GIS-BASED MULTI-CRITERIA DECISION ANALYSIS FOR FOREST FIRE RISK MAPPING

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ABSTRACT:

The forested areas along the coastal zone of the Mediterranean region in Turkey are classified as first-degree fire sensitive areas. Forest fires are major environmental disaster that affects the sustainability of forest ecosystems. Besides, forest fires result in important economic losses and even threaten human lives. Thus, it is critical to determine the forested areas with fire risks and thereby minimize the damages on forest resources by taking necessary precaution measures in these areas. The risk of forest fire can be assessed based on various factors such as forest vegetation structures (tree species, crown closure, tree stage), topographic features (slope and aspect), and climatic parameters (temperature, wind). In this study, GIS-based Multi-Criteria Decision Analysis (MCDA) method was used to generate forest fire risk map. The study was implemented in the forested areas within Yayla Forest Enterprise Chiefs at Dursunbey Forest Enterprise Directorate which is classified as first degree fire sensitive area. In the solution process, "extAhp 2.0" plug-in running Analytic Hierarchy Process (AHP) method in ArcGIS 10.4.1 was used to categorize study area under five fire risk classes: extreme risk, high risk, moderate risk, and low risk,. The results indicated that 23.81% of the area was of extreme risk, while 25.81% was of high risk. The result indicated that the most effective criterion was tree species, followed by tree stages. The aspect had the least effective criterion on forest fire risk. It was revealed that GIS techniques integrated with MCDA methods are effective tools to quickly estimate forest fire risk at low cost. The integration of these factors into GIS can be very useful to determine forested areas with high fire risk and also to plan forestry management after fire.

1. INTRODUCTION

Forest fires seriously affect sustainability of forest resources especially in the dry regions covered with fire sensitive tree species (Demir et al. 2009). The coastline of Turkey from the eastern Mediterranean region to the Marmara Region, about 5.5 million hectares of forest lands are classified as first-degree fire sensitive areas (Akay et al., 2017). The average of 10,000-14,000 ha forests are burned annually as a result of over 2,000 forest fires occurred in Turkey (Sağlam et al., 2008).

Forest fires can cause serious damages on forest ecosystem that negatively affects sustainability of forest resources (Bilici, 2009). Forest fires reduce the economic value of trees and even cause loss of human lives. Besides, forest fires produce great amount of greenhouse gasses (CO_2 and CH_4) (Guido et al., 2004). After fire incidents, fire-damaged trees become more vulnerable to insects and fungus (Akay et al., 2007).

Forest fire risk mainly depends on various factors such as forest vegetation structures, topographic features, and climatic parameters (Carmel et al., 2009). Forest vegetation structures such as tree species, crown closure, and tree stage are separate factors that influences forest fire ignition and fire severity (Gao et al., 2011). The fire risk increases as the proportion of coniferous trees increases in a forest stand, while deciduous trees can increase fire resistance (Gazzard, 2012). Crown closure is another factor that has a positive relationship with forest fire risk (Bilgili, 2003). The fire risk is relatively low at early stages of trees, while risk is very high at young generations (Sağlam et al., 2008). Then, fire risk decreases from the mature to over mature stages, since accumulation of crown and surface fuels increases with stand age (Bilgili, 2003).

Topography is an important factor that affects the fire risk of the area (Erten et al., 2004). Fire potentially moves least rapidly down slopes and most rapidly up slopes. Besides, the fire risk increases as ground slope increases (Jaiswal et al., 2002). In term of aspect, fire risk is higher in south-facing aspects due to high temperature and low humidity (Lin and Sergio, 2009). Climatic parameters such as temperature, precipitation, and wind also play important role in forest fire risks.

In order to minimize the potential effects of fires on forest resources, forest fire risk zones should be determined and necessary precaution measures should be taken in these areas. Forest fire risk zones are defined as the areas where a fire is likely to start, and from where it can spread to other areas (Erten et al., 2004). A fire risk zone mapping is essential for an accurate assessment of forest fire problems (Jaiswal et al., 2002).

