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Fuzzy and Boolean operation based modelling for evaluation of ecological capability in the Hyrcanian Forests

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Abstract: Over the past four decades, management plan based on the Boolean Ecological Capability model has caused major problems in the management of the Hyrcanian Forests. The aim of this study is to evaluate ecological capability of five proposed sites including Golestan National Park, Afra Takhteh Yew Forest, Kojoor Forest, Cypress Woodland of Hassanabad-e Chalous, Lomer forest along the Hyrcanian region from east to west, using both Boolean and fuzzy logic and to compare these two models. A total of 10 important factors including slope, aspect, elevation, soil types, soil erosion, soil transformation, canopy cover, the value of species, distance to streams and climate were investigated in this study. The results show that elevation, slope and aspect have the most important role in the classification of the studied area. The results of model validation with field data indicate that the fuzzy gamma model shows the better assessment, accuracy and reliability compared to the Boolean model. Based on the obtained results we suggest the fuzzy-based operation model in sustainable protection planning in the Hyrcanian Forests.

Keywords: fuzzy gamma; model validation; sustainable protection; Golestan National Park

Forests are one of the most important ecosystems on the Earth for several ecological reasons. These ecosystems host a great amount of Earth's biodiversity (Sohngen et al. 1999); they prevent soil erosion, replenish groundwater by reducing water runoff, control flooding, enhance infiltration, and store carbon (Perry 1994; Oren et al. 2001). One of these valuable ecosystems is the Hyrcanian Forests on the southern shores of the Caspian Sea. These valuable forests contain the remnants of broadleaved forests that once covered most of the North Temperate Zone 25–50 million years ago, in the early Cenozoic Era. The Hyrcanian Forests are called "the mother" of European forests, because when large parts of Europe were covered by ice during the Pleistocene Epoch, these forests remained alive, and at the end of the ice age trees and other plant species from refuge areas extended their range to Europe.

These forests were inscribed on the UNESCO's Natural World Heritage List, at the 43rd session of the World Heritage Committee, Baku, Republic of Azerbaijan, 30 June – 10 July 2019. However, in the last few decades, the Hyrcanian forests, in general, have faced many threats affecting both forest cover and forest condition, and, therefore, biodiversity. Since 1950, the surface area of the Hyrcanian forests has decreased significantly from 2 750 000 ha to 1 850 000 ha, indicating a 32.7 percent loss (one third of the forests) of the surface area. There were several reasons involved in the degradation of the Hyrcanian Forests including: connectivity loss and fragmentation due to road construction or other

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developments, harvesting dead trees for firewood, illegal hunting and direct killing, water pollution, garbage dumping or dropping, land use change and converting forests to orchards, cultivated land or villa, livestock overgrazing, collecting medicinal, industrial or edible herbs, unsustainable timber harvesting etc. (Tohidifar et al. 2016).

Managing forests sustainably for the benefit of present and future generations at the first step needs to evaluate ecological capability, which is one of the useful tools for strategic planning of forests (Rossiter 1996; Siyag 2014). This method predicts potential capability and the type of land use. Identification of environmental and ecological characteristics helps us to classify the capabilities of a habitat. Thematic maps, e.g. land cover, forest cover and forest habitats which are being increasingly used for these goals (Kepner et al. 2000; Butler et al. 2004; Romero-Calcerrada, Acosta et al. 2005; Rocchini et al. 2006), are provided from both classifications of remotely sensed (RS) images and from data analysis in Geographic Information System (GIS) technology (Gopal, Woodcock 1994). Multi-Criteria Evaluation (MCE) in GIS is to investigate the allocation of land to suit a specific purpose based on a variety of attributes that the selected areas have. Boolean overlay is a common procedure for MCE. In this method, a polygon or a pixel in a classical land cover map can describe only a single land cover category applying a Boolean membership function in the integer set (0, 1); thus, the degree to which it is in reality mixed cannot be differentiated (Rocchini, Ricotta 2007). But fuzzy sets differ from traditional Boolean set theory and allow map producers to maintain uncertainty information of each class by taking into account the gradual change from class membership to non-membership (Gopal, Woodcock 1994). In fuzzy sets, the degree of membership, known as the truth value which associates for each polygon or pixel a membership level in the range 0 to 1, describes the possibility that a given entity belongs to the thematic map class (Zadeh 1999).

First, Makhdoom (2001) used the Boolean logic for the evaluation of ecological capability (ECE) in the Hyrcanian Forests. This model has 7 classes to investigate the allocation of land to suit a specific land use; but it does not seem to have the potential to evaluate the EC of the Hyrcanian forest based on reality. However, this model is being used currently and degradation in the Hyrcanian Forests continues (Tohidifar et al. 2016). The aim of this study is the evaluation of ecological capability of some proposed sites along the Hyrcanian Forests by both Boolean and fuzzy logic and comparison of these two models.

MATERIAL AND METHODS

Preparing data layer. The first step in the study was to identify the geographic boundaries for analyses and define which input variables to use. We used UNESCO's World Heritage Criteria (Criteria VI, VII, VIII, IX, X) (UNESCO 2017) to define the input variables. Finally, a total of 10 important factors were determined. These factors include slope, aspect, elevation, soil types, soil erosion, soil transformation, canopy cover, the value of species, distance to streams and climate. Information related to each of the 10 selected factors was compiled from Hyrcanian Project database, Forest Rangeland and Watershed Management Organization (FRWO) and Department of Environment Organization (DOE) GIS database. Data are assembled as unique GIS themes, or layers.

To create an elevation input grid for this application, elevations were taken directly from a 10-meter Digital Elevation Model (DEM). Slope and aspect were derived using surface analysis functions in ArcGIS (ESRI, Redlands, Version 10.2) Spatial Analyst in combination with the 10-meter DEM. Aspect was first calculated to identify the direction each slope is facing and classified in 9 categories: (*i*) Flat, (*ii*)) North, (*iii*) North East, (*iv*) East, (*v*) South East, (*vi*) South, (*vii*) South West, (*viii*) West, and (*ix*) North West. Information regarding underlying geology of the area was obtained via the digital geologic map. This data set included polygon information defining the lithology and geologic name of all units.

Digital vegetation data were acquired directly from the Forest Rangeland and Watershed Management Organization database.

Digital map of climate was produced by climatic information (precipitation and temperature) obtained from a meteorological station near the studied areas. Classification of climate was performed by the De Martonne method, which is based on both precipitation and temperature. Digital soil information for this study was taken from Forest Rangeland and Watershed Management Organization's GIS database. Soil polygons were mapped and classified according to their type and erosion potential.

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Table 1. Characteristics of the study areas

Study area	Coordinates of central point	Altitude (m)	Precipitation (mm)	Temperature (° C)	Area size (ha)	Legal protection since
GNP*	55°43'27.4"E, 37°25'17.3"N	471–234	500–1 000	16–20	92 830	1957
ATYF*	52°31'30"E, 36°45'24"N	1 400–2 991	400–900	8–16	1 200	1992
KF*	51°40'3.5"E, 36°32'45.7"N	–27–2 640	800–1 200	8–16	25 241	1975
CWHC	51°18'30"E, 36°26'31"N	279–1 696	600–800	6–10	7 357	
LF	48°42'27"E, 37°32'38"N	275–1 613	1 200–1 600	10–14	3 471	–

GNP – Golestan National Park, ATYF – Afra-Takhteh yew forest, KF – Kojoor Forest, CWHC – Cypress Woodland of Zarbian Hassanabad-e Chalus, LF – Lomer Forest, *inscribed sites on the UNESCO's Natural World Heritage List

Euclidian distance from streams was calculated for each site at three levels of 0–125 m, 125–250 m, and 250 up to the end of the range and assigned priority code 1 to 3. The distance of 500 to 1 000 m from the forest boundaries was calculated to decrease the marginal effects. At the final step, because of the high value of some forest types, 10% of the total area comprise high value types selected as a conservation reserve.

