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Controlling Spatial Forest Structure with Spatial Simulation in Forest Management Planning: A Case Study from Turkey

(Mengawal Struktur Hutan Reruang dengan Simulasi Reruang dalam Perancangan Pengurusan Hutan: Suatu Kajian Kes dari Turki)

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ABSTRACT

Decision Support Systems (DSS) is widely used to develop spatially explicit forest management plans through the integration of spatial parameters. As a part of this study, a simulation-based spatial DSS, the ETÇAPSimülasyon program was developed and tested in a case study area. The system has the capability to control the spatial structure of forests based on a geodatabase. Geographical Information Systems (GIS) was used to generate the database, using spatial parameters including opening size, block size and green-up delay in addition to other attribute data such as the empirical yield table and the product assortment table. Based on the simulation technique, a spatial forest management model was developed to link strategic planning with tactical planning on a stand base and to present results with a number of performance indicators. One important component of the model determined all spatial characteristics with spatial parameters and patch descriptions. A stand growth and yield simulation model (BARSM) based on the relationship between current and optimal basal area development was also generated to project future stand characteristics and analyze the effects of various silvicultural treatments. A number of spatial forest management strategies were developed to generate spatially implementable harvest schedules and perform spatial analyses. The forest management concept was enhanced by employing a spatial simulation technique to help analyzing the ecosystem structure. Spatial characteristics for an on-the-ground forest management plan were then developed. The model was tested in Altınoluk Planning Unit (APU) using a spatial simulation technique based on various spatial parameters. The results indicated that the spatial model was able to satisfy the spatial restriction requirements of the forest management plan.

Keywords: Block size; fragmentation metrics; green-up delay; opening size; spatial forest planning

ABSTRAK

Sistem sokongan keputusan (DSS) digunakan secara meluas untuk membangunkan pelan pengurusan hutan reruang nyata melalui integrasi parameter reruang. Sebagai sebahagian daripada kajian ini, simulasi berasaskan reruang DSS, program ETÇAPSimülasyon, dibangunkan dan diuji di kawasan kajian kes. Sistem ini berkeupayaan untuk mengawal struktur reruang hutan berdasarkan pangkalan data geo. Sistem maklumat geografi (GIS) telah digunakan untuk menghasilkan pangkalan data, menggunakan parameter reruang termasuk saiz pembuka, saiz blok dan lewat hijau-naik selain data atribut lain seperti jadual hasil empirik dan jadual pelbagai produk. Berdasarkan teknik simulasi, model pengurusan hutan reruang telah dibangunkan untuk menghubungkan perancangan strategik dengan perancangan taktikal di suatu asas dan membentangkan keputusan dengan beberapa petunjuk prestasi. Suatu komponen penting model menentukan semua ciri-ciri reruang dengan parameter reruang dan tampalan penerangan. Pertumbuhan dirian dan hasil simulasi model (BARSM) berdasarkan hubungan antara pembangunan kawasan asas semasa dan optimum juga dijana untuk projek ciri-ciri dirian masa depan dan menganalisis kesan-kesan rawatan silvikultur yang pelbagai. Beberapa strategi pengurusan hutan reruang dibangunkan untuk menjana jadual tuai reruang yang dapat dilaksanakan dan melakukan analisis reruang. Konsep pengurusan hutan ini telah ditingkatkan dengan menggunakan teknik simulasi reruang untuk membantu menganalisis struktur ekosistem. Ciri-ciri reruang untuk rancangan pengurusan hutan dirian telah dibangunkan. Model ini diuji dalam Unit Perancangan Altınoluk (APU) menggunakan teknik simulasi reruang berdasarkan pelbagai parameter reruang. Keputusan menunjukkan bahawa model reruang telah berjaya memenuhi syarat-syarat sekatan reruang rancangan pengurusan hutan.

Kata kunci: Lewat hijau-naik; matriks perpecahan; perancangan hutan reruang; saiz blok; saiz pembuka

INTRODUCTION

The crucial components of a forest landscape include structure (species composition with numerical distribution of stands) in addition to geographic configuration (size, shape, distribution, adjacency, opening size, proximity and core area of stands or patches over landscape). A true assessment of sustainable forest management requires quantification and control of the forest landscape structure.

Accommodation of these two comprehensive components of management planning requires the sound design and implementation of a forest-management modeling process. Information technologies such as Geographical Information Systems (GIS) and remote sensing along with decision-making techniques such as simulation, optimization and meta-heuristics provide excellent opportunities for designing and implementing a spatially feasible forest management plan.

Since the introduction of GIS in natural resource management, there has been a logical increase in the application of GIS to forest planning. The role of GIS technology in spatial forest planning has, however, changed significantly from the source of input to the analytical tool of spatial models. One vital function of GIS is the ability to address both absolute and relative locational issues and manage spatial information in digital form through a powerful connection between locational and attribute databases, i.e. a geodatabase. GIS has traditionally been used in forestry to store maps in electronic form and to make calculations to determine areas and distances. It was rarely used in spatial analysis and modeling. The concept of spatial forest management planning or spatial forest modeling was first developed by a number of researchers (Başkent & Jordan 1991; Jamnick & Walters 1993; Jordan & Başkent 1992; Sessions & Sessions 1991) through comprehensive application of the spatial analysis and modeling tools of GIS. In addition to the traditional aspects of forest management planning, spatial forest modeling focuses primarily on the quantification and control of spatial structure. Spatial objectives are achieved based on spatial constraints, with the goal of creating a target landscape over time (Kadıoğulları 2009; Korosuo 2013). However, if the spatial restrictions and/or objectives have not been accommodated in a forest planning problem and a subsequent spatial analysis is necessarily carried out, GIS is then only utilized to address these post-plan development issues. More recently, its use has been extended to analysis of potential land use and other complex problems which also have a spatial context. However, it is not uncommon to see GIS used as an input facilitator rather than as a spatial analysis and modeling tool. Spatial forest modeling calls for an extensive use of a geodatabase and the powerful functions of GIS, such as spatial analysis, modeling and display.

Forest management problems revolve around management objectives and constraints, most of which are spatially oriented. Management constraints, primarily relating to fragmentation or involving harvest size or adjacency issues, have dominated forest planning problems over the last 20 years. Adjacency and green-up constraints, which address the juxtaposition of harvests and habitat, are perhaps the single most widely-used spatial constraints in forest planning today. The use of spatial objectives implies that the sizes, shapes and juxtapositions of different forest stands and planned management operations are taken into account when designing a particular forested landscape (Başkent & Keleş 2005; Kurttila 2001).

