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GIS-based multi-criteria decision analysis for forest fire susceptibility mapping: a case study in Harenna forest, southwestern Ethiopia

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Abstract: Forest fire is influenced by ecological, human and climatic factors. Forest fire directly causes biodiversity loss and forest degradation and affects global climate change. The present study deals with identification of fire-prone areas in Harenna forest using remote sensing and GIS techniques. Parameters used for the analysis of the forest fire risk susceptibility were physiographic data and proximity factors, such as elevation, slope, aspect, vegetation type, proximity to settlements and distance from roads. All these parameters have direct and or indirect influence on the occurrence of fire. Multi-criteria decision-making technique was adopted to derive fire susceptibility map of the area. The final output shows forest fire-risk areas of Harenna forest in four categories such as very high risk, high risk, moderate risk and low risk. An extent of 22,981 ha (3.4 %) of forest cover in the area was of very high risk and 1,59,229 ha (24 %) was of high risk to forest fire. The extents of moderate and low fire-risk areas were 2,52,327 ha (37.3 %) and 1022 ha (0.15 %), respectively. Identity of locations of fire-prone areas in advance can be used effectively to plan fire control measures in forest and wildlife management areas.

Resumen: Los incendios forestales son influenciados por factores ecológicos, humanos y climáticos. El fuego en el bosque causa directamente pérdida de biodiversidad y degradación del bosque, y afecta el clima del planeta. En este estudio se aborda la identificación de áreas con posibilidades de incendiarse en el bosque Harenna usando técnicas de percepción remota y SIG. Los parámetros usados para el análisis de la susceptibilidad al riesgo de incendios forestales fueron datos fisiográficos y factores de proximidad, como altitud, pendiente, orientación, tipo de vegetación, proximidad a asentamientos humanos y distancia desde los caminos. Todos estos parámetros tienen una influencia directa o indirecta sobre la ocurrencia del fuego. Se adoptó la técnica multicriterio de toma de decisiones para elaborar un mapa de susceptibilidad al fuego del área. El resultado final muestra áreas del bosque Harenna con riesgo de incendio forestal en cuatro categorías: riesgo muy alto, riesgo alto, riesgo moderato y riesgo bajo. Una extensión de 22,981 ha (3.4 %) de cobertura forestal en el área fue de riesgo muy alto y 1,59,229 ha (24 %) fue de riesgo alto de incendio forestal. Las extensiones de las áreas con riesgo de fuego moderado y bajo fueron 2,52,327 ha (37.3 %) y 1022 ha (0.15 %), respectivamente. El conocer con anticipación la identidad de las localidades de áreas susceptibles al fuego puede usarse de forma efectiva para planear medidas de control del fuego en el bosque y en áreas de manejo de vida silvestre.

Resumo: O incêndio florestal é influenciado por fatores ecológicos, humanos e climáticos. O incêndio florestal é uma causa direta da perda de biodiversidade e de degradação da floresta, afetando o clima global. O presente estudo debruça-se sobre a identificação de áreas susceptíveis ao fogo na floresta de Harenna utilizando técnicas de deteção remota e de SIG. Os parâmetros utilizados para a análise da susceptibilidade de risco aos incêndios florestais foram os dados

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fisiográficos e os fatores de proximidade, tais como a elevação, o declividade, o aspecto, o tipo de vegetação, a proximidade de assentamentos e a distância às estradas. Todos estes parâmetros têm uma influência direta e ou indireta, sobre a ocorrência de incêndios. Técnicas multicritério de tomada de decisão foram adoptadas para elaborar o mapa de susceptibilidade da área ao fogo. O resultado final mostra as áreas de risco de incêndio na floresta de Harenna em quatro categorias: risco muito alto, alto risco, risco moderado e risco baixo. Uma extensão de 22,981 ha (3.4%) de cobertura florestal na área foi classificada como sendo de muito alto risco e 1,59,229 ha (24%) de alto risco para incêndios florestais. As extensões de áreas de risco de incêndio moderado e baixo foram de 2,52,327 ha (37.3%) e 1,022 ha (0.15%), respectivamente. A identificação antecipada dos locais das áreas propensas ao fogo pode ser utilizada de forma eficaz para planear medidas de controle de incêndio em áreas florestais e de gestão da vida selvagem.

