lowering landscape fragmentation. In terms of forest structure, the age-class distribution was largely affected by regular harvesting events that renew the stands at the cutting age and afforestation activities throughout the simulation in all scenarios. A potential trade-offs derived from the HMI scenario, for example, was that lower diversity of age-classes would result in higher vulnerability of forest ecosystems for biodiversity conservation.

Except the BASE scenario in 2050, all scenarios created positive carbon balance over 100 years indicating a total carbon sink in the Hamidiye FPU. These favorable conditions could be related to age-class shifts towards mature stands (Fig. 1), the increase of productive forest areas (Fig. 5) due to afforestation of degraded stands and bare forest lands, and regenerated stands growing in optimal conditions with empirical yield curves. As well, the forests becoming a carbon sink might well also be due to continuous increase in volume increment and a low level of clear-felling towards the end of the planning horizon in all scenarios. Such positive trend was consistent with national projected forest carbon 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) and the findings by Böttcher et al. (2008). Overall, the carbon sequestration capacity of Turkish forests has been mainly enhanced by the gradual increase of forest area as well as their productivity over the last three decades as forest policy shifted towards ecosystem based multifunctional forest management philosophy (Baskent et al., 2008; Baskent, 2019).

The differences in the total carbon balance as well as cumulative carbon increases among the scenarios, however, were related to a higher increase in standing volume and volume increment in all other scenarios (highest in the MMI scenario, from 1.5 to 3.7 m^3 ha^{-1} year-1 in 2110), except the BASE scenario, higher allocation of harvest to energy production for the LMI and MMI scenarios and higher allocation of harvested products into long-term HWP pools (Baskent, 2019). Similar results were observed in Baskent (2019), Lundholm et al. (2020) and Mozgeris et al. (2021) where they projected climate driven management scenarios, indicating that total carbon balance remain positive over a hundred years. However, Lundholm et al. (2020) and Mozgeris et al. (2021) cautioned that steadily increasing harvesting and decreasing forest productivity caused a small decrease in carbon balance in the long future. Similar caution was reflected by Carpentier et al. (2017) that the intensive management scenarios yielded greater timber volumes but resulted in the weakest carbon and habitat quality scores. Nevertheless, certain level of trade-offs exists between the parameters such as volume increment, the natural mortality, harvest levels and afforestation. For example, Valade et al (2017) found that while reducing the harvest would increase the net forest sink in the short to medium term (2030–2050), it would slow down forest growth in the long-term, with a likely consequent decrease (saturation) in the net forest carbon sink at stand level (Smyth et al., 2020). Therefore, the results should be cautiously interpreted due to such some limitations on the trade-offs between the parameters affecting the carbon balance over time.

Both soil loss and ground water production processes continuously decreased over the planning horizon as a result of steady increase of basal area due to gradual increase of afforestation and stand productivity after regeneration. The management scenarios provide opportunities to reduce the risk of soil erosion and regulate ground water runoff, to a greater extent. It is apparent that intensive management scenarios protected higher amount of soil (i.e., less amount of soil loss) than that of the BASE scenario, although the regenerated areas loss their forest cover for a certain period and in consequence their erosion risk is high for a while. This mainly issues from the fact that the BASE scenario harvested less amount of areas with lesser amount of volume harvested over time horizon. As expected, high rate of afforestation in both the MMI and HMI scenarios results in less amount of soil loss than that of the LMP and BASE scenarios. Overall, the projection of future forest developments with the planning scenarios allows better production of ground water and soil protection over time as pointed out by Baskent (2019). The differences among the output of management scenarios, however, expand towards the end of simulation due to the increasing levels of afforestation, thinning and harvesting with a better performed future stand development after regeneration and thinning. This result is consistent with the fact that increase of forest area or stand development shows lower levels of runoff or ground water (Bentley and Coomes 2020;

Roces-Díaz et al., 2021). Thus, temporal changes of ES are mainly driven by stand or forest development, requiring extensive studies to explore the causes of changes in forest structure over time in relation to various ES (Roces-Díaz et al., 2021).

While water quality was not directly assessed, some indirect cautions were considered as part of overall management scenarios. For example, the management guidelines ensure the provision of riparian buffers around all season streams, lakes and wetlands to maintain the wildlife habitat and contribute to increase water quality (Baskent, 2019). Specifically, the high turnover rate of forest openings and degraded areas (crown closure less than 10%) with afforestation and speed replacement of them with productive regenerated stands enable to regulate water quality. It is important to note that multi-functionality levels of low-productivity forests is not always lower in comparison with very productive forest landscape (Jönsson and Snäll, 2020). However, this is a rather qualitative assessment of water quality and a quantitative assessment of fresh water dynamics is needed to forecast the future forest conditions with respect to water quality as explored by Lundholm et al. (2020. Long rotation periods in management units allocated for conservation targets help increase quality water provision as stands develop more towards overmature stages of development to support conditions for water quality. Furthermore, certain criteria and indicators have been used in determining *a priory* hydrologic management units where light silvicultural interventions are applied to improve water quality (Pamukçu et al., 2020). In fact, maintaining natural distribution of development stages and species composition along with thorough stratification of areas for appropriate forest uses create better opportunities for better water management (Anonymous, 2014; Subramanian, 2016; Daniel et al., 2017). It is crucial, however, to highlight that the temporal changes of forest cover have potential positive and negative effects on water provision. Increase of forest cover will affect hydrological cycle and causes increase in water interception and retention, reducing the amount of runoff water. Although this has a positive side, the amount of water available for human use is reduced. This trade-off among blue (runoff) and green water (evapotranspiration) shows a more complicate picture of water provision ES and requires extensive analysis of water-forest cover interactions, particularly in the presence of climate change (Bentley and Coomes, 2020; Mastrotheodoros et al., 2020; Roces-Díaz et al., 2021).