Forest fire risk maps can be generated based on spatial data layers representing various fire risk factors. Geographical Information System (GIS) techniques integrated with Multi-Criteria Decision Analysis (MCDA) method provides quick and effective solutions to such complex spatial problems (Jaiswal et al., 2002; Carmel et al., 2009). Analytical Hierarchy Process (AHP) is one of the widely used multi-criteria decision-support methods used in the field of forestry (Coulter et al., 2006; Gülci, 2014).

In this study, GIS-based AHP method was used to generate forest fire risk map. The method was implemented in Dursunbey Forest Enterprise Directorate (FED) which was categorized as one of the first-degree fire sensitive FEDs in Turkey.

2. MATERIAL AND METHODS

2.1 Study Area

The study area was Yayla FEC within the borders of Dursunbey FED in Balıkesir, Turkey (Figure 1). The areal distribution of forest resources with respect to FECs located in the Dursunbey FED is indicated in Table 1. The elevation ranges from 360 m to 1625 m with the average of 859.27 m. The ground slope varies between 0 and 208.89% with the average of 24.96%. The dominant trees in the study area are Black Pine, Brutian Pine, Oak, and Beech.

Figure 1. The study area map

FECs	High Forest	Degraded Forest	Total Forest
Candere	9475.00	1420.20	10895.20
Civana	6745.60	3095.30	9840.90
Çamlık	6379.50	729.10	7108.60
Durabeyler	11283.80	3998.30	15282.10
Dursunbey	7116.10	9533.30	16649.40
Gökçedağ	8987.00	5593.90	14580.90
Yayla	8521.60	5157.10	13678.70
Total	58508.60	29527.20	88035.80

Table 1.Forest resources in Dursunbey FED (ha) (URL-1)

2.2 GIS Database

The forest fire risk map was planned by using GIS-based AHP methods by considering risk factors including forest vegetation structures and topographic features. Climatic parameters were not included since they are uniform in the study area. To generate data layers for the risk factors, necessary digital data including forest management maps and topographic maps were obtained from Dursunbey FED. GIS applications were implemented by using ArcGIS 10.4.1.

2.2.1 Forest Vegetation Structures

Forest vegetation structures considered in this study were tree species, crown closure, and tree stage. The forest management map (1:25000) was used to generate land use map of Yayla FEC. Then, land use types (forest, agriculture, open areas, rocky areas, residential area, open areas-rocky areas, mines) were delineated (Figure 2). Finally, forest cover was produced by delineating the forested area which is border of the study site.
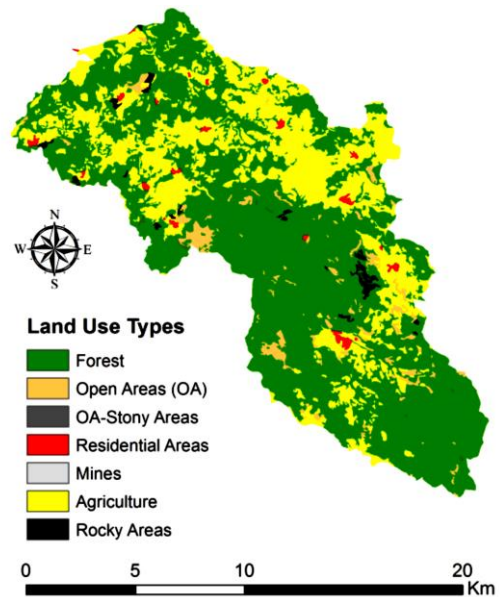

Figure 2. Land use map

The forest cover map was used to generate data layers for vegetation structures. There were total of 21 tree species or species compositions in the study area. Table 2 indicates tree species compositions and their stand type codes.