Study area. The Iranian part of the Hyrcanian Forests covers a total area of 1.85 million ha and they grow like a thin strip (850 km long and 20–70 km wide) and cover 15% of the total Iranian forests (Sagheb-Talebi et al. 2014). These forests stretch from 28 meters below sea level, rising to an altitude of 2 800 m a.s.l. and receive most of their precipitation from the Caspian and Black Seas (Sagheb-Talebi et al. 2014). Alborz mountains in the south of the Hyrcanian region act as a climatic wall, producing dense clouds and discharges of rain or snow; this, in turn, creates a very dense forest on the northern slope of the Alborz mountains, while the southern slopes end in the Kavir desert, one of the driest deserts in the world (Knapp 2005). The western and eastern parts of the Hyrcanian region have noticeably different regimes (Domoers et al. 1998). Unlike the eastern parts, the western part boasts of the highest amount of rainfall occurring during autumn (Sagheb-Talebi et al. 2014). These forests with considerable species richness (including a large number of endemic, rare and threatened species) are among 25 global hotspots of biodiversity. The Hyrcanian Forests are also categorized among the IUCN's recognized centres of plant diversity and endemism (Davis et al. 1995).

Because of different ecological gradient in the Hyrcanian region, for this study, five forest sites have been selected from east to west of the Hyrcanian Forests and from sea shore to the tree line. Three

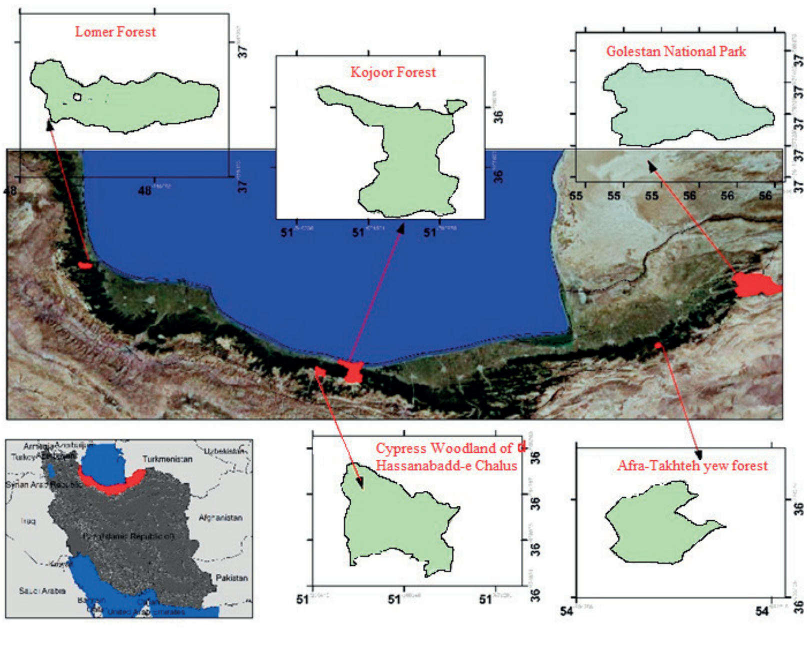

Figure 1. Study areas on the map

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Table 2. Effective parameters based on Makhdoom's model (Overlapping Model)

Factors	Ecological Capability Classes						
	I	II	III	IV	V	VI	VII
	Unlimited	Very little constraint	Moderate constraint	Medium restrictions	Severe restrictions	The limit is too severe	Protected
Elevation	0–1 000 m	0–1 000 m	0–1 400 m	1 400–1 800 m	1 800–2 600 m	0–2 600 m	0–2 800 m
Slope	0–25%	0–35%	0–45%	0–55%	0–65%	0–75%	> 75%
Exposition	north- south-east	north- south-east	north- south	eastern western	eastern western	all	all
Soil type	clay loam, silty clay loam, silty clay, clay	clay loam, silty clay loam, silty clay, clay	loamy, loamy clay, sandy clay, silt, silt clay, clay	sandy, sandy loam, loamy sand, silt, silt loam, loam, silty clay loam, sandy clay, silty clay, clay	sandy, sandy loamy, sandy loamy, silty, loamy silty, clay loam, clay loam clay, sandy clay, clayey silty, clay, rossoul and lithosol	sandy, sandy loamy, sandy loamy, silty, loamy silty, clay loam, clay loam clay, sandy clay, clayey silty, clay, rossoul and lithosol	rossoul and lithosoll
Soil erosion	no erosion (mild)	no erosion (mild)	no erosion (mild)	no erosion to very erosive	no erosion to very erosive (groove)	no erosion to very erosive (gully)	no erosion to erosion
Soil transformation	evolved	evolved	evolved	semi-transformed – evolving	semi-transformed – evolving	transformed, the initial stage	transformed, the initial stage
Canopy cover	100–75%	100–75%	75–50%	50–25%	< 25%	< 25%	< 25%
The value of tree species	beech, oak alder, ash, maple, walnut, maple-hornbeam	beech, oak alder, ash, maple, walnut, maple, hornbeam	beech, oak, alder, ash, lime, walnut, maple-hornbeam	other species	other species	other species	other species
Climate	humid-most humid	most humid-semi-humid	most humid-semi-humid	humid, semi-humid	humid-Mediterranean	humid-Mediterranean	humid-Mediterranean

of these sites are proposed for inscription on the UNESCO's Natural World Heritage List (Table 1, Figure 1).

Boolean logic. Boolean algebra which was introduced by George Booleis (1847) is the branch of algebra in which the values of the variables are the truth values true and false, usually defined 1 and 0, respectively. Boolean Logic is centred around three simple words known as Boolean Operators: "Or," "And," and "Not". The basis of this model is the multi-factor evaluation. In this study the model contains 7 classes (a set of ecological factors) that indicate the degree of quality and capability of the natural environment (Makhdoom 2001). Details of these classes are represented in Tables 2 and 3.

Fuzzy gamma method. Fuzzy logic, which was introduced by Zadeh (1999), is based upon the fuzzy set which expresses the degree in which an entity belongs to some category. Fuzzy sets differ from traditional Boolean set theory in which only two degrees of membership are possible for an entity: an entity can either belong completely (1) or not at all (0). The degree of membership in the fuzzy set can take on any continuous value in the real number interval (0, 1) (Dewitte et al. 2006). Variables consist of a collection of membership functions made up of fuzzy sets, which can then be related to those of one or more output variables through a configuration of IF-THEN rules known as the fuzzy logic system. Most fuzzy-based systems use a series of "IF-THEN" rules to combine membership functions of the various inputs. Such fuzzy rules are composed of two parts: the antecedent condition (IF) and the consequent conclusion (THEN). The IF-part can consist of more than one variable linked together by fuzzy operators: conjunctions like AND or OR that express conditions in the rule base. This "IF-THEN" form of expression can be constructed using one variable for the input and one variable for the output. The most popular op-

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Table 3. Effective parameters based on the Boolean model (Overlapping Model) for each study area

Factors	Study area				
	Golestan National Park	Afra-Takhte yew forest	Kojoor Forest	Cypress woodland of Hassan Abade Chalus	Lomer forest
Elevation	471–2 342 m	1 409–2 299 m	0–2 640 m	279–1 696 m	275–1 613 m
Slope	0–75%	0–35%	0–75%	0–75%	0–75%
Exposition	all	all	all	all	all
Soil type	clay loam, silty clay loam, silty clay, clay, sandy clay, clayey silty	clay loam, silty clay loam, silty clay, clay	clay loam, silty clay loam, silty clay, clay	sandy, sandy loamy, sandy loamy, silty, loamy silty, clay loam, clay loam clay, sandy clay, clayey silty, clay, rossoul and lithosol	clay loam, silty clay loam, silty clay, clay
Soil erosion	no erosion to very erosive (gully)	no erosion (mild), no erosion to very erosive (grooves)	no erosion to very erosive (grooves)	no erosion to very erosive	no erosion to very erosive (grooves)
Soil transformation	evolved	evolved	evolved	semi-transformed	evolved
Canopy cover	0–100%	50–75%	0–100%	50–75%	< 25%
The value of tree species	oak alder, maple, walnut, maple, hornbeam and other species	oak hornbeam linden, ironwood	beech, oak, alder, ash, lime, walnut, maple, hornbeam	other species	beech, oak, alder, ash, lime, walnut, maple, hornbeam
Climate	most humid semi-humid humid- Mediterranean	humid, semi-humid	humid, semi-humid	humid, semi-humid	most humid

erator for rule aggregation is fuzzy gamma, which is defined as Equation (1):

$$\mu\text{combination} = (\text{Fuzzy algebraic sum})\ \lambda \times \times (\text{Fuzzy algebraic product})\ 1-\lambda \quad (1)$$

where:

λ – chosen value between 0 and 1.