Generally, there was a small decline in the first half of the simulation and a gradual improvement in RAFL-index values over the planning horizon in all scenarios. The sharp decrease was mainly due to starting harvesting from the older forests first and an increased area of mature and over-mature stands that were regenerated or afforested early in the simulation. Initial harvesting followed by planting increased the number of trees per hectare, reduced the average stand age and increased the volume of harvest residues, all causing lower values of the RAFL-index. However, the apparent smaller yet parallel progression of RAFL-Index in the HMI scenario over time can well be attributed to the higher thinning intensity and shorter rotation period used in the management units. In other words, unthinned Red pine and Anatolian pine stands contained more natural mortality volume causing the wilderness score to increase in other scenarios.

There are a series of caveats and limitations derived from the approach used in the study to consider in understanding forest dynamics. The overall results of the simulation do not guarantee optimal solutions and spatial layout of harvesting as inexact models and aspatial modeling approaches were used in planning. Disturbance regimes and their potential effects on forest ES were not included in the study. Both water provision and erosion control models are based exclusively on the basal area with relatively low determination of coefficients and the absence of the effects of disturbances on the model is a critical limitation. One caveat is that the RAFL-index was developed based on landscape averages and overlooked the potential high level contribution of some local areas with high aesthetic values and recreation activities (Lundhol et al., 2020). Similarly, the results should cautiously be interpreted as the limits for the RAFL-index attributes were set subjectively depending on the specific conditions within the CSA. Furthermore, the biological and economic risks and uncertainties were not considered in the simulation, leaving with an assumption that the modeling was deterministic. In determining the better estimation of total biomass, species based biomass models need to be developed and used for more accurate calculation of carbon stocks as also recommended by Baskent (2019). Furthermore, various climate change scenarios need to be projected and incorporated into the modeling approach using a DSS-based approach to evaluate the long-term potential climate change effects on various ecosystem services (Irauschek et al., 2017; Mina et al., 2017; Lundhol et al., 2020). Multiple harvesting systems and zoning or pre-stratification of forest landscape into a specific objective focused zones may well be explored as an alternative approach (Carpentier et al., 2017). Water quality needs to be measured with nutrient emissions of N and P from different land use areas and should be implemented in a DSS to model long-term forestry impacts on water quality and emission levels. Nevertheless, forest management scenarios need to be developed to find the best possible combination of ES provision levels using advanced decision making techniques such as goal programming, Pareto frontier and MCDA techniques (Kangas and Kangas, 2005; Borges et al., 2014; Marques et al., 2021).

6. Conclusion

Four management scenarios were developed and implemented with ETÇAP DSS to forecast and understand forest dynamics under various management intensities. The study was conducted in a real case study area representative of central Anatolian and upper Mediterranean forest ecosystems, based on the forest management guidelines in Turkey. The values of stated ecosystem services varied between the scenarios, primarily due to the level of harvesting, afforestation, rotation periods and treatment intensities. The largest differences in the values of ES between scenarios were observed in wood production and carbon storage, with smaller differences for ground water run-off, soil loss, biodiversity and cultural services. The scenarios demonstrated similar temporal trends due mainly to the overall objective function of maximizing timber production in the simulation approach. The current forest management guidelines and policies allowing a priory allocation of critical areas to either protected management units or multiple use management units impacted positively on several ES. Based on the results of the projections and the discussions some apparent conclusions can be highlighted below:

Intensified forest management actions powered by gradual increase of afforestation rates over time are the crucial parameters of forest dynamics, affecting the level of all ES over the planning horizon. However, strong effects of high intensity management with high rate of afforestation were not observed to be proportional to the level of ES, particularly wood production and NPV, due mainly to skewed or irregular initial age-class structure.

An impact of medium (i.e., near optimal) rotation periods was observed to have significant positive impact on carbon storage in the MMI scenario. However, the effect of short rotation with highest growth rate on carbon storage in the HMI scenario was not observed as produced small materials have short-term maintenance of carbon in harvested wood products. The total amount of harvest was the highest in the HMI scenario, as expected, due to intensive treatment and high level of afforestation over time.

Intensified afforestation of bare forest lands and degraded areas, and regeneration of current stands lead to more productive forest areas over time, causing important forest performance indicators such as basal area, growing stock and volume increment to help improve the associated ES over time in all scenarios.

The per ha sizes of wood assortments (particularly sawlog volume) strikingly decreased in all scenarios over time as smaller material was harvested and total forested areas increased.

In conclusion, the intensity of forest management interventions greatly impacts on the provision of ecosystem services. Thus, the premises or postulation for designing various management scenarios in this study relates to the fact that the impacts of types and intensities of management actions on forest development and ES are substantial. The novelty of the research relates to the fact that none of the planning alternatives can optimize all ecosystem services simultaneously; a variety of management intensification needs to be explored for each planning area before implementation and *a priori* stratification of a forest landscape with the primary ES as leading/governing management objective determined by the stakeholders may well be required as a prerequisite. Overall, our study provides new visions into the interactions among multiple ecosystem services, providing a valuable foundation to support decision making process for developing sound forest policies across the country. In fact, the forest management modeling tool allowed to better understand forest dynamics with respect to various ecosystem services including water runoffs, wood production, carbon storage, soil loss to erosion, aesthetic and recreation and habitat for biodiversity conservation. Accordingly, versatile decision support tools or models play a critical role to test the postulation and explore opportunities for the adaptation of appropriate future management actions. The capacity of forest ecosystems to be a net carbon sink is definitely associated with increased rate of productive forests, afforesting bare lands and degraded areas, and age-class alterations towards older development stages.

CRediT authorship contribution statement

Emin Zeki Baskent: 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 Statement

Data available on request.

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