No	Stand Type Codes	Tree Species Composition
1	Çz	Brutian pine
2	Çf-Çz	Stone pine-Brutian pine
3	Çz-Çk	Brutian pine-Black pine
4	Çk-Çz	Black pine -Brutian pine
5	Çk	Black pine
6	Ar	Juniper
7	Çz-M	Brutian pine-Oak
8	Çk-M	Black pine- Oak
9	Ar-Dy	Juniper-Other deciduous trees
10	Ar-M	Juniper- Oak
11	M-Çz	Oak-Brutian pine
12	M-Çk	Oak-Black pine
13	Çk-Çs	Black pine-Yellow pine
14	Çs-Çk	Yellow pine-Black pine
15	M-Ar	Oak-Juniper
16	Çk-Kn	Black pine-Beech
17	Çk-Dy	Black pine- Other deciduous trees
18	Çk-G	Black pine- Hornbeam
19	Kn-Çk	Beech-Black pine
20	M	Oak
21	Dy	Other deciduous trees

Table 2. Tree species and species compositions in the study area

The crown closure is as a percent of total ground area covered by the crowns of trees or woody vegetation. The crown closure is divided into four classes including bare-land, sparse, moderate, and dense closures (Table 3). The fire risk increases as crown closure increases in the forested areas (Bilgili, 2003).

No	Crown closures	Total Covered Ground Area
1	Bare-land	0-10
2	Sparse	11-40
3	Moderate	41-70
4	Dense	>70

Table 3. Areal distribution (%) of crown closure classes

The tree stages, also defined as stage of forest stand development, are generally categorized under seven classes (Table 4). The fire risk is very high at young generations, while it decreases from the mature to over mature stages (Sağlam et al., 2008).

No	Tree Stages
1	(a) newly planted-average DBH*: < 8 cm
2	(a) regenerated and (b) young-average DBH: < 0-8 and 8-19.9 cm
3	(b) young-average DBH: 8-19.9 cm
4	(b) young and (c) mature-average DBH: 8-19.9 cm and 20-35.9 cm
5	(c) mature-average DBH: 20-35.9 cm
6	(c) mature and (d) overmature-average DBH: 20-35.9 and >36 cm
7	(d) overmature-average DBH: >36 cm

* DBH: Diameter of breast height taken as 1.3 m above the ground or above buttresses

Table 4. Tree stages

2.2.2 Topographic Features

Firstly, Digital Elevation Model (DEM) was generated using the contour lines (with 10 m intervals) on topographical maps (1:25000) (Figure 3). The slope map was produced based on the DEM (10 x 10 m). Then, slope map was reclassified into five classes (Table 5). Finally, the aspect map was produced based on the same DEM.

No	Slope Classes	Slope Values
1	Gentle	0-5
2	Low	5-15
3	Medium	15-25
4	High	25-35
5	Steep	>35

Table 5. Ground slope (%) classes

2.3 AHP Method

The fire risk map was developed by GIS-based Analytic Hierarchy Process (AHP) method. Myers and Alpert (1968) first described AHP and then it was modelled by Saaty (1977). The AHP method evaluates a set of evaluation criteria and search for the optimal solution among a set of alternative options. In the solution process of AHP, the study area was classified into four forest fire risk classes (options): low, moderate, high, and extreme. The main criteria were tree species, crown closure, tree stage, slope, and aspect. Decision maker's pairwise comparisons were used to generate a weight for each criterion. The relative importance between two criteria was measured based on a numerical scale from 1 to 9 (Table 6).

Importance Scale	Definitions
1	Equal importance
3	Weak importance of one over another
5	Essential or strong importance
7	Demonstrated importance
9	Absolute importance
2, 4, 6, 8	Intermediate values between the two adjacent judgments

Table 6. The relative importance values

Firstly, the relative importance values among sub-criteria were evaluated regarding with potential fires risk. The higher score was given when the criterion was more important. The normalized pairwise comparison matrix was used to compute the weighted averages of the sub-criteria. Then, "Reclassify" tool under "Spatial Analyst" extension of ArcGIS 10.2 was used to assign weighted average values to the corresponding criteria.