This operator produces output values that ensure a flexible compromise between the "increasive" trends of fuzzy algebraic sum and the "decreasive" effects of fuzzy algebraic product (Champati ray et al. 2007). Then, the gamma operator was selected as the method for input rule aggregation in this study. Different values for gamma were tested on the input fuzzy membership functions to generate the most reliable EC map. A gamma value of 0.5 was specifically used because it routinely showed the highest prediction accuracy. Performing the fuzzy gamma operation and classifying the area yielded an output EC map with seven zones: unlimited, very little constraint, moderate constraint, medium restrictions, severe restrictions, the limit is too severe, protected (Table 2). The quality of the forest decreased from class I to class VII. It means that class I is the highest quality of the vegetation habitat for timber trade and class VII has the lowest quality for timber trade and needs high protection actions. Arc GIS Ver. 10.5 was used for the Boolean Model.

Model evaluation. Area Under the Curve (AUC) Receiver Operating Characteristics (ROC) curve were used to check the performance of the multi-class classification problem. It is one of the most important evaluation metrics for checking any classification model performance.

Height, diameter at breath height (DBH), number of trees, existence of dead trees in 250 randomly selected plots were sampled to evaluate the accuracy of fuzzy models under gamma procedure and overlay (Quétier, Lavorel 2011). D/H index was used to investigate the model validation. SPSS (IBM, New York, Version 25) was used to draw these curves.

The value of 0.5 indicates model performance no better than randomness and the value of 1.0 represents perfect performance (Equation 2):

$$\text{AUC} = 1/2\sum_{i=1}^{N}(x_{i+1} - x_i) \times (y_i + y_{i+1}) \quad (2)$$

where:

x – interval on x axis,

y – height on y axis.

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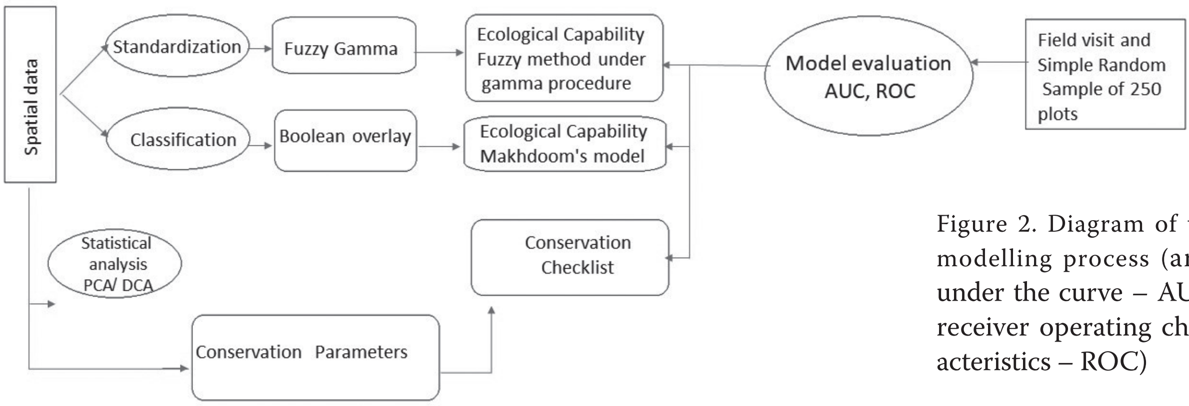

Figure 2. Diagram of the modelling process (area under the curve – AUC, receiver operating characteristics – ROC)

Principal Component Analysis (PCA) was used for multivariate analysis and multidimensional datasets with quantitative variables were investigates. PCA analysis was performed by PAST software (Hammer, University of Oslo, Oslo). Figure 2 shows the diagram of the modelling process.

RESULTS

Our results revealed that two models differ in the classification of the studied area in the last three classes including: "severe restriction", "the limit is too severe" and "protected".

Golestan National Park

As shown in Figure 1, the elevation and slope have a significant effect on the forest type. The composition of plant species changes based on the elevation from lowland area to upper lands. The Oak-Maple stands have a greater degree of differentiation than other stands due to their minimum altitude and geographic position; the results also show that the Oak-Alder stands are distinguished from other stands.

Based on the ecological capability modelling maps, a major part of the area of Golestan National Park faces severe ecological limits. Our results show the fuzzy gamma model classified more than 94% of the study area as a protective zone. In contrast, in the Boolean model only 7% of the area in the east, north and south of GNP were determined as protective zone and 82% of the total area were categorized as "the limit is too severe" class. Oak-Linden stands at a minimum altitude were classified as the best area for a conservation reserve with hard access and out of reach (Figure 3).

Afra-Takhteh Yew forest

The results obtained from the gamma model show that the topographical parameters (elevation, aspect) have significant effects on forest types. The three main forest types including Oak-Hornbeam and Linden are mainly influenced by environmental parameters including the elevation and aspect. Generally, at a high elevation diversity of these species tends to form pure stands (Figure 4).

Both models show differences in the estimation of EC. The gamma model determines the southeastern part as a protected area. In this model the marginal area with high erosion and degradation avoided to be included as a protective zone and the area with highly homogeneous ecological conditions was proposed as conservation reserves. The gamma model categorized 52% of the total area as "the limit is too severe" and 33% in "protected" classes. In contrast, the Boolean model determines over 61% of the study site as "severe restriction" class.

Kojoor Forest - Watershed 46

The results of PCA show that pure stands of Oak and Hornbeam may tolerate severe ecological limits like high steep slopes and restrict to their ultimate tolerance. But in mixed stands the soil type has an important role in species distribution and provides a suitable substrate for other species. Results also show that the elevation as an ecological parameter is important to distinguish the forest type and the centre of the area with mild elevation has the highest forest type biodiversity with high protection degree. Against the Boolean model (38% of the total area determined as a protected zone), the map produced by the gamma model categorized 15% of the total area as "protected" class. The gamma model

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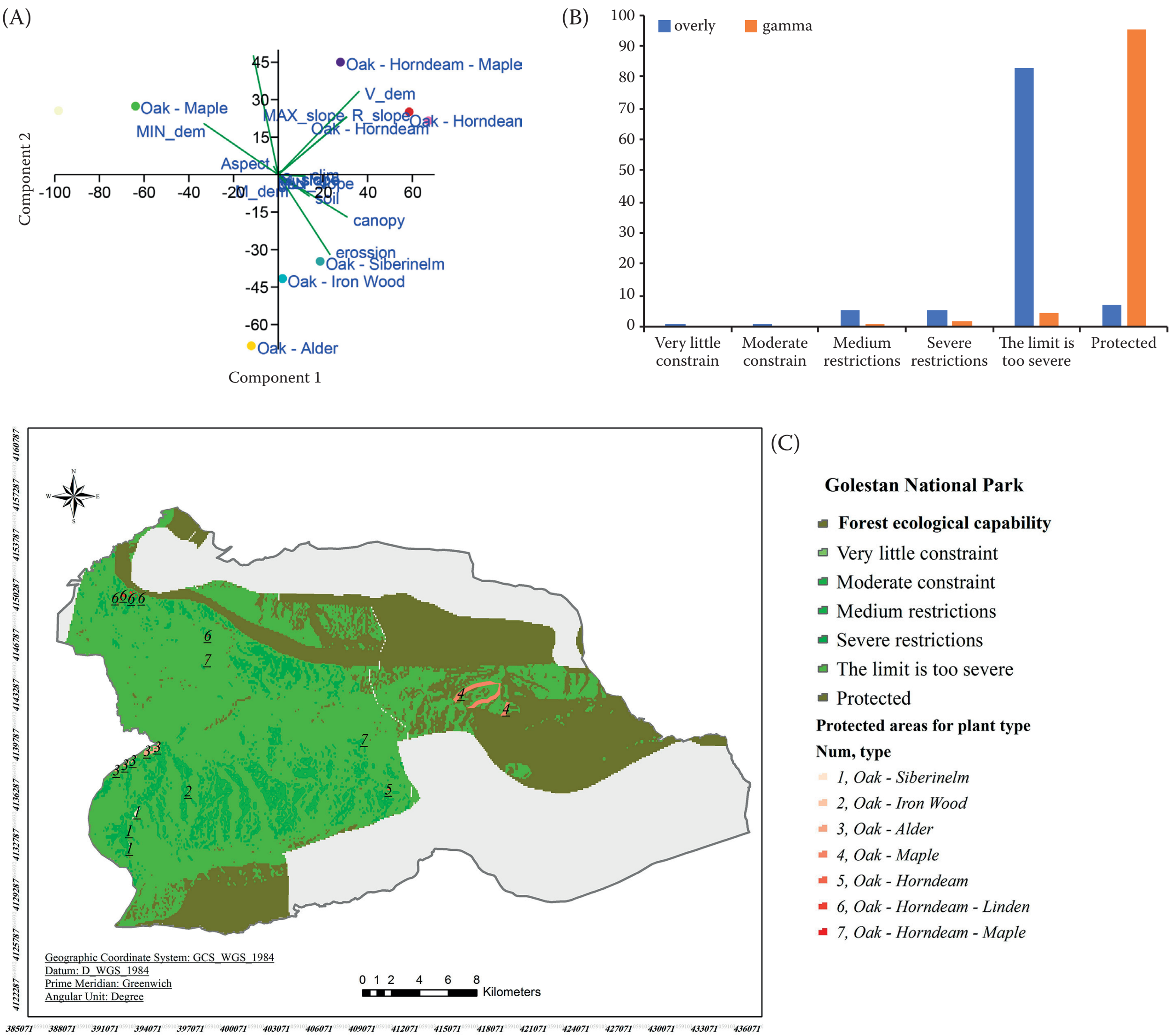