Key words: Forest fire-risk zone, multi-criteria decision-making, remote sensing.

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Introduction

Forest is a major natural resource, which plays an important role in maintaining natural ecological balance. The health of a forest in any given area is a true indicator of the ecological conditions, habitat composition and species richness prevailing in that area (Demeke & Afework 2014). The spread of invasive align species (Joshi *et al.* 2015) has become a threat for the sustenance of natural habitats in several tropical nations. Further, fire is one of the greatest enemies of standing vegetation and wildlife (Jaiswal *et al.* 2002; Levine *et al.* 1999) and is a dominant disturbance in many wild ecosystems worldwide (Morgan *et al.* 2001; Xuefei *et al.* 2007). Fire has application in traditional agricultural and pastoral systems and in natural ecosystem processes. Small trees and their regeneration are often adversely affected by fire. Even big trees are not safe if the fire is severe. Ground fire destroys organic matter, which is needed to maintain an optimum level of humus in the soil (Geldenhuys *et al.* 2004). Annual fires affect the growth of grass, herbs and shrubs, which may result in increased soil erosion (Kandya *et al.* 1998). Forest fires are considered to be a potential hazard with physical, biological, ecological and environmental consequences (Goldammer 1999). According to FAO (2009), global forest habitats have been declining at a rate of over 1,41,000 ha per year. Forest areas in Ethiopia now stand at around 13 million ha, which is 11.9 % of the total land area of the country. Even remnant forests and woodlands are under serious pressure as a result of high human population and livestock density.

The Bale Mountains of Ethiopia is the largest area of the Afro-alpine habitat in the African continent, which is considered as a unique biodiversity hotspot (Williams *et al.* 2004). This area hosts numerous endemic species. However, fire is one of the serious problems in the area (Gutema *et al.* 2013; Misrak *et al.* 2012). To understand the behaviour of forest fire, factors that contribute to make the habitat fire-prone and influence fire behaviour are also essential, which would arise in forest fire-risk zone mapping (Chuvieco & Congalton 1989). Satellite remote sensing has opened up opportunities for qualitative and quantitative analyses of forest and other ecosystems at all geographic and spatial scales. It has also been effectively used in monitoring to detect forest fire. GIS-based models offer better understanding about the conditions where a major part of the forest land is being encroached upon by human population (Jain *et al.* 1996) and forest fire. Such maps will help forest administration to prevent, minimize or control fire-risk, and take proper actions when fire breaks out (Chuvieco & Sales 1996). During the present investigation, fire susceptibility area identification was done in the Harenna forest of Bale Mountains National Park (BMNP) to formulate strategies to reduce adverse effects of forest fire in the area.

Materials and methods

Study area

Bale Mountains National Park lies in the southeastern part of Ethiopia, bounded by latitudes 6° 0' 00" N - 6° 57' 28" N and longitudes 39° 15'00 E - 40° 42'25" E, covering a total area of