A pairwise comparison matrix A was generated to compute the weights for the different criteria (or sub-criteria). Each entry ($a_{ji} = 1/a_{ij}$) of the matrix A represents the importance of the jth criterion relative to the ith criterion. If $a_{ji} > 1$, the jth criterion is more important than the ith criterion.

In the next step, normalized pairwise comparison matrix was generated. The column vector of B was produced by using fallowing formula (Gülci, 2014):

$$b_{ji} = \frac{a_{ji}}{\sum_{j=1}^{n} a_{ji}} \tag{1}$$

where b_{ji} is each entry at the column and n is the number of criteria. Then, weighted averages of the criteria (w_j) were computed by averaging the entries on each row using formula below (Gülci, 2014):

$$w_j = \frac{\sum_{i=1}^{n} c_{ji}}{n} \tag{2}$$

The ratio of Consistency Index (CI) and Random Index (RI) were also computed to check the consistency of the evaluations made for the pairwise comparison matrices. The small value of this ratio (<0.1) reveals that consistent results can be achieved from the AHP method.

After consistency analysis, "Spatial Analyst" extension of ArcGIS 10.4.1 was used to assign weighted average values (w_j) to the corresponding criteria. Then, "extAhp 2.0" plug-in was used to combine the weighted averages of the criteria and determine the AHP scores. Finally, the forest cover in the study area was categorized according to fire risk classes.

3. RESULTS AND DISCUSSION

3.1 GIS Data Layers

3.1.1 Forest Vegetation Structures

The areal distribution of land use types is indicated in Table 7. It was found that most of the study area was covered by forests (65.26%), followed by agriculture (29.54%) and open areas (3.46%). Other land use types were insignificant. In terms of tree species, the most common species was Black pine (45.55%), followed by Oaks (12%). Figure 3 indicates the map of tree species represented by their associated stand type codes.

Land Use Types	Area
Forest	65.26
Agriculture	29.54
Open Areas (OA)	3.46
Rocky Areas	0.85
Residential Areas	0.81
OA-Stony Areas	0.07
Mines	0.01

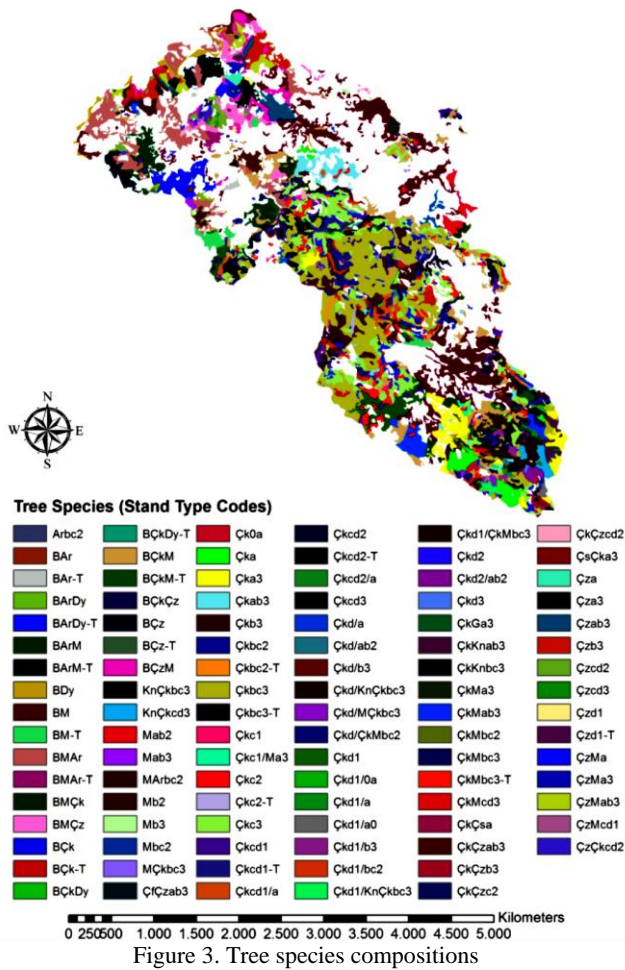Table 7. Areal distribution (%) of the land use types