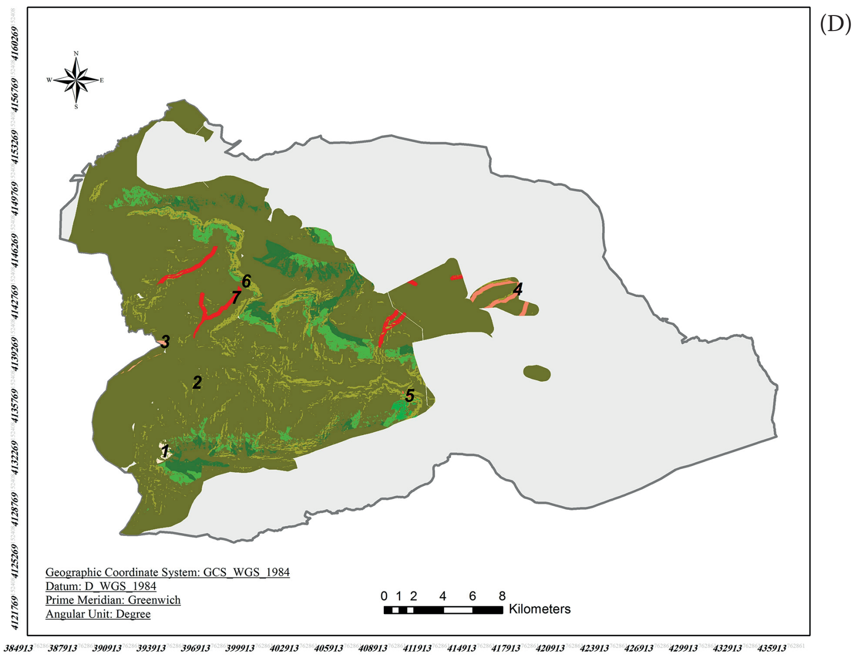

Figure 3. Analysis of Golestan National Park: (A) Analysis of the main components; (B) The frequency chart of ecological capability classes; (C) Gamma Model Ecology Model; (D) Ecology map of Boolean model

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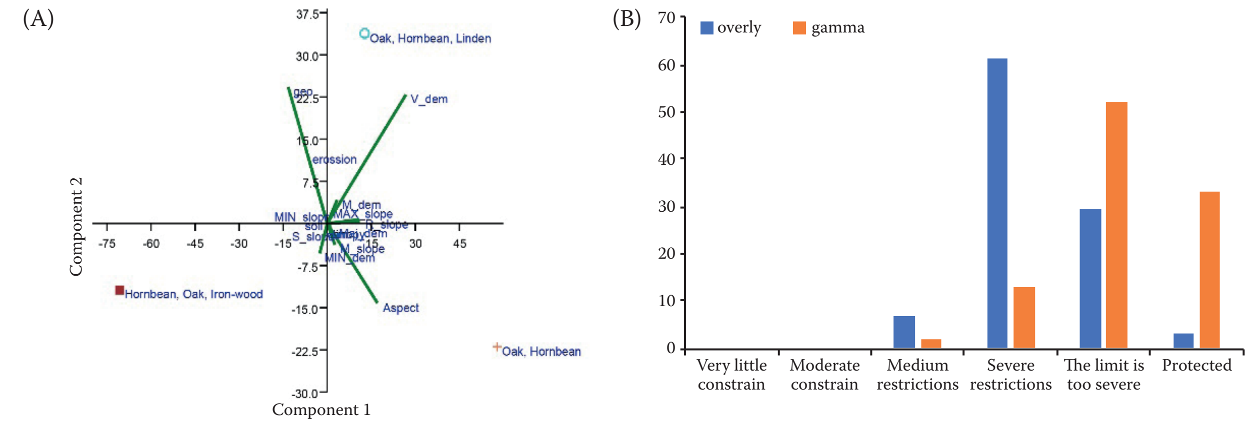