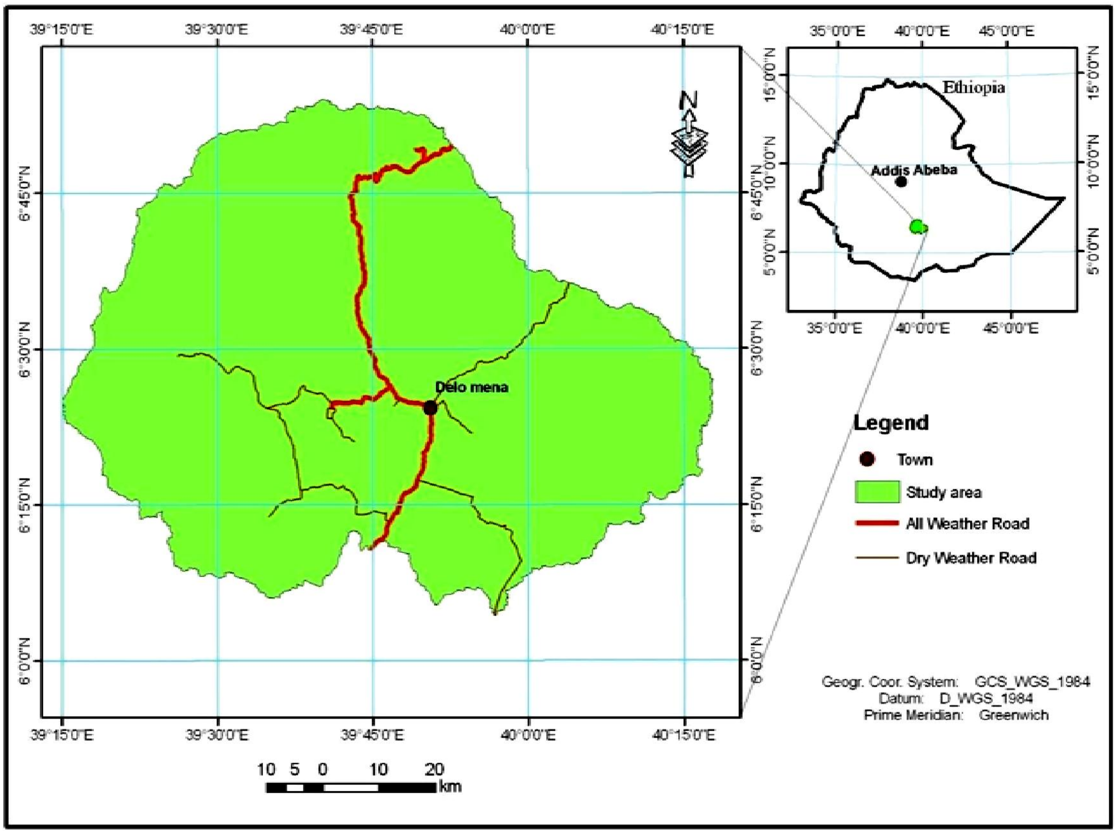


Fig. 1. Location map of the study area.

6805.92 km² (Fig. 1). The study area is characterized by highly rugged topography. The altitudinal variation of the area ranges from 735 to 4377 m asl. The climate in BMNP is characterized by a high rainfall and periods of cloudy weather, interspersed with periods of sunny days with brilliant blue skies. The dry season is from November to February and wet season is from March to October. The annual rainfall in the area ranges from 822 mm to 1447 mm.

The extensive natural forest in the southern declivity of the Bale massif is known as 'Harenna Forest'. Vegetation in different altitudinal zones in the study area was described by Miehe & Miehe (1994). It includes *Erica* forest as well as rainforest and subtropical savanna habitats (Chiodi & Pinard 2011). At around 1450 m altitude, the open sclerophyllous Combretaceae forests form the lowest zone of the montane forest belt of relatively dry, up to 40 m tall rainforest belt with scattered emergence of *Podocarpus gracilior,* an open upper canopy of *Warburgia ugandensis*, *Croton macrostachyus* and *Syzygium guineense*. More densely covered, 10-30 m tall stratum consisting of *Filicium decipiens, Celtis gomphophylla* and *Trema orientalis* forms the upper limits of this stratum. The uppermost montane forest belt is the *Hagenia-Hypericum* zone mainly characterized by *Hagenia abyssinica*, *Hypericum revolutum*, *Rapanea melanophloeos* and *Pittosporum viridiflorum*.

Methods

For the present study, Landsat 7 Enhanced Thematic Mapper (ETM with path/row 167/168 and 055/056) 1986, satellite data SPOT 2006 (path 167/168 and row of 055/056) and topographic map of the scale 1:50,000 (EMA) were used for digitizing roads and settlements. Digital Elevation Model (DEM) of the study area was obtained from 90 m resolution SRTM data to derive elevation, slope and aspect for forest fire susceptibility. Ground points for classification of SPOT 2006 and verification of accuracy assessment of the classified images were achieved using a GPS. A flow chart of the procedures followed is presented in Fig. 2. All the input datasets were georeferenced to Adindan UTM Zone 37 N coordinate reference system and thematic maps were generated (Fig. 3).