Figure 3. Tree species compositions

The crown closure map is shown in Figure 4. The results indicated that crown closure was dense in 43% of the study area, while it was bare-land in 41% of the area. The percentages of the sparse and moderate closure were 6% and 10%, respectively.
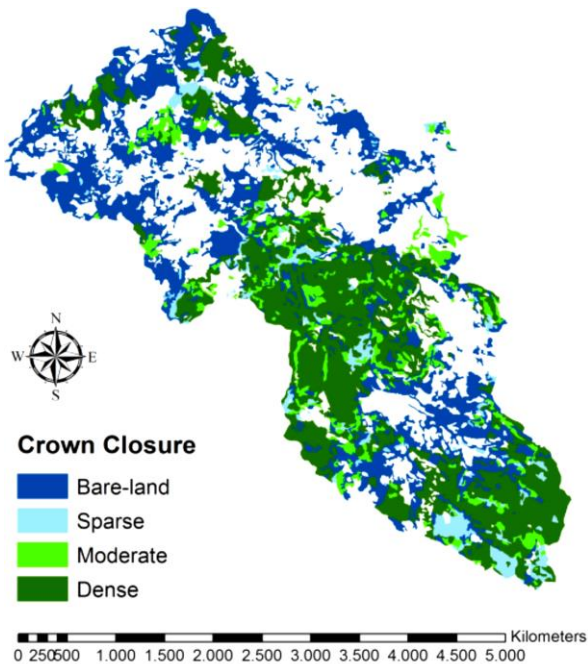

Figure 4. The crown closure map
The results indicated that half of the study area was covered by

mature tree stages (DBH: 20-35.9 cm). The tree stages at young and mature combination covered the second largest area (19%). It was reported that the fire risk is very high at young generations (Sağlam et al., 2008).

3.1.2 Topographic Features

The ground slope map indicated that 31.76% of the study area was on very steep slope class, while 22.19% was on medium slope class (Figure 5, Table 8). Previous studies marked that fire risk is relatively higher on steep terrains (Jaiswal et al., 2002).
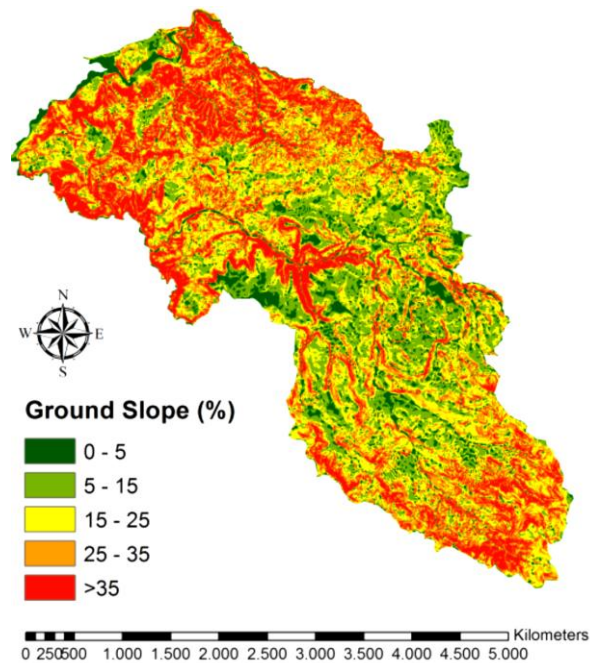

Figure 5. Ground slope map

Slope Classes	Area
Gentle	8.00
Low	16.35
Medium	22.19
High	21.70
Steep	31.76

Table 8. Areal distribution (%) of slope classes

The aspect map of the study area was also generated. The results indicated that 20.37% of the study area was located on north aspect, followed by north-east aspect (14.80%) (Table 9, Figure 6). The proportion of south-facing aspects was 28.12%, which has higher fire risk due to high temperature and low humidity (Lin and Sergio, 2009).