Adjacency constraints related to spatial forest planning can be used to disperse or aggregate certain features. The constraints may be formulated as a 'unit restriction model' (URM) in the form of either a stand or a patch, usually represented by a polygon, or an 'area restriction model' (ARM) in the form of a group of stands adjacent to each other (Murray 1999). The URM refers to operational restrictions of any two adjacent stands or harvest blocks while the ARM specifies constraints that are valid for certain groups of spatial units, so that the specified open area limit will not be exceeded. The URM greatly simplifies the problem, as it ignores the importance of the desired size of each block and focuses solely on the adjacency of two blocks. Since the size of blocks in a forest may vary considerably, several small adjacent blocks can often be harvested without exceeding the maximum opening size and even a close proximity might not pose any adjacently problem. While it is relatively easy and straightforward to represent URM, ARM is more difficult and needs to be addressed, as it involves varying sizes of opening areas with certain green-up delays. An area-restricted model as suggested by Murray (1999) implies that adjacent management units can be scheduled for clear-cut harvest during the green-up period. However, this can be done only as long as the total size of the clearcut area does not exceed the maximum clearcut area (Kadıoğulları 2009). In addition to distributing the cutting, it is sometimes desirable to spread the characteristics of stands over different points in time. Spreading out the fire risk areas or those of habitat suitability are two examples. Thus, controlling spatial layout of either harvesting blocks or habitat patches in a forest landscape becomes paramount when designing and implementing a spatial forest management plan.

On the other hand, in spatial planning it is also essential to formulate and realize spatial objectives such as minimizing the number of patches and maximizing core areas. Here, a number of fragmentation indices or metrics can be utilized as management objectives to control the spatial configuration of either harvest blocks or habitat patches in a landscape (Korosuo 2013). Generally, various landscape metrics may be computed from the stand-level indices. Landscape metrics are variables that measure the sizes, shapes, relative arrangement and connectivity of habitat patches in the form of a stand or a group of adjacent stands with certain features as well as their total area (Başkent & Jordan 1995; McGarigal & Marks 1995). These metrics can be used as objective variables in forest landscape design. However, very few researchers have treated fragmentation metrics as management objectives in spatial forest planning. Therefore, there is a great need to control forest fragmentation proactively by using landscape metrics as direct management objectives rather than constraints or merely by-products.

Various management science techniques can potentially be used in developing a management model to control landscape fragmentation. Simulation models are commonly used to estimate future landscape conditions under various deterministic management strategies (Wimberly 2002) and to analyze historical landscape dynamics emphasizing stochastic natural disturbances (Morgan et al. 1994). Simulation and other similar techniques are generally considered for spatial requirements such as opening size (Başkent & Jordan 2002; Boston & Bettinger 1999; Caro et al. 2003; Clark et al. 2000; Clements et al. 1990; Crowe & Nelson 2003; Falcao & Borges 2002; Hoganson & Borges 1998; McDill & Braze 2000; Mullen & Butler 1997; Murray & Church 1995; Murray & Weintraub 2002; Nelson & Brodie 1990; Richards & Gunn 2000; Snyder & ReVelle 1997), core area (Başkent & Jordan 1995) and importantly patch-size distribution (Başkent & Jordan 1996, 1995; Liu et al. 2000; Nur et al. 2000). Optimization or near optimization techniques such as the branch and bound process (Borges & Hoganson 2000, 1999; Nelson & Brodie 1990) can be applied to model spatial adjacency problems using the ARM approach. However, pure or exact optimization techniques have not been used to solve larger spatial forest management problems when both spatial objectives and constraints are involved.

This study has attempted to develop a spatial simulation model under the decision support system of ETÇAP (Kadıoğulları 2009; Keleş 2008). The ETÇAPSimülasyon was used to assist in the formulation of forest management plans to control spatial forest structure with blocking size, opening size parameters and fragmentation metrics. The primary objective of this research was to examine the effects of one aspatial and four spatial forest management strategies on forest ecosystem development. The second objective was to predict the long-term effects of these policies on spatial forest structure by analyzing fragmentation metrics on patch, class and landscape scales.

Materials and Methods

ETÇAPSIMÜLASYON MODEL DESCRIPTION

The ETÇAPSimülasyon (Ecosystem-based multiple-use planning simulation) model was generated with an object-oriented design using Delphi language programming. The ETÇAPSimülasyon is a stand-based forest-level spatial decision support system (DSS) for assessing the effects of forest management practices on forest dynamics, functions and spatial structures. The effects of spatial parameters such as block size, opening size, green-up delay and landscape metrics, including proximity and patch size, can be analyzed from the viewpoints of total timber production, total harvested areas and fragmentation metrics (Figure 1). The ETÇAPSimülasyon is a regular deterministic simulation model consisting of a number of primary components: Data input, actions, and an output.

The model applied here is deterministic. It means that biological, ecological and economic risks are not involved in the modeling process. However, a collapse of a forest stand due to wind, insects, wildfire and fungi will affect the growth and yield of forest stands and some forest ecosystem values (i.e. timber production, soil and water protection, oxygen production and net carbon sequestration in terms of both in monetary values and quantitative amounts). For example, estimated prices of forest ecosystem values will change over time because of a number of factors such as climate change, population and economic growth. In addition, the empirical yield tables as used in this study do not often represent the actual development of forest stands over time as the conditions change with respect to various levels of silvicultural interventions, climate change and surrounding environment (Başkent & Keleş 2009; Başkent et al. 2014).

If stochastic events are incorporated into forest management planning process, the credibility, quality and realism of long term projections over large areas increases and the decision makers can better understand the relative risks of alternative forest management planning strategies for forest ecosystems (Başkent & Keleş 2009; Davis et al. 2001). Hence, planning models that incorporate the high levels of planning uncertainty in forest management should be designed in the future studies. In this context, stochastic events should be included in forest management planning, and on the other hand, growth and yield projection of forest stands under human-based or natural disturbances should be modeled on permanent sample plots. Again process-based growth and yield models could be considered as an alternative modeling approach (Başkent et al. 2014).