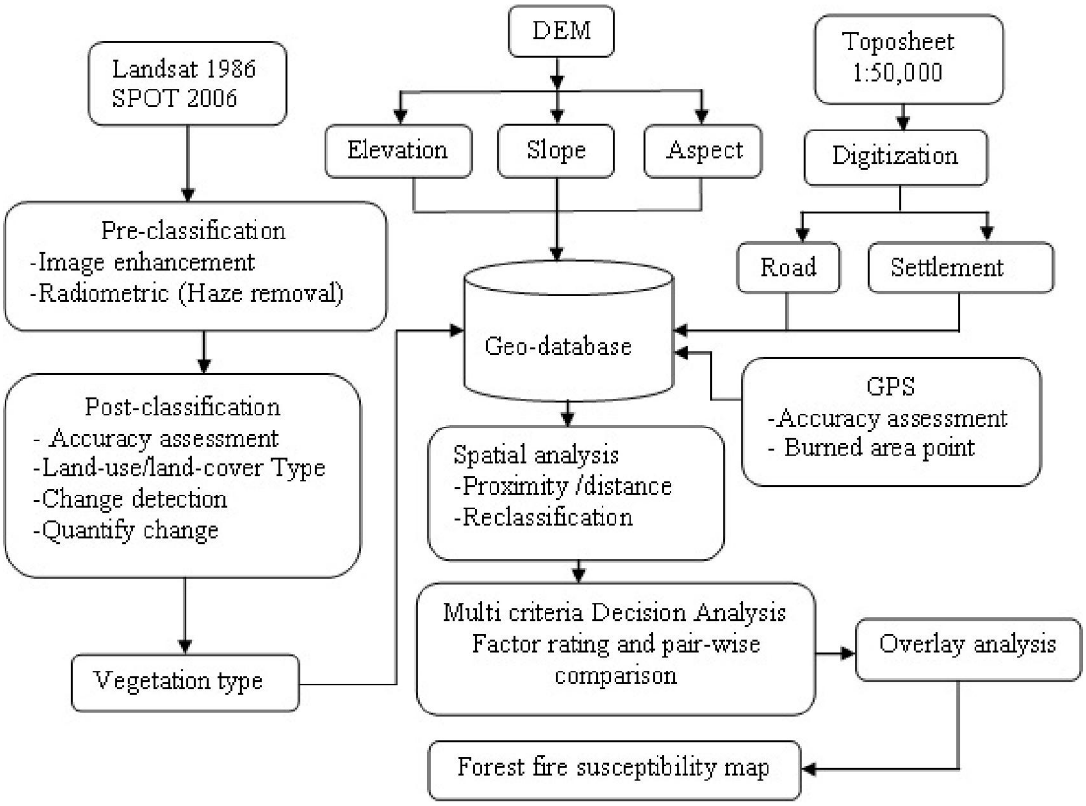
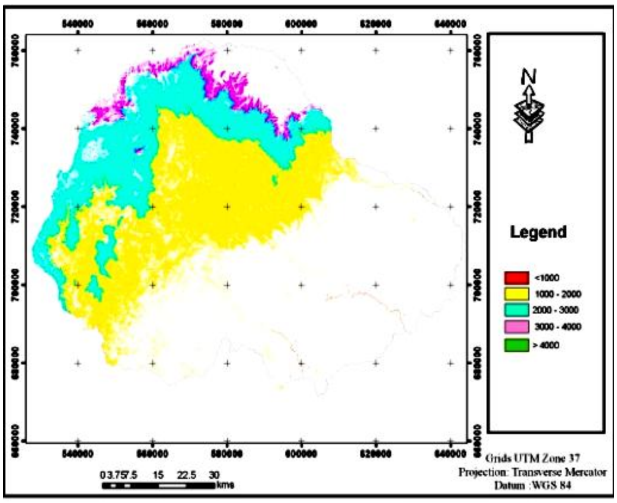


Fig. 2. Methodology flow chart.