Aspects	Area
N	20.37
NE	14.80
E	9.62
SE	7.10
S	8.11
SW	12.91
W	13.22
NW	13.86

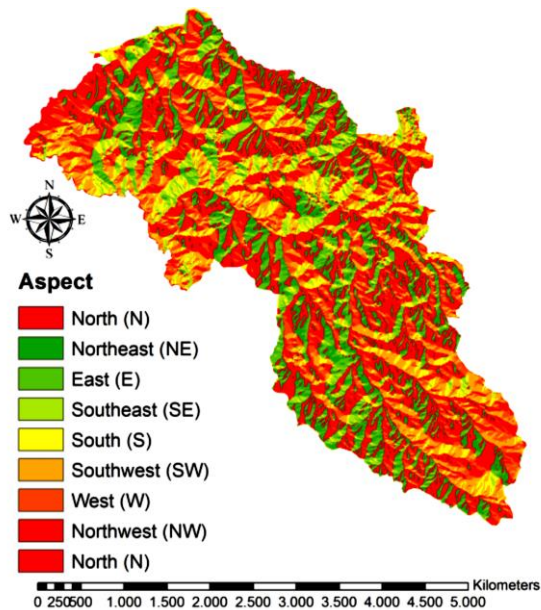Table 9. Areal distribution (%) of the aspects

Figure 6. Aspect map

3.2 AHP Results

A pairwise comparison matrix was generated to compute the weighted values for the criteria and their sub-criteria. The weighted values of tree species criteria (and sub-criteria) were indicated in Table 10. The pure coniferous forest followed by mixed coniferous forest had the highest weighted values. Oak tree and other deciduous trees had the lowest weighted values (Gazzard, 2012).

No	Tree Species Composition	Values
1	Brutian pine	0.084
2	Stone pine-Brutian pine	0.084
3	Brutian pine-Black pine	0.075
4	Black pine -Brutian pine	0.075
5	Black pine	0.065
6	Juniper	0.065
7	Brutian pine-Oak	0.056
8	Black pine- Oak	0.047
9	Juniper-Other deciduous trees	0.047
10	Juniper- Oak	0.047
11	Oak-Brutian pine	0.047
12	Oak-Black pine	0.037
13	Black pine-Yellow pine	0.037
14	Yellow pine-Black pine	0.037
15	Oak-Juniper	0.037
16	Black pine-Beech	0.037
17	Black pine- Other deciduous trees	0.028
18	Black pine- Hornbeam	0.028
19	Beech-Black pine	0.028
20	Oak	0.019
21	Other deciduous trees	0.019

Table 10. The weighted values of tree species

Table 11 indicates the weighted values of crown closure criteria (and sub-criteria). It was found that forests with dense crown closure had the highest weighted values, followed by moderate crown closure (Bilgili, 2003). The weighted values of tree stage criteria (and sub-criteria) were indicated in Table 12. The regenerated and young stages had the highest weighted values, while overmature stage had the lowest values.

No	Crown closures	Values
1	Bare-land	0.09
2	Sparse	0.18
3	Moderate	0.32
4	Dense	0.41

Table 11. The weighted values of crown closure

Tree Stages	Values
(a) newly planted-average DBH*: < 8 cm	0.08
(a) regenerated and (b) young-average DBH: < 0-8 and 8-19.9 cm	0.24
(b) young-average DBH: 8-19.9 cm	0.24
(b) young and (c) mature-average DBH: 8-19.9 cm and 20-35.9 cm	0.18
(c) mature-average DBH: 20-35.9 cm	0.16
(c) mature and (d) overmature-average DBH: 20-35.9 and >36 cm	0.08
(d) overmature-average DBH: >36 cm	0.03

Table 12. The weighted values of tree stages

The weighted values of ground slope criteria (and sub-criteria) were indicated in Table 13. The steep slope and high slope areas had the highest weighted values. For the aspect criterion, south and southwest aspects had the highest weighted values, while north aspect had the lowest (Table 14).