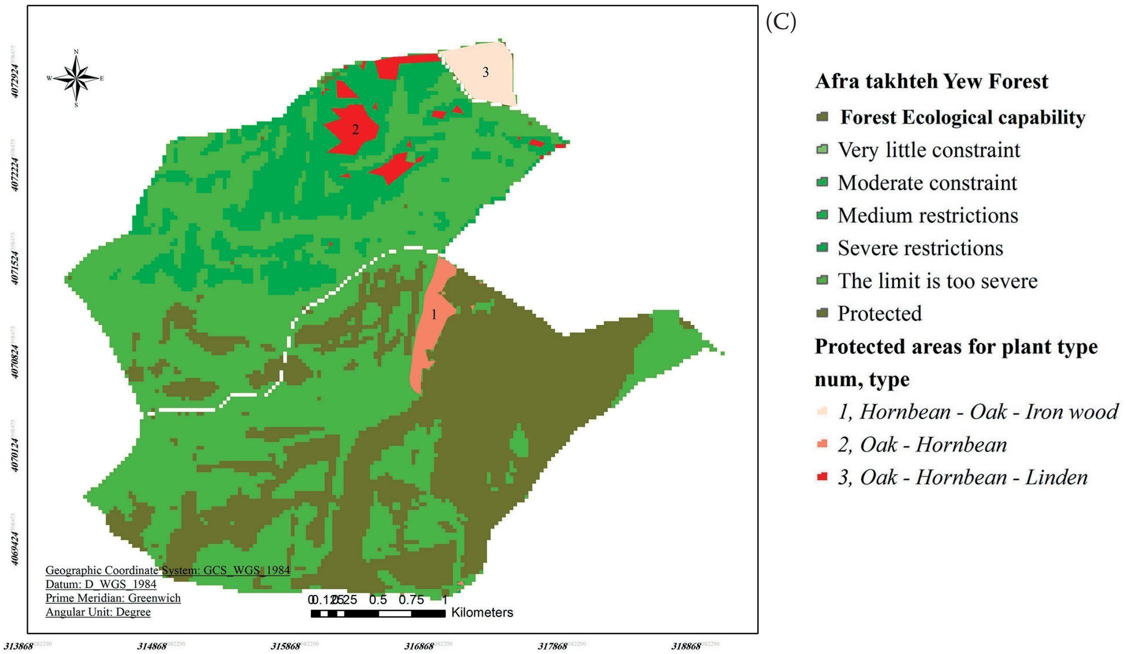

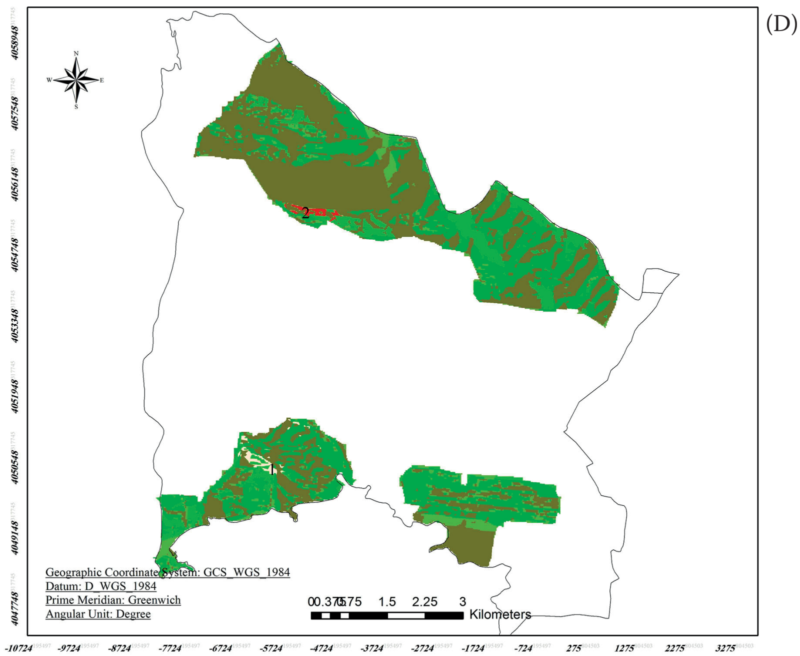

Figure 4. Analysis of Afra Takhte Yew Forest: (A) Analysis of the main components; (B) The frequency chart of ecological capability classes; (C) Gamma Model Ecology Model; (D) Ecology map of Boolean model

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determined over 54% of the total area with high restriction (Figure 5).

Cypress Woodland of Hassanabad-e Chalus

The three main forest types in CWHC are separated from each other by elevation and slope. The high altitude is covered by Oak-Hornbeam stands, while the Oak-Hornbeam-Elm stands are found on high steep slopes.

CWHC has many limitations and a forest plantation is recommended to maintain ecosystems. One of the restrictive factors at this site is a high altitude which requires a high degree of adaptation.

Against the Boolean model which categorized 51% of the total area as a protected zone, the gamma model proposed 61% of the total area as "the limit is too severe". The gamma EC map shows ecological imbalance in nature, but unlike other areas, it does not advocate more protection, but also it represents a kind of fragile stability for the site. It is hard to propose a part of the area for a conservation reserve due to the severe ecological limits. However, the Boolean model determines an area with low EC for a conservation reserve (Figure 6).

Lomer Forest

The results of the PCA analysis indicate that ecological competition is affected by the elevation. The dominant species in this site include *Buxus sempervirens* and *Fagus orientalis-Quercus castaneifolia*, which are also affected by elevation diversity. At the upper land Beech is a dominant species. Diversity in aspect, soil type and slope accompanied by elevation has caused high forest type diversity in this site. This forest is considered as a climax forest with Beech as a shade-tolerant species.

The EC map produced by the Boolean model proposed 10% of the total area for protection but in the fuzzy gamma model this site has been determined as a protected area (50% of the total site area) (Figure 7).

Validation

The results of model validation with field data indicate that the fuzzy gamma model shows the better assessment, accuracy and reliability compared to the Boolean model (Figure 8, Table 4).

The accuracy of the fuzzy gamma model in relation to elevation and D/H index shows the highest accuracy compared to the Boolean model.

In general, our results indicate the low EC of the studied sites. Over 77% (91 484.16 ha) of the total studied area (117 959.15 ha) are located in the protected class, however, the fuzzy gamma and Boolean model differed in the classification of "the limit is too severe" and "protected" classes (Figure 9). The fuzzy gamma model shows a gradual change from class membership to non-membership, then the response of the natural environment to the evaluated parameters is more obvious.

The results of cluster analysis in both models grouped KF, CWHC, and ATYF in the same cluster which reveals similar EC of these sites (Figure 9C, D). In the gamma model GNP and LF were grouped in the same cluster but in the Boolean model these sites had the highest Euclidian distance and were located in separate groups.

DISCUSSION

High topographic diversity and geographical position create restrictions for species distribution and limit other land uses. Topographic parameters are frequently used for designation of a site as a protected zone. In the present study we considered some most important topographic parameters including elevation, aspect and slope. Results of the PCA indicate that the parameters have an important role in forest type diversity. Elevation as an important topographical parameter has a crucial role in the variation of weather and climate conditions and this is reflected in differences in soil and vegetation (Aniya 1985). Elevation also influences an amount of precipitation that falls as rain or snow events. In the Hyrcanian region, the high elevation diversity in a short distance (50 km from the sea shore up to the tree line at 2 800 m a.s.l) creates an ecological gradient which caused high diversity in plant communities (Knapp 2005) and animal habitats in the northern range of the Alborz mountains. Then, a wide range of elevations from lowland to high mountains with stands of high integrity selected for this study and results revealed the importance of elevation for forest type distribution and designation of sites as protected areas. Gioia and Pigott (2001) reported the elevation as an effective factor on conservation planning.

Slope and aspect are the other most important and frequently used parameters in designation of a site as a protected area. The aspect influences the soil moisture content and the amount of solar radiation, plant species distribution, and also rainfall distribution (Gorsevski et al. 2003). West-

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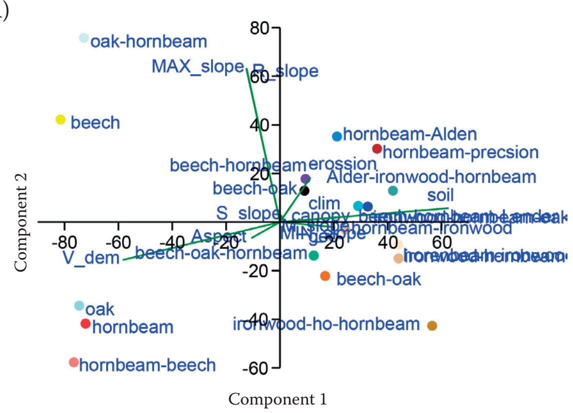
(A)



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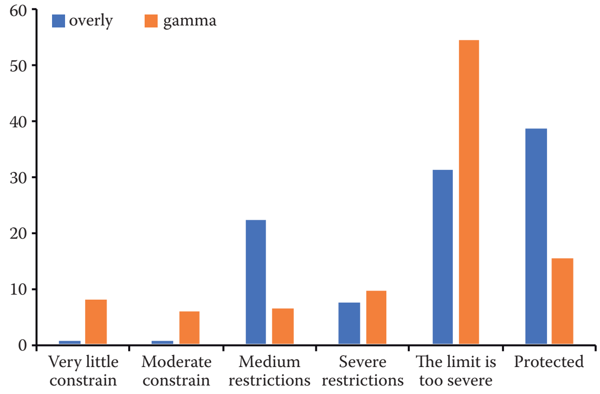