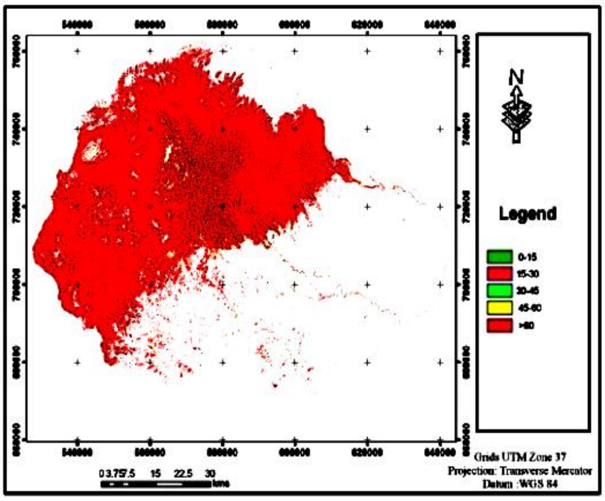
Image analysis software ERDAS Imagine 9.2 was used in the pre-image processing and post-classification investigation of land-use/land-cover types. ArcGIS 10.1 was applied for the organization of raster and vector data in personal geodatabase, and used for analysis. Factor maps of forest fire-risk were reclassified and standardized by ArcGIS 10.1. Forest fire susceptibility map was generated by IDRISI Andes through multi-criteria evaluation (MCE). The land-use/land-cover classification was done on the basis of reflectance characteristics of different land-use/land-cover types using false colour composites (FCCs) of TM bands 5, 4, and 2 (RGB). In the field, it was cross checked using Garmin GPS. Based on the field check points, supervised classification with maximum likelihood classifier decision rule was done following three stages, *viz.*, assigning training sites, classification and outputs. Proximity to roads and settlements were consi-dered as proximity data sets. Elevation, slope and aspect were used as major inputs for physiographic factors. From land-use/land-cover map of 2006, bareland, agriculture and settle-ments were excluded for consideration in fire-risk susceptibility analysis. Therefore, these zones were given no weights in determination of fire rating classes. All vector parameters were rasterized and determined to the fixed spatial extent and cell size of 30 m x 30 m. Natural physiographic data sets were re-classified to scale the data as the proximity data set. The level of influence of each of these factors was quantified before running the analysis. Consequently, Satty's technique (Saaty 1980) was applied to derive weight factor map (level of influence) through pair-wise comparison between criteria using IDRISI Andes. The weight of each of the factors was determined by taking the principal eigenvector of square reciprocal matrix of pair-wise comparison between criteria. Finally, by using raster calculator of spatial analyst extension, the weighted factor map data layers of fire-risk were integrated using weighted overlay method to produce forest fire susceptibility map of the study area.

Multi-criteria decision-making (MCDM) technique

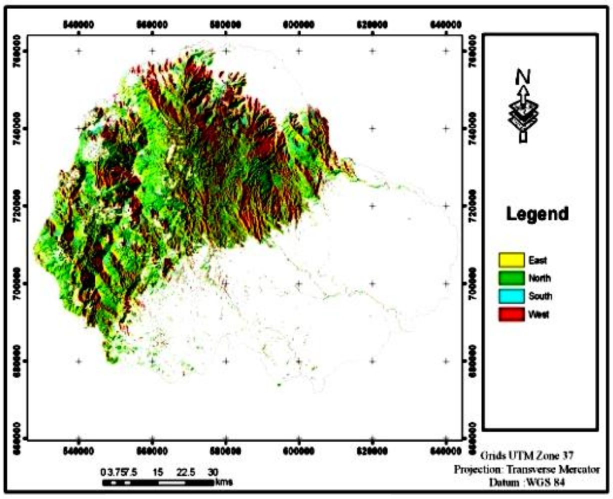
Factors that influence fire-risk in the study area were analyzed in the following order of importance: vegetation type, slope, elevation, aspect, settlements and roads. Prior to the inte-