The data input includes all the required procedures to enter the spatial data (locational and attribute data) about initial forest structure, yield tables, economic revenues and costs, silvicultural regimes, adjacency tables and management policies. A forest cover type map with its attribute data is also required in order to use stand-specific information and calculate landscape metrics and to map out the spatial distribution of management decisions based on sub-compartment IDs.

The actions component refers to silvicultural prescriptions identified and applied for each stand type (sub-compartment) based on topography, site condition, species mix and management policies for the whole forest. A prescription is a series of silvicultural treatments or management interventions to be applied to each stand over a planning horizon. The performance of the model is highly dependent upon the ability to set up potential prescriptions on a wider perspective.

The model output component covers both the forest performance indicators as well as other regular results in the form of tables, figures and maps showing the temporal change of the forest structure. Performance indicators were used to evaluate the performance of a management strategy and compare it to another strategy. The model is able to present results at both landscape and stand level, i.e. the development and the history of an individual stand over time is recorded and presented. Defining management strategies in the model include spatial parameters and fragmentation metrics in addition to the regular information. A management strategy generally accommodates blocking rules (minimum block size, target block size and adjacency distance), opening rules (proximal distance, maximum opening size and green-up delay) and fragmentation metrics, class area (CA), number of patches (NP), largest patch index (LPI), mean patch size (MPS), patch density (PD), patch size coefficient of variation (PSCV) and landscape similarity index (LSI). The rules and the metrics were used to control the numerical and geographic distribution of patches over the landscape (Figure 1). Here, a patch is defined as a stand or a cluster of stands with certain conditions.

The functionality provided by ETÇAPSimülasyon may be interpreted as the generation and real-time visual display of different management strategies and alternatives over time. The results can be displayed in the formats of tables, graphics and forest maps. In order to increase the visual representation of the forest landscape, a module was created to analyze all values based on stands or stratification units, using GIS techniques in the ArcGIS program. Basically, all stand parameters including standing timber volume, volume increment, basal area, average height, average diameter at breast height (dbh) and tree number can be displayed in maps using the ArcGIS graph module. These parameters generally were saved in a database and then joined to stand type maps. Stand type parameters over the planning horizon could be analyzed based on stand type maps in ArcInfo 10.0™. In addition, all harvested, thinning and reforestation areas could be analyzed and shown on the map by using this module.

GROWTH AND YIELD PROJECTION

A stand growth and yield simulation model (BARSM) based on the relationship between current and optimal basal area development was also generated to project future stand characteristics and analyze the effects of various silvicultural treatments. This inherent practical growth and yield model was included in the ETÇAPSimülasyon in order to project the growth of each stand based on the relationship between the inventory data and the empirical yield table. Primarily, the basal area of a stand in the next period was predicted, based on the ratio of the current basal area to the optimal basal area of the same stand type. In the meantime, however, stands were not allowed to exceed the performance of the empirical yield tables. Additionally,

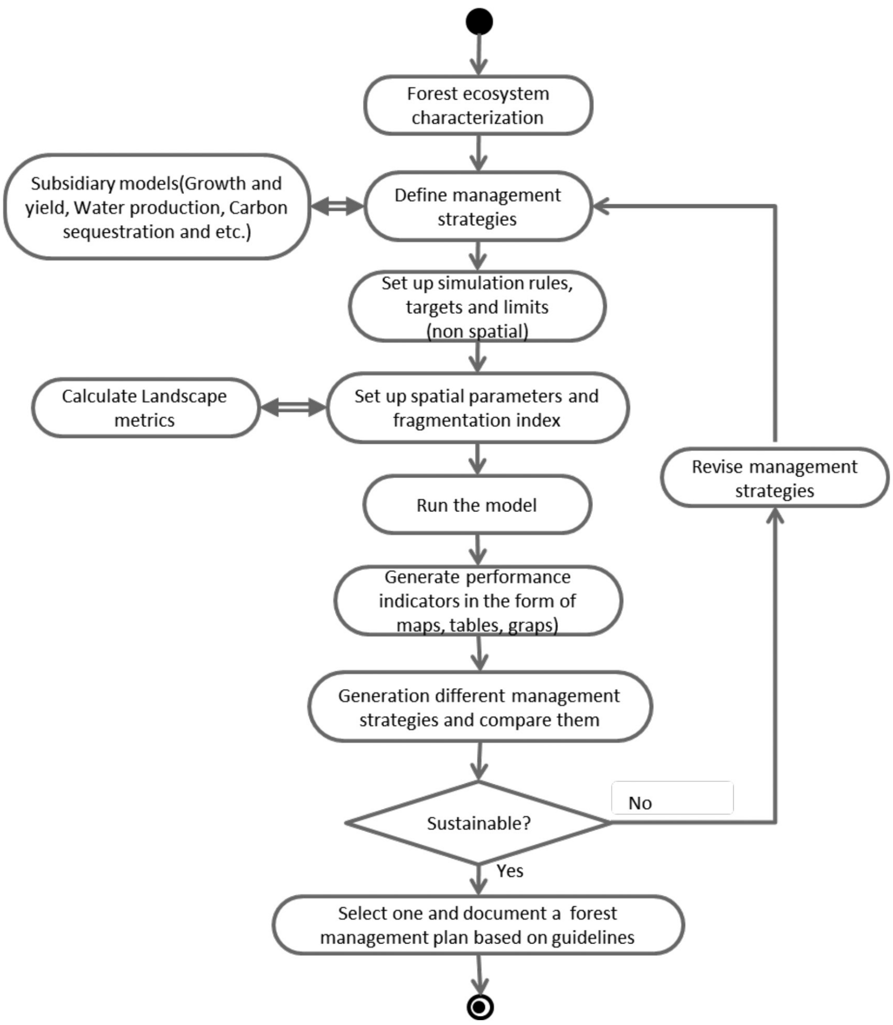

FIGURE 1. A typical process of forest management spatial simulation model of ETÇAPSimülation (Kadıoğulları 2009)

the response of interventions after thinning was accelerated by a variable (*k*) as the ratio of the normal basal area to the actual basal area. The yield tables were used to predict the growth of the regenerated stands (Başkent et al. 2014; Kadıoğulları 2009). Thus, the model estimated all stand parameters such as basal area, growing stock, timber volume increment, average height, average dbh and the number of trees. Regardless of final felling, the stands were assumed to terminate and regenerate naturally within the model as soon as they reached the age of mortality, as defined by the user.