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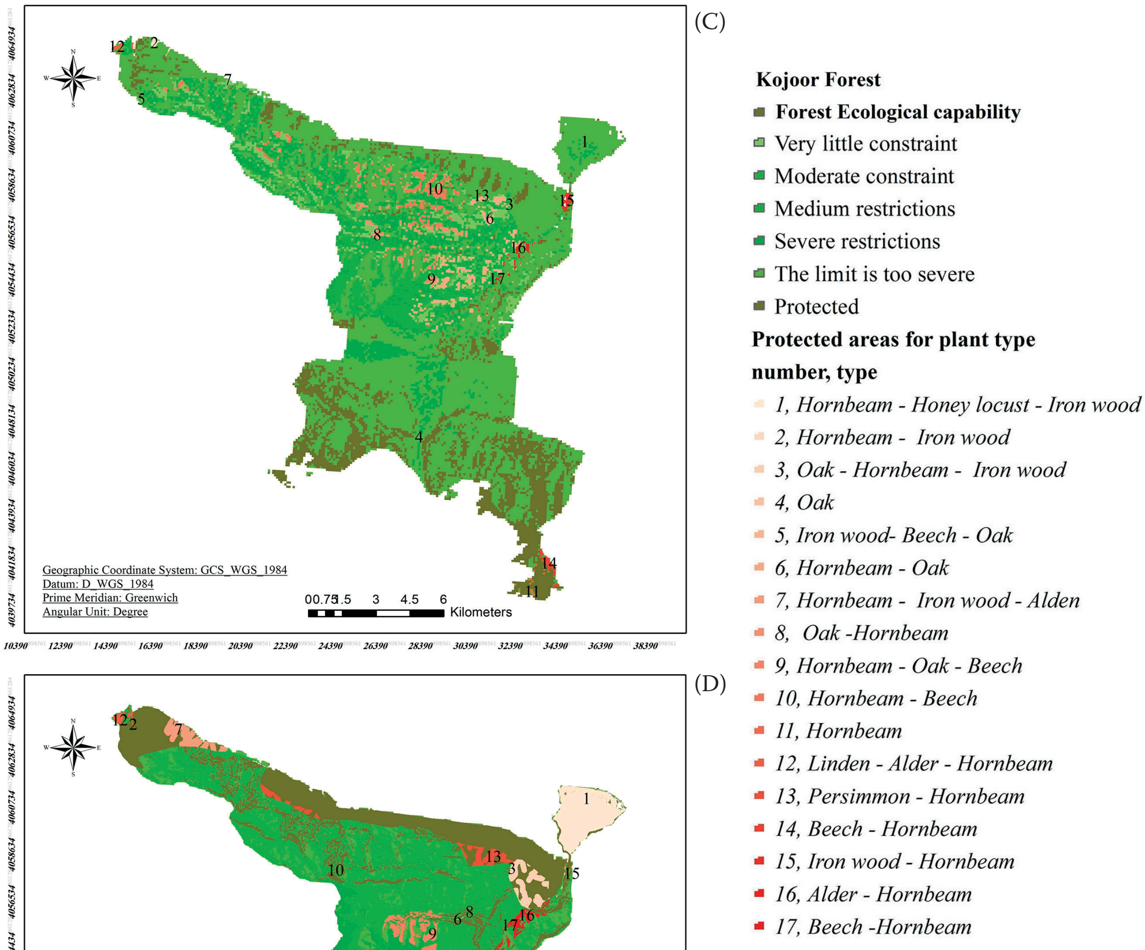

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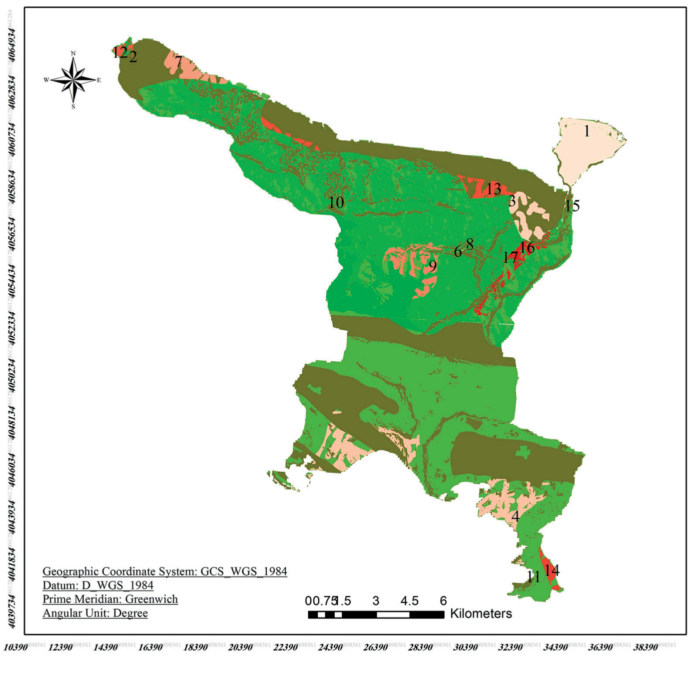

Figure 5. Analysis of Kojoor Forest: (A) Analysis of the main components; (B) The frequency chart of ecological capability classes; (C) Gamma Model Ecology Model; (D) Ecology map of Boolean model

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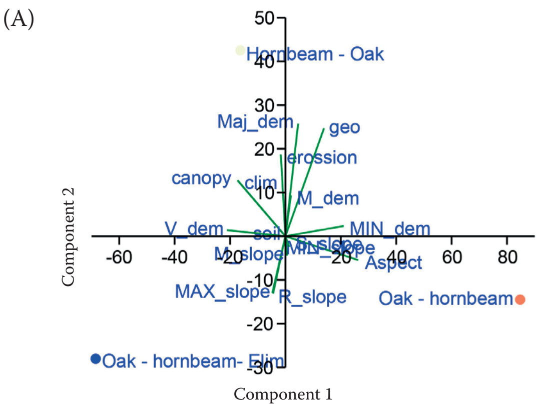