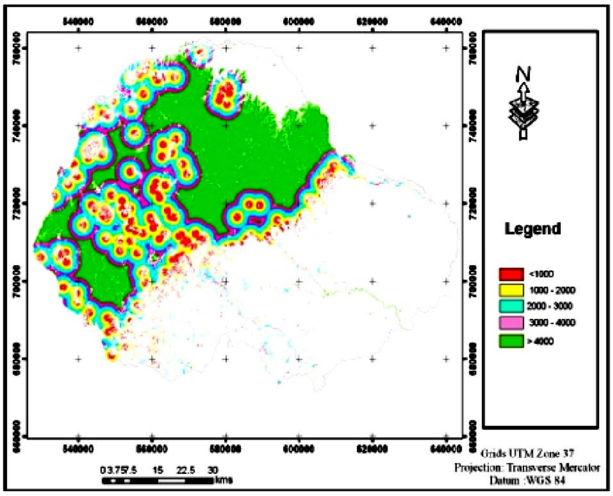
Forest elevation



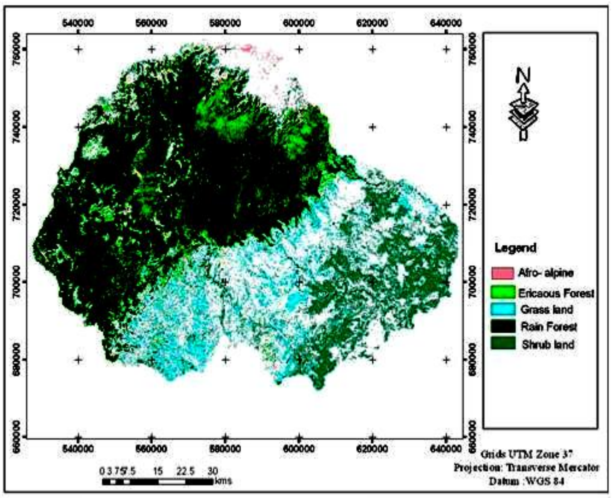
Forest slope



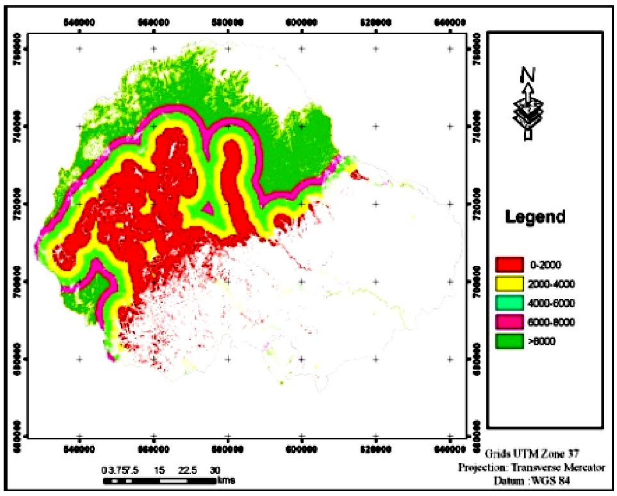
Forest aspect map



Settlement proximity to forest



Vegetation map

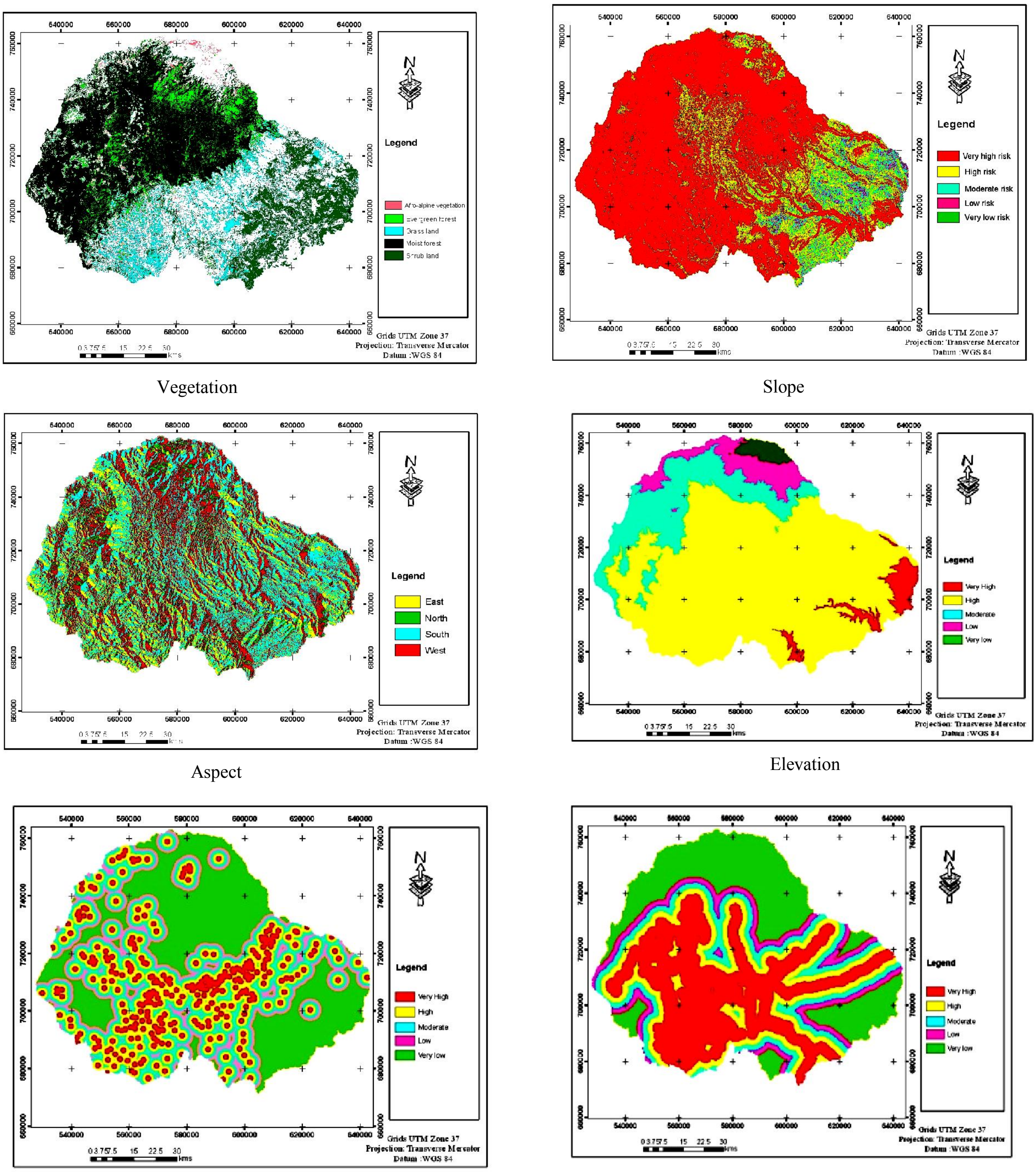


Road proximity to forest map

Fig. 3. Thematic maps.

Table 1. Pair-wise comparisons of factor layers.

Layers	Road	Settlement	Elevation	Aspect	Slope
Settlement	2				
Elevation	3	2			
Aspect	5	3	2		
Slope	6	4	3	2	
Vegetation type	7	5	4	3	2



Vegetation

Slope

Aspect

Elevation

Settlement

Road

Fig. 4. Integration of reclassified thematic maps.

Table 2. Principal eigenvector of the pair-wise comparison matrix Consistency ratio (CR) = 0.02.

Factor	Weight
Vegetation type	0.3854
Slope	0.2531
Aspect	0.1626
Elevation	0.0983
Settlement	0.0627
Road	0.0380

gration of the factors, weights and map scores were assessed based on analytic hierarchy process (AHP). A pair-wise comparison matrix (Table 1) was developed using nine point importance scale of less importance (extremely, very strongly, strongly and moderately) and more importance (equally, moderately, strongly, very strongly and extremely), following Jose & Duckstein (1993) based on physiographical and proximity factors for forest fire. To produce the best fit set of weights, the principal eigenvector of the above pair-wise comparison matrix was computed using weights. From the principal eigenvector calculation, the relative importance of each of the parameters was determined as the higher the weight, the more influence a particular factor on forest fire occurrence. Accordingly, all reclassified factor layers were used in weighted overlay analysis (Fig. 4) by applying equation given below, and the Harenna forest fire susceptibility map was produced.