SPATIAL PARAMETERS

Many spatial modeling strategies have been applied in forest management planning. Blocking factors (adjacent distance, minimum block size and target block size) and opening factors (proximal distance, maximum opening size and green-up delay) were used as spatial parameters in this model (Figures 2-4). Desired buffers for all sub-compartments (i.e. polygons) were set in the GIS and then the adjacency and proximity distances were calculated automatically by ETÇAP. For example, a user would be able to define varying adjacency/proximity distances of sub-compartments as 0.50 and 100 m. Then, multiple ring buffer maps would be created for the sub-compartments based on the user-defined distances. These maps provide the adjacency/proximity values of the sub-compartments. Adjacency/proximity data can be presented as a look-up table defined by the unique IDs of the sub-compartments. For example, Figures 2-4 show how to define block size, opening size and spatial parameters. In Figure 2, numbers (#19 and #13) show sub compartment ID and red color indicating the sub compartment has shown in the same harvest block by using different adjacency distance. Also, in Figure 3, numbers (#19 and #13) show sub compartment ID. Red and yellow colors indicate the different harvest blocks and it is defined in the same opening size area by using different proximal distance. Finally, Figure 4 shows how to define this spatial parameters in the ETÇAPSimülasyon program. A similar method was used to determine the full (0 m) and other varying adjacency distances for the

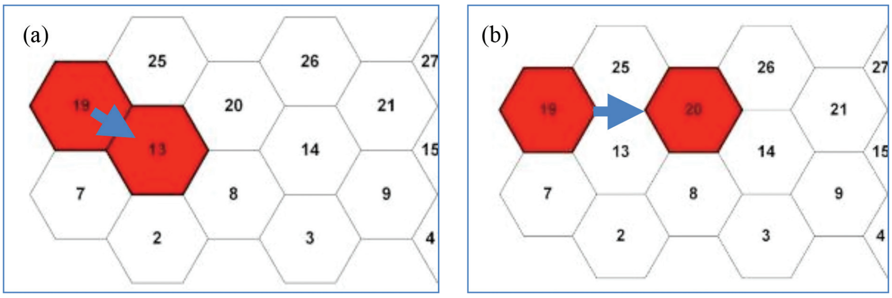

FIGURE 2. Defining harvest block size with different adjacent distances; 0 meters (a) and x meters (b) (Kadıoğulları 2009)

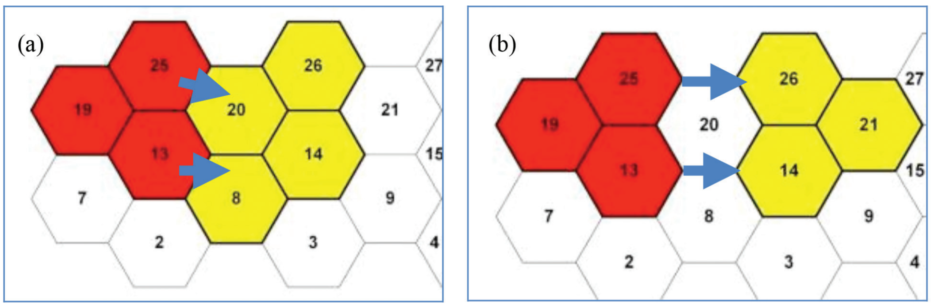

FIGURE 3. Defining opening size with different proximal distances; 0 meters (a) and x meters (b) (Kadıoğulları 2009)

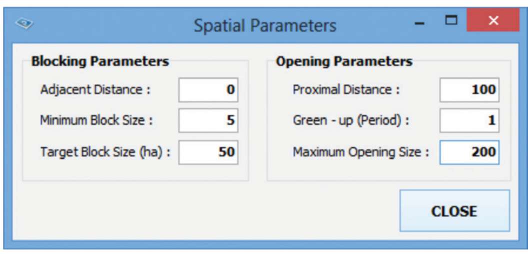

FIGURE 4. Defining spatial parameters in ETÇAPSimülasyon (Kadıoğulları 2009)

fragmentation analysis in order to calculate other related landscape metrics. In the ETÇAPSimülasyon model, the green-up (opening size) and block size constraints were enabled by using area restriction methods (Kadıoğulları 2009; Murray 1999).

FRAGMENTATION METRICS

The FragstatsTM (McGarigal & Marks 1995) is not comprehensive enough to accommodate adjacency/ proximity distances. Therefore, the ETÇAPSimülasyon model was equipped with functions to calculate fragmentation metrics at patch, class and landscape levels to analyze landscape fragmentation in any period of the simulation. In the ETÇAP model, distance-dependent patches and classes were formed based on tree species, land use type and forest stratification units defined by using age class, volume and basal area.

The landscape metrics that were used in the ETÇAPSimülasyon model were: Percent of landscape (PLAND), class area (CA; sum of the areas of all patches belonging to a given class, in map units), number of patches (NP), largest patch index (LPI; percentage of the landscape comprised by the largest patch), mean patch size (MPS; the average patch size within a particular class), patch density (PD; number of patches per 100 ha), patch size coefficient of variation (PSCV) and landscape similarity index (LSI; equal to the percentage of the landscape occupied by the same patch type as the patch and equivalent to PLAND) (Kadıoğulları 2009; McGarigal & Marks 1995).

CASE STUDY AREA

The study area of Altınoluk Forest Planning Unit is situated in the province of Balıkesir in western Turkey (Figure 5). The area consists primarily of mountain forests and scattered settlements with low-lying agricultural areas. The altitude varies between 0 and 1450 m. The region is covered naturally by *Pinus brutia*, *Pinus nigra* and *Quercus subs*., the most widely-distributed species in the country. Altınoluk Planning Unit covers an area of 12265 ha and 8234 ha of which is forestland. The total number of stands in forested areas is 1596, with an average size of 5.15 ha. Forest stand types in the study area are classified