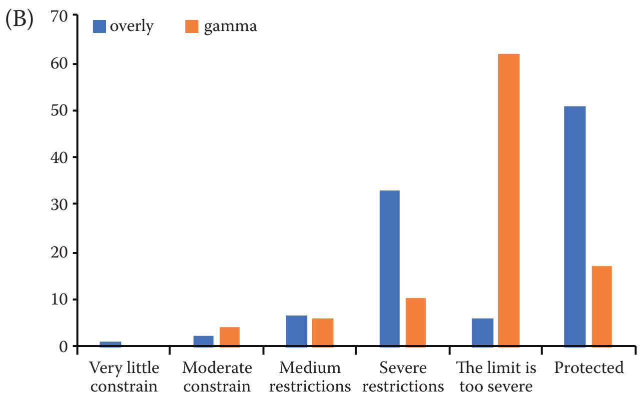

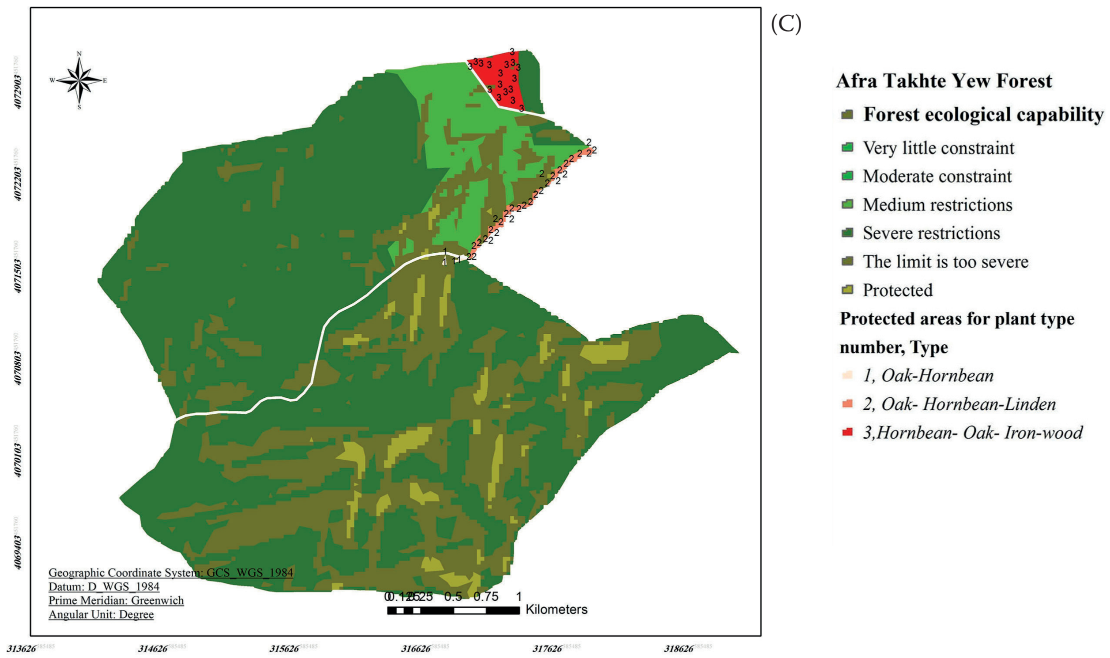

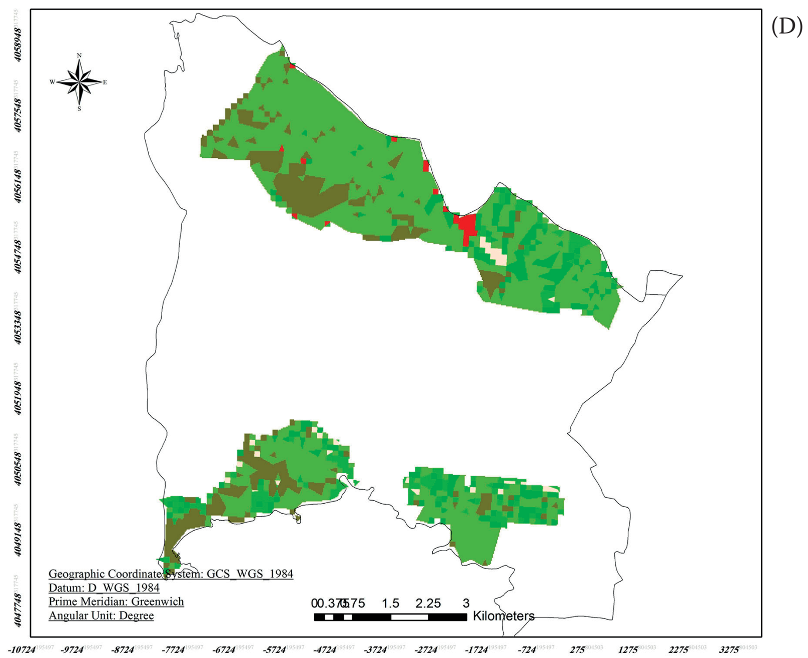

Figure 6. Analysis of Cypress Woodland of Hassanabad-e Chalus: (A) Analysis of the main components; (B) The frequency chart of ecological capability classes; (C) Gamma Model Ecology Model; (D) Ecology map of Boolean model

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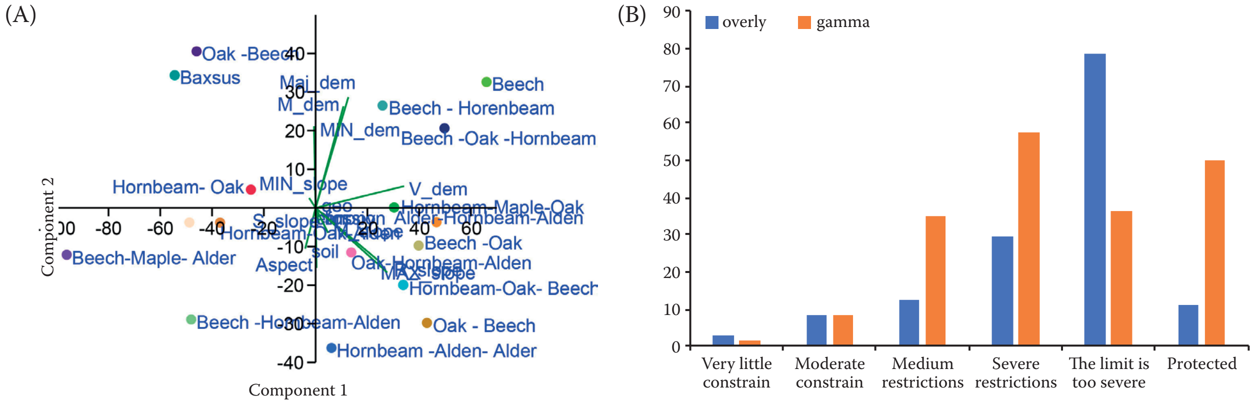

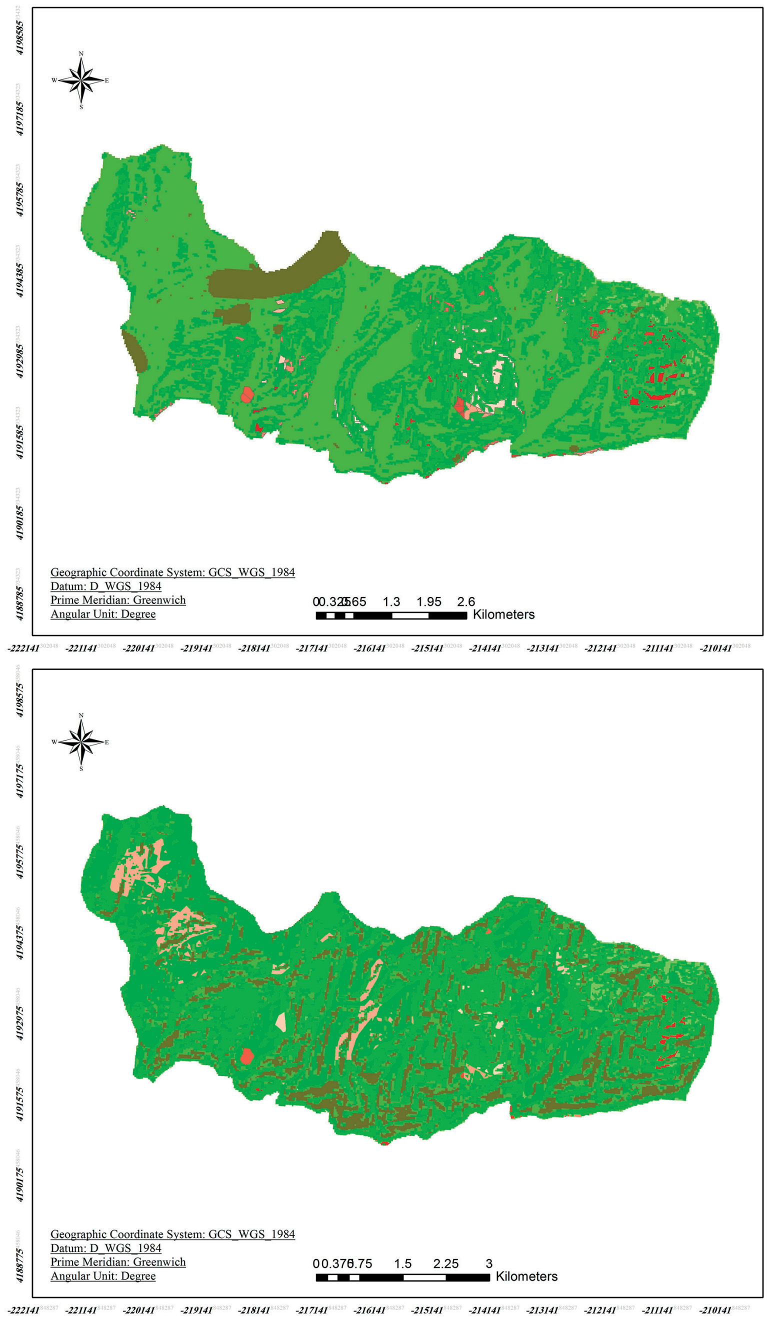

Figure 7. Analysis of Lomer Forest: (A) Analysis of the main components; (B) The frequency chart of ecological capability classes; (C) Gamma Model Ecology Model; (D) Ecology map of Boolean model