The equation: The Forest Fire Susceptibility Map = (Vegetation type) × 0.3854 + (Slope) × 0.2531 + (Aspect) × 0.1626 + (Elevation) × 0.0983 + (Settlement) × 0.0627 + (Road) × 0.0380.

Results

The consistency ratio (CR) calculated was 0.02, and each of the parameters were assigned weights as given in Table 2. Table 3 shows the derived factor layers relative value and assigned rank 1 to 5 showing the fire sensitivity. Grassland had highest ignition risk, which was accounted for 48603 ha (7.1 %) in the present study area. Shrubland was the second highest flammable area, with an extent of 81805 ha (12 %), followed by Afro-alpine vegetation (22827 ha, 3.4 %), evergreen forest (55298 ha, 8.1 %) and moist forest (236976 ha, 34.8 %). Vegetation type, temperature and humidity are correlated with altitudinal factors. In the present study area, afro-alpine vegetation is limited to higher altitudes, while deciduous forest and shrub lands are found in lower altitudes. The elevation index relates this information with forest fire, as high temperatures, low humidity and availability of more dry organic matters on the ground increase the chance of ignition. Slope influences forest fire as it determines the speed of fire, which travels most rapidly up-slopes and least rapidly down slopes. Steep slope increases the rate of spread of fire due to more efficient connective preheating and ignition. Aspect has potential influence on forest fire weighted next to slope, and classified in to four major classes such as east (45°-136°) south (136° - 225°), west (225° - 315°) and north (315° - 345°). Forest fire-risk decreases farther from the centre. Forests located near roads are more fire-prone. While collecting leaves and preparing charcoal, people carelessly throw matches and burning ends of cigarettes, which cause of forest fires in the study area.