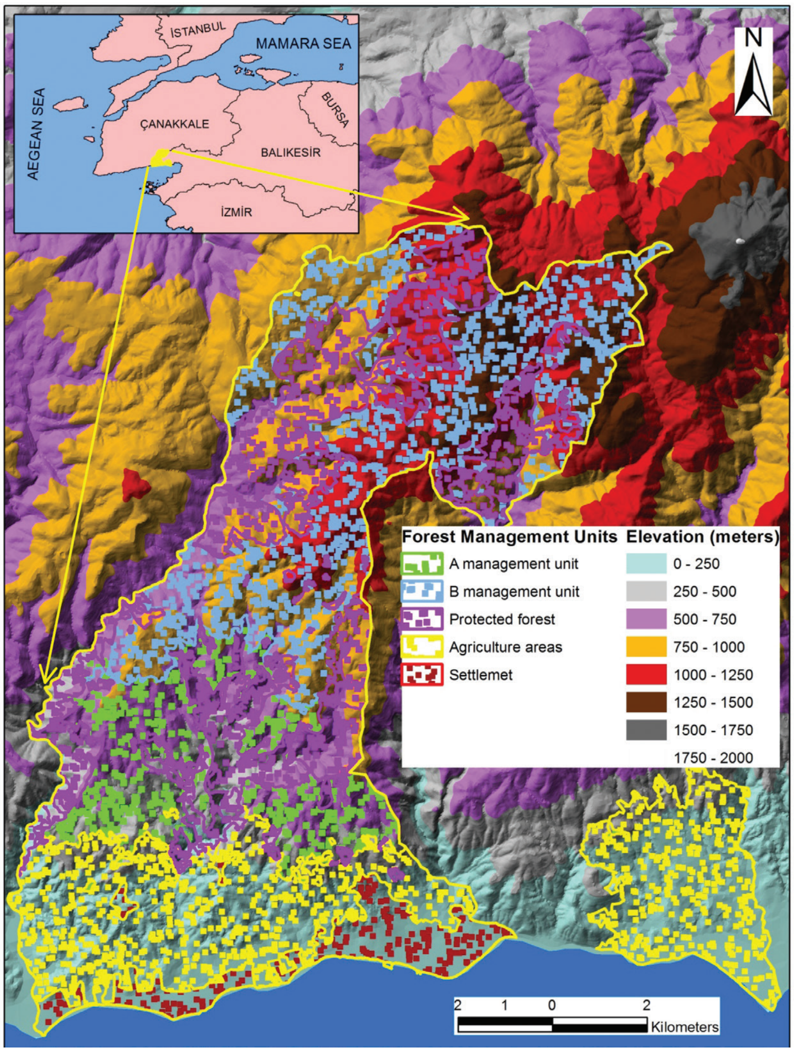

FIGURE 5. Geographic distribution of forest uses or management units in the case study area

according to the mixture of tree species, developmental stage and crown closure. Forest ecosystems were stratified into eight management units according to various forest values present in the study area such as timber production, biodiversity conservation, soil protection and aesthetic-recreation. Two management units (Management Unit A is dominated by *Pinus brutia* stands and Management Unit B is dominated by *Pinus nigra* stands), stratified primarily for wood production, were both subjected to regeneration and all other appropriate silvicultural actions. These management units have 5228 ha of forest areas with 1050 sub-compartments having an average size of 4.97 ha. Six other management units were primarily classified for protection and conservation of designated forest values and during the planning horizon they were to be subjected only to limited thinnings without final felling or regeneration.

FOREST MANAGEMENT STRATEGIES

This study focused on the analysis of the performance of the ETÇAP spatial simulation model in accommodating previously-defined spatial objectives and constraints. The analysis was conducted using a list of different management strategies with a mix of spatial parameters or with no spatial requirements. Therefore, based on the area control method, five major forest management strategies were developed in both aspatial and spatial simulation models (Table 1). The area control method focuses on the sustainability of harvested/regenerated areas over time to create an even age class distribution at the end of the planning horizon. Known as the optimal periodic area method, it includes, for flexibility, regenerated area flow constraints restricting the harvested areas to decrease or increase a maximum of the given proportion (here 5%) from one period to the next. For example, if the proportion is 0, then no deviation is tolerated between the two subsequent periods for periodical harvested areas. In all forest management strategies, the optimal periodic area for regeneration was calculated to be 180 ha for Management Unit A and 200 ha for Management Unit B. The minimum rotation or cutting ages were determined to be 60 years for all stands under Management Unit A and 120 years for the stands under Management Unit B. The maximum rotation age, however, was set at 120 years for all stands in both management units. These age limits define the operability window of the stands and are reference cases adopted from the Turkish Forest Management Guidelines for the timber-oriented forest management planning approach. Commercial thinning was designed for the timber production-dominated stands with a window of ages ranging from 30 to 120 years and in the conservation-dominated stands, ranging from 40 to 160 years. The ETÇAP simulation model used the 'oldest first' harvesting rule for all forest management strategies. The model applied commercial thinning actions to the forest stands within the thinning window at a rate varying at 4-10% of standing volume levels. All forest stands are subjected to harvesting unless they are stratified in protection or conservation-dominated areas. All forest values and stand parameters were estimated at stand level at the mid-point of each period. Regeneration of forest stands was assumed to follow immediately after harvesting and to develop according to empirical yield tables. The aspatial simulation strategy had no spatial restrictions, whereas the spatial planning strategies were created by changing spatial parameters such as opening size, block size, adjacent/proximal distance and green-up restriction values. In all spatial management strategies, within '0 m' adjacent, patches and classes based on forest stratification units were defined using 10-years-of-age class intervals.

RESULTS AND DISCUSSION

Among the results of the simulation-based forest management strategies, the aspatial (classic) strategy produced the highest amount of timber volume (2568963 m^3) over the planning horizon, including 809831 m^3 of thinning and 1758564m^3 of final felling. However, the SPT1 spatial strategy produced the lowest amount of timber volume (2430714 m^3) over the planning horizon (804077m^3 of thinning and 1626637m^3 of final felling). Among the spatial simulation strategies, the SPT4 strategy produced the highest timber production (2506773m^3) (Figure 6; Table 2).