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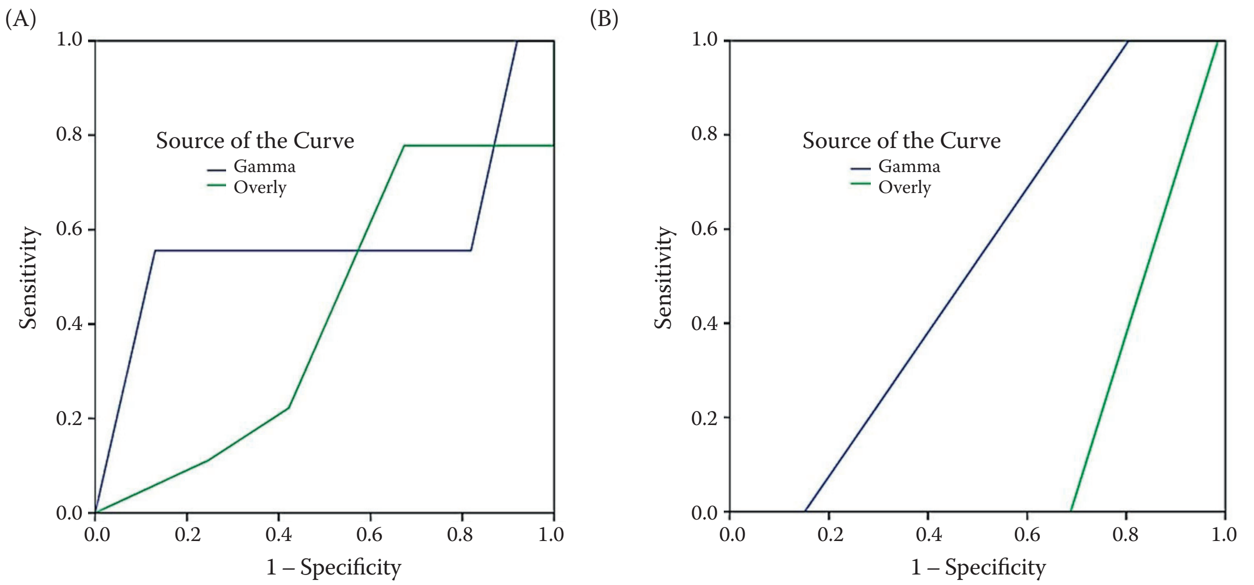
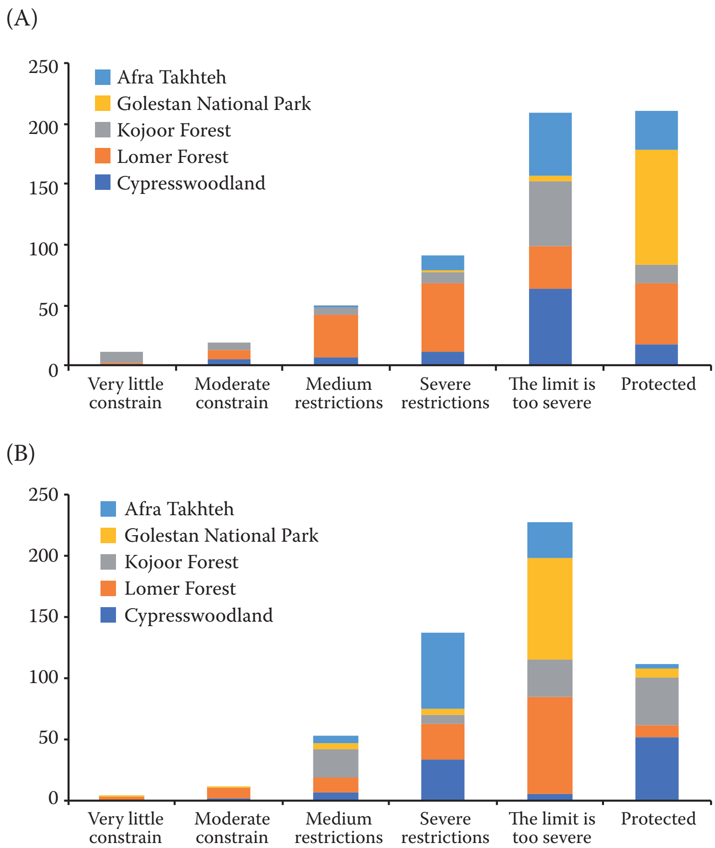


Figure 8. Characteristics of the model validation with the field data of the tree height (A), Diagram of the accuracy of the models with the field data of D/H index (diameter/height) (B)



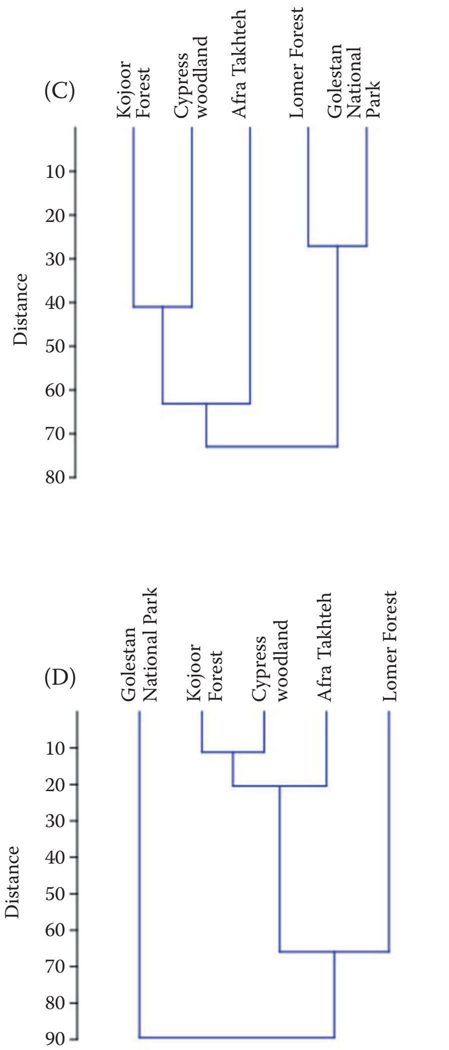


Figure 9. Ecological capability cumulative chart using the fuzzy gamma method at all sites (A); Ecological capability cumulative chart using the Boolean method at all sites (B); Ecosystem capacity cluster chart for fuzzy gamma modelling (C); Site clustering chart for ecological power for overlapping model (D)

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and south-facing slopes receive more precipitation (Gardner 2006), so they are more likely suitable for hygrophilous species. Control of surface runoff, water flow and other materials, flow acceleration and velocity are related to the slope angle (Aniya 1985; Gorsevski et al. 2000). The slope also influences vegetation community by controlling soil thickness. Because of hard access, high slope areas in the Hyrcanian region remain intact and are habitats of rare and endangered plant and animal species. Our results showed the importance of slope and aspect on the EC map classification by both used models.

Soil properties, such as material type, texture, erosion, and transformation, have the potential to influence vegetation type and vulnerability by altering the relative strength of the slope. Poor drainage, combined with thin soils exhibiting poor permeability, will likely decrease the slope strength (Lee, Min 2001). The Hyrcanian region comprises different kinds of soil with different levels of transformation leading to different types of forest communities (Sagheb-Talebi et al. 2014). Our results showed that in the same environmental conditions in terms of elevation, slope and aspect diversity of soil types may be considered as an important factor for the classification of EC map.

Evaluation of EC by use of two different models indicates low EC of the Hyrcanian forests. Due to low EC over 77% of the total studied area is located at the protected class in both models. It seems that the low EC is a result of anthropogenic effects and climate changes during recent decades (Tohidifar et al. 2016). Although the Hyrcanian forests are a fragile ecosystem with high vulnerability to the land use change and anthropogenic effects, over 90% of the studied sites have a high ecological value. Unlike the Boolean model, the EC map produced by the gamma model is closer to reality and shows the ecosystem vulnerability and categorized the areas with high ecological values in the protected class. It is so because the fuzzy gamma model shows the gradual change from class membership to non-membership, but in the Boolean model an entity can either belong completely (1) or not at all (0). The fuzzy method in this study was selected based upon the purpose of the assessment, extent of the study area, availability of data, and limiting environmental conditions. One of the benefits of the fuzzy method is its linguistic rules which allow users to easily understand the make-up of the model components and influence of inputs, while the system outputs can be implemented with a GIS modelling language. Combining the fuzzy method with GIS technology enables pixel by pixel calculation for increased resolution, visualization, and communication of the results (Stinson 2009). Fuzzy model used by another studies showed the potential of this model for evaluation of EC (Andriantiatsaholiniaina et al. 2004; Iliadis 2005).

KF, GNP and ATYF are proposed as candidate sites for inscription on the UNESCO's Natural World Heritage List with long history of protection (Table 1, Figure 1). These sites benefit from suitable protection management. In contrast, CWHC with the high value tree species (Cypress) was determined by the gamma model as a fragile ecosystem. The management plan in this site is based on reforestation and human interventions which increased the ecosystem vulnerability. It seems that a functional protection plan in this site should be based on strict protection without human interventions to achieve the climax stage. Management plan in LF is now based on the Boolean EC map. For a long time harvesting and human interventions have degraded this site. GNP and LF showed the highest Euclidian distance which may be a result of the geographical location of these sites, one in the west and the other in the east.

Due to the high ecological value of the Hyrcanian forests and vulnerability of this valuable ecosystem to the anthropogenic effects and climatic change, we could conclude that sustainable protection planning in these forests should be based on reality and use new models like fuzzy gamma model.

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