Slope Classes	Values
Gentle	0.04
Low	0.12
Medium	0.20
High	0.28
Steep	0.36

Table 13. The weighted values of slopes

Aspects	Values
N	0.05
NE	0.09
E	0.09
SE	0.14
S	0.20
SW	0.20
W	0.09
NW	0.09
N	0.05

Table 14. The weighted values of the aspects

The weighted averages of the criteria were combined and foret fire risk map was generated by using "extAhp 2.0" tool in ArcGIS 10.4.1. Table 15 shows the weighted average values of criteria assigned to forest fire risk map. The result indicated that the most effective criterion was tree species, followed by tree stages. Crown closure and slope criteria had the similar effect of fire risk, while aspect had the least effective criterion on forest fire risk.

Criteria	Values
Tree species	0.28
Crown Closure	0.19
Tree Stage	0.22
Slope	0.19
Aspect	0.13

Table 15. The weighted values of criteria

Figure 7 indicates the distribution of forest fire risk map with respect to all the criteria. Based on the GIS-based AHP method,

about 32% and 26% of the forests in the study area were within the moderate and high fire risk zones, respectively (Table 16). About 24% of the forests were classified as extreme fire risk areas.
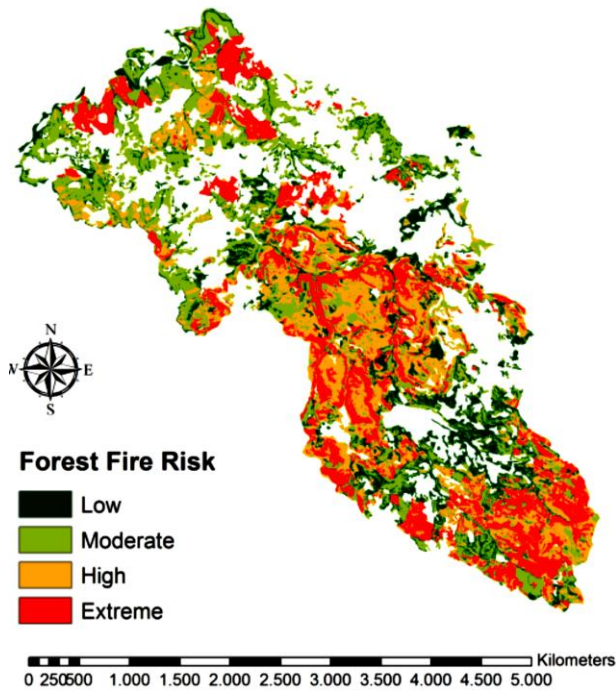

Forest Fire Risk

- Low
- Moderate
- High
- Extreme

Figure 7. Forest fire risk map

Fire Risk	Area
Low	17.97
Moderate	32.41
High	25.81
Extreme	23.81

Table 16. The areal distribution (%) of fire risk levels

4. CONCLUSIONS

Forest fires may cause devastating impacts on forest resources, and important economic losses and even threaten human lives. It is critical to determine the forested areas with fire risks and thereby taking necessary precaution measures to minimize the damages on forest resources. In this study, GIS-based Multi-Criteria Decision Analysis (MCDA) using AHP method was used to generate forest fire risk map. The method was implemented in Dursunbey Forest Enterprise Directorate which is classified as first degree fire sensitive area in Turkey. In the solution process, forest vegetation structures (i.e. tree species, crown closure, tree stage) and topographic features (i.e. slope and aspect) were considered as main criteria. Quick and effective prediction of forest fire risk will assist decision makers take necessary action and minimize fire damage on the forest resources. Possible future studies may include considering additional fire risk factors such as distance to road network, distance to residential areas, and climatic parameters in developing fire risk maps.

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