The actual deviation of harvested/regenerated areas between successive periods was almost constant due to the constraint of the area control method. While the temporal trends of growing stocks of the five planning strategies

TABLE 1. Forest management strategies based on spatial parameters

Strategies	Adjacent distance (meters)	Minimum block size (ha)	Target block size (ha)	Proximal distance (meters)	Green up (period)	Maximum opening size (ha)	Adjacent distance for patch analysis
Aspatial simulation	No spatial restrictions included						
Spatial 1 (SPT1)	0	2	20	25	2	120	0
Spatial 2 (SPT2)	0	5	25	0	2	100	0
Spatial 3 (SPT3)	0	5	20	0	2	180	0
Spatial 4 (SPT4)	25	1	25	25	1	50	0

differed slightly from one another, they consistently increased in the first five periods and then decreased over the planning horizon. The trends of the basal area of the spatial forest management strategies (SPT1- 4) showed a similar pattern. However, the aspatial strategy exhibited a slightly higher basal area in some periods (Figure 6). It is logical that a higher level of area harvested in the aspatial strategy caused it to have a lower level of growing stock as well as basal area compared with the spatial strategies (Figure 6). The 25 m adjacency/proximal distance used to form harvest blocks and opening sizes could be considered as a kind of relaxation, as it was able to compensate for the effects of the lower level of opening size limit (30 ha in SPT4).

There were 1053 appropriate sub-compartments (5232 ha) for harvesting in the APB for over 120 years. While the aspatial strategy had the lowest total harvested areas (4586 ha) over the planning horizon, the level of the final harvest (1,758,564m^3) was the highest among all the strategies (Figure 6). In this strategy, 784 sub-compartments had been harvested over the planning horizon, but no action was assigned to 269 sub-compartments for final felling. All spatial strategies, on the other hand, regenerated more areas compared with the spatial strategy (Table 2). The model searched for different combinations of harvesting stands that complied with the spatial constraints, resulting in a larger number of harvesting areas. Many sub-compartments in Management Unit A (60 years), for example, were to be felled more than once in spatial strategies over longer planning horizons (Figure 7; Table 3). The spatial strategies harvested stands were scattered over the forest landscape in order to escape spatial constraints. These harvested stands

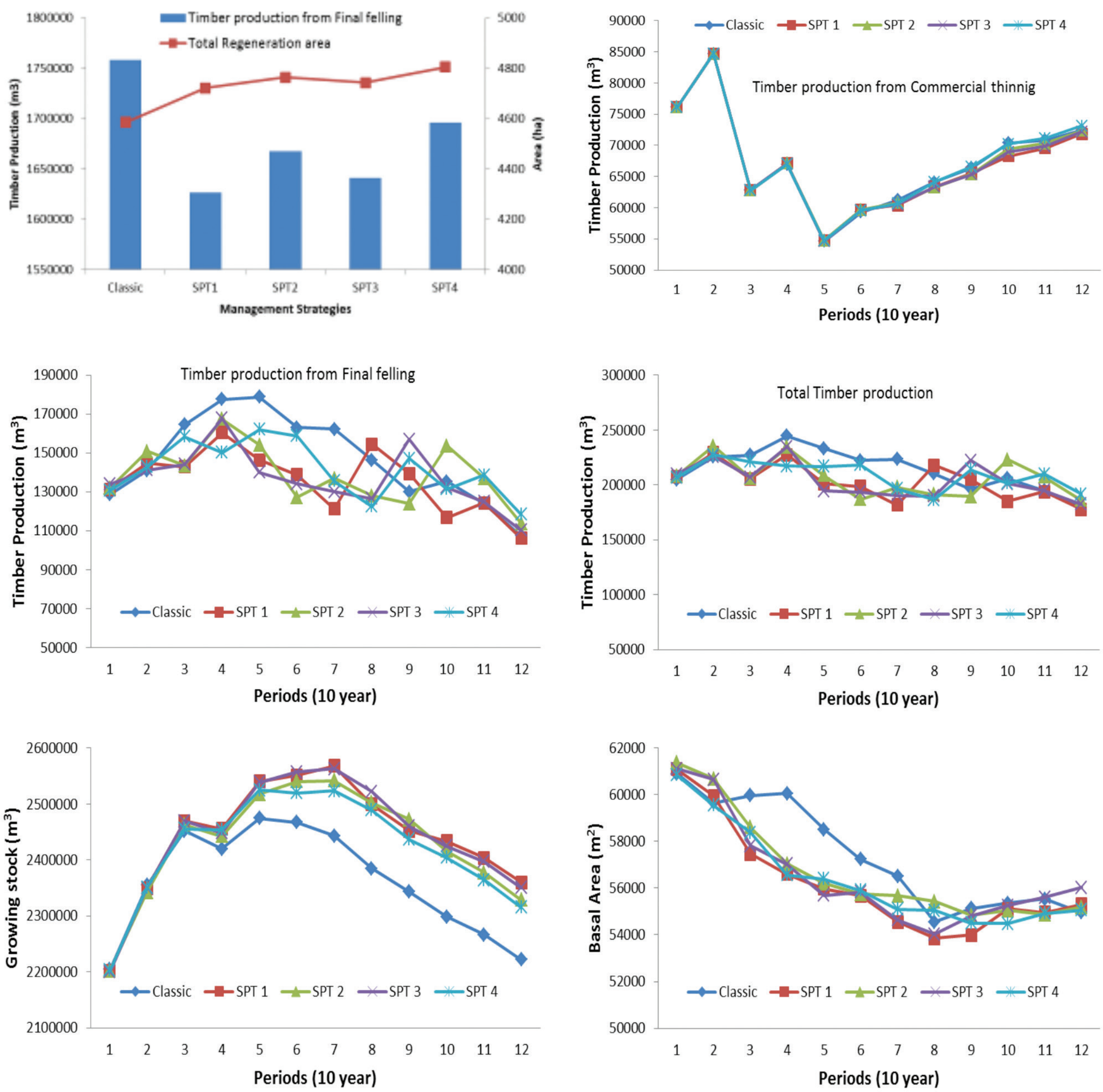

FIGURE 6. The model results of management strategies depicted by the performance indicators

TABLE 2. Some important performance indicators of forest management strategies

Strategies	Harvested timber volume of thinning	Harvested timber volume of final felling	Total harvested timber volume	Area of thinning	Area of final felling
Aspatial Simulation	809,831	1,758,564	2,568,395	59,227	4,586
Spatial 1 (SPT1)	804,077	1,626,637	2,430,714	58,916	4,723
Spatial 2 (SPT2)	806,864	1,667,659	2,474,523	59,174	4,764
Spatial 3 (SPT3)	805,013	1,641,504	2,446,517	58,861	4,743
Spatial 4 (SPT4)	810,551	1,696,222	2,506,773	59,372	4,805

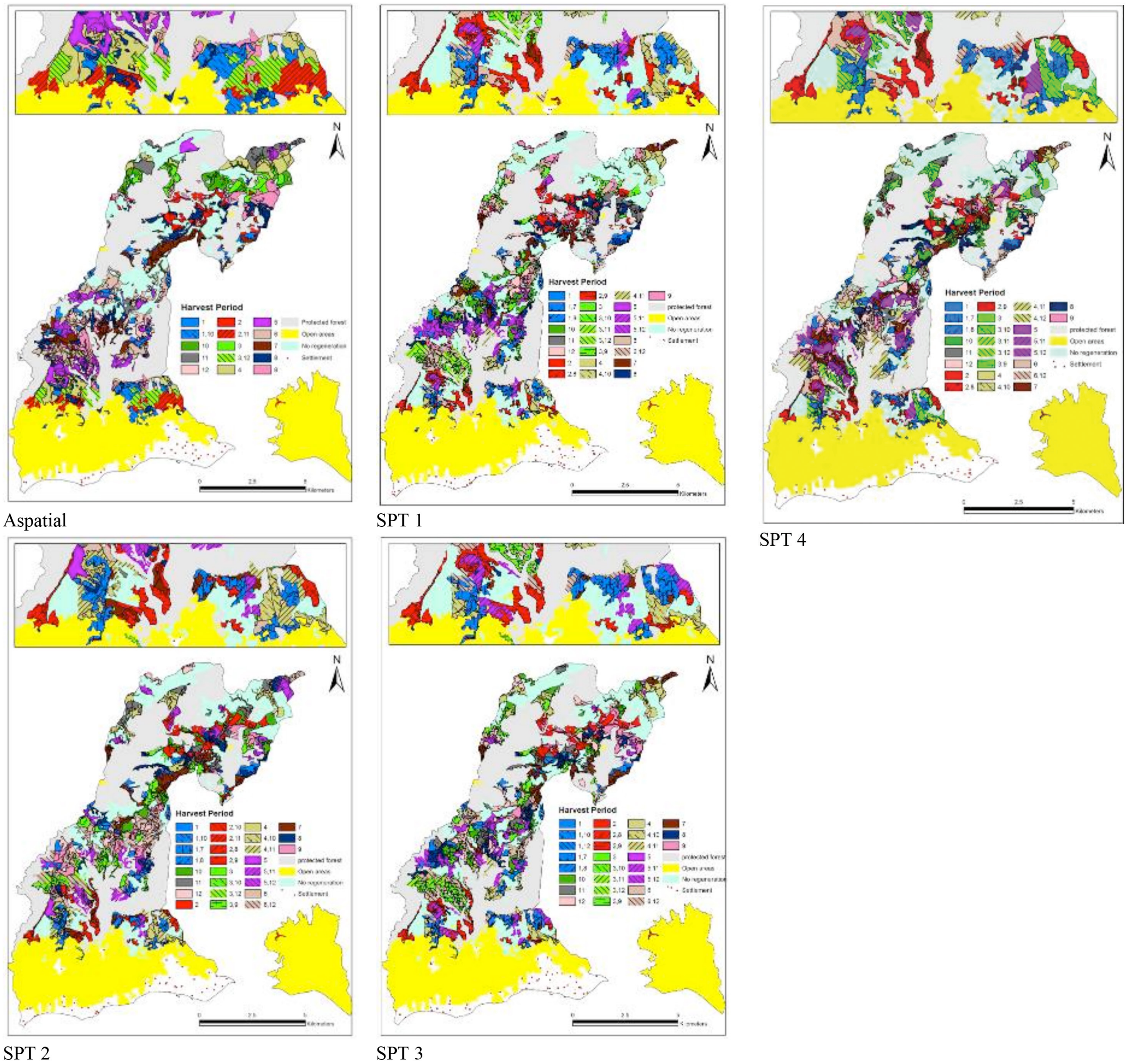

FIGURE 7. Spatial distribution of harvesting areas over the planning horizon in different management strategies

were mostly growing on poor sites or they bore lower levels of standing volume. Thus, although more areas were harvested by the spatial strategies, the harvested volume levels were lower.

Landscape fragmentation was analyzed using a number of patch, class and landscape level metrics over the planning horizon. While the temporal trends of fragmentation metrics for the four spatial forest management strategies were most affected by the opening size and blocking parameters, the values of the landscape metrics were different. For example, the momentum of changes of landscape metrics occurred in the same direction over the planning horizon (Figure 8). The SPT2 strategy had the highest MPS and PSCV, while it had the lowest PD and NP over the 120 years of planning horizon. It was generally apparent that the MPS and PSCV consistently increased over time, while the NP and PD consistently decreased over the planning horizon. These results showed that the spatial management strategies were able to create landscapes approaching the desired target structure.

Further analyses of fragmentation metrics were carried out separately for the two management units. Temporal trends of NP for Management Units A and B had a similar pattern of changes over the planning horizon (Figure 8). However, in both management units, the SPT2 strategy

TABLE 3. The number of harvested and unharvested subcompartments of forest management strategies

Strategies	Number of harvested subcompartments for final felling (at least once) over planning horizon	Number of unharvested subcompartments for final felling over planning horizon
Aspatial Simulation	784	269
Spatial 1 (SPT1)	912	141
Spatial 2 (SPT2)	856	197
Spatial 3 (SPT3)	889	164
Spatial 4 (SPT4)	911	142

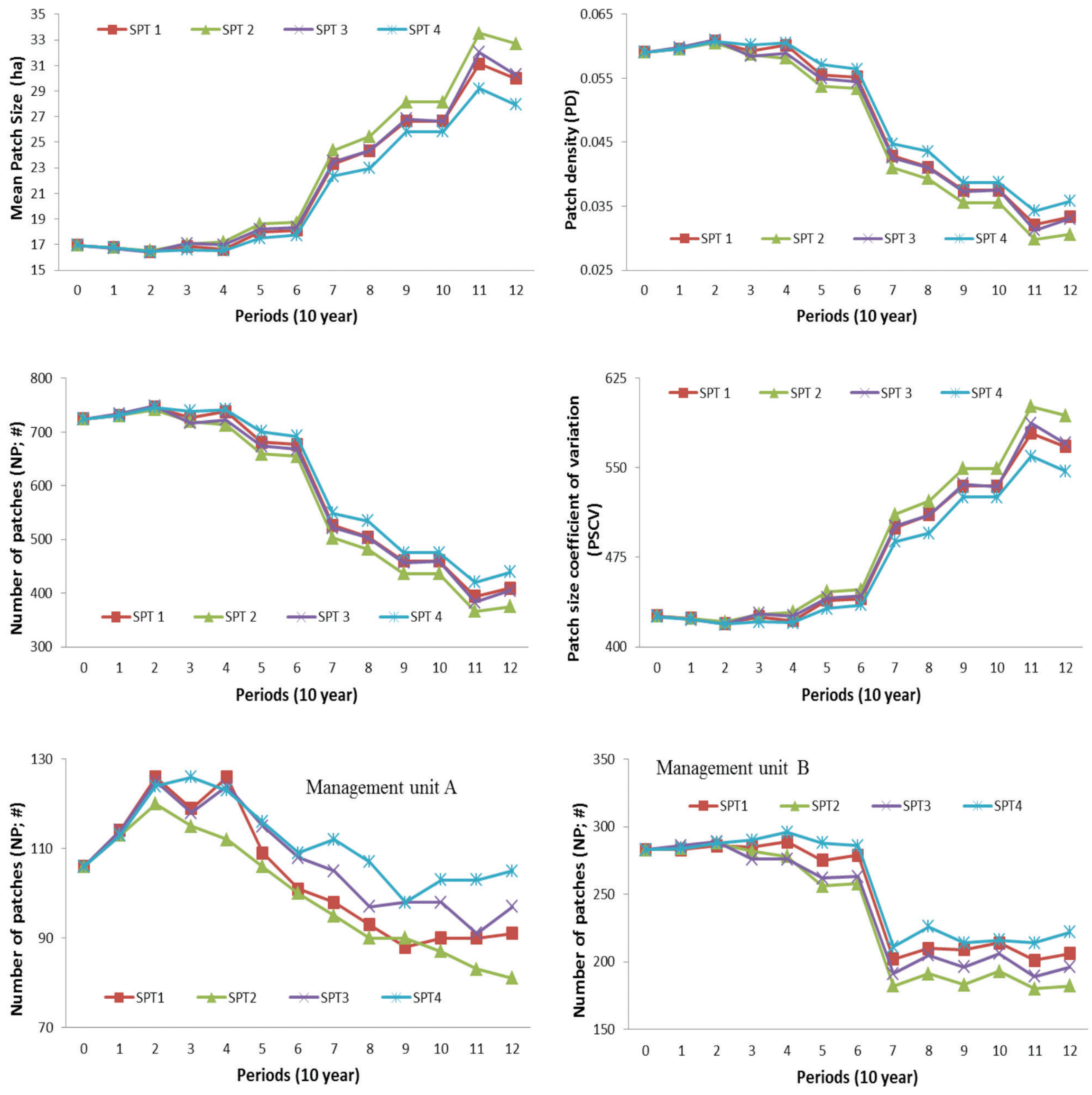

FIGURE 8. Temporal changes of landscape metrics under different spatial strategies with different spatial constraints

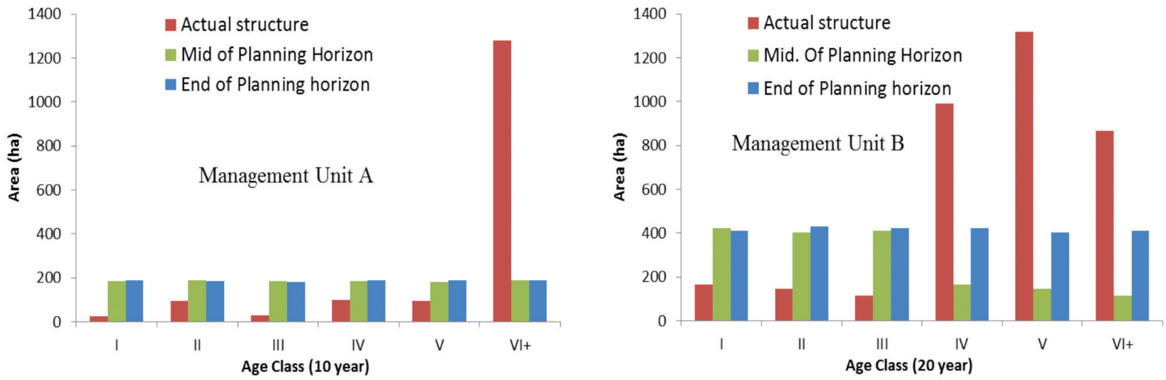

FIGURE 9. Changes of age class distribution for the management units A and B based on management strategy SPT1

produced a lower number of patches and the SPT4 created more patches over time. This was mainly due to the fact that the SPT2 strategy did not allow smaller harvest blocks but, on the other hand, allowed larger blocks and openings, 25 and 100 ha, respectively. In contrast, SPT4 allowed smaller harvest blocks and limited larger openings to 50 ha.

Another parameter to help analyze forest structure was the age class distribution for both management units over the planning horizon. For instance, the SPT1 strategy was able to satisfy optimal periodical area-OPA (regenerated area or final felling area) constraints in Forest Management Unit A at the middle of the planning horizon, while the same strategy in Forest Management Unit B satisfied the even age class distribution only at the end of the planning horizon (Figure 9). This most likely happens from the fact that Management Unit A had a shorter minimum cutting age (60 years) and Management Unit B had a longer minimum cutting age (120 years).

CONCLUSION

In this study, a stand-based forest-level spatial simulation model, ETÇAPSimülasyon, was designed and used to control forest structure. The model simulated the development of a forest ecosystem over time and provided tools to analyze the long-term effects of spatial parameters on the forest ecosystem structure. The spatial parameters (block size, opening size and green-up delay) were successfully incorporated into the forest management planning process through different spatial management strategies and were used to control future landscape structure. In the meantime, forest structures created by the mix of spatial parameters were further analyzed by various landscape fragmentation metrics (NP, PD, MPS, PSCV, CA etc.) with four spatial management strategies. The spatial forest management strategies were developed to generate spatially implementable harvest schedules and perform spatial analyses as part of multiple-use forest management planning. The results of the management strategies indicated that the spatial models were able to satisfy the spatial restrictions based on blocking and opening parameters.

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