Table 4 describes the forest fire susceptibility levels and the corresponding degree of fire risk susceptibility. Out of the total area of 6,80,592 ha., 3.4 % falls in the category of 'very high' fire susceptibility risk, followed by 24 % under high risk, 37.3 % moderate risk and 0.15 % low risk. Validation of the output map tested by overlaying fire spot points revealed that burnt areas were located in the very high fire-risk susceptibility areas (Fig. 5). The areas under very high, high and moderate forest fire susceptibility levels are those areas where fire is unintentionally caused by human activities.

Discussion

In the study area, forests are traversed by several foot paths (forest tracks), allowing local people and herders to cause forest fire. Locations closer to settlements and tracks are found to be of high fire-risk areas. Cultural practices of villagers can lead to accidental fires. The fire-risk factor decreases farther from the centre of human activities. Human, animal and vehicular movement and activities on tracks provide opportunities for accidental and intentional fires. The rank decreased with the increase in distance from settlements and tracks. Vegetation in higher slopes is seasonally dry and gets fire during summer months (Lawrence *et al.* 2006). Once fire starts, it spreads faster through up-slopes than down-slopes, and along steeper slopes than gentle ones. The main cause for forest fire in the area is intentional fire put by villagers, who move through

Table 3. Derived layers and ranking for forest fire susceptibility.

Derived layers	Eigen vector	Sub classes	Rank	Fire sensitivity
Vegetation type	0.3854	Grass land	5	Very high risk
		Shrub land	4	High risk
		Evergreen forest	3	Moderate
		Moist forest	2	Low risk
		Afro-alpine vegetation	1	Very low risk
Slope (°)	0.2531	0 -15	1	Very low risk
		15-30	2	Low risk
		30-45	3	Moderate
		45-60	4	High risk
		> 60	5	Very high risk
Aspect	0.1626	West	5	Very high risk
		East	5	Very high risk
		South	3	Moderate risk
		North	3	Moderate risk
Elevation (m)	0.0983	0 - 1000	5	Very high risk
		1000-2000	4	High risk
		2000-3000	3	Moderate risk
		3000-4000	2	Low risk
		> 4000	1	Very low risk
Settlement (m)	0.0627	< 1000	5	Very high risk
		1000-2000	4	High risk
		2000-3000	3	Moderate risk
		3000-4000	2	Low risk
		> 4000	1	Very low
Road (m)	0.0380	0-2000	5	Very high risk
		2000-4000	4	High risk
		4000-6000	3	Moderate risk
		6000-8000	2	Low risk
		>8000	1	Very low risk

Table 4. Extent of forest fire susceptibility levels.

Risk level	Degree of fire susceptibility	Area (ha)	Area (%)
I	Very high risk	22981	3.4
II	High risk	159229	24
III	Moderate risk	252327	37.3
IV	Low risk	1022	0.15

the area. The local community uses fire for honey harvest. They burn dry shrub vegetation during the summer months (Misrak *et al.* 2012) to generate fresh pasture immediately when it rains, to support their livestock.

Vegetation type contributes very high effect in the ignition and to spread fire due to flammability difference as compared to other factors. Ignition of fire depends on fuel flammability (Albini 1976; Rothermel 1983). Though the environment is suitable for a fire to start, it cannot start in the absence of ignition and essential quantity of flammable materials. In the study area, most fires have originated from grass and shrub lands, due to high flammability of these fuel sources. Fire easily spreads the surrounding forest areas, which results severe damage on forest. Slope and aspect of the terrain also have influence on fire-risk, as they control the vegetation density and composition in the area. Steeper slopes lead to less fuel moisture and less air humidity (Pandey & Barik 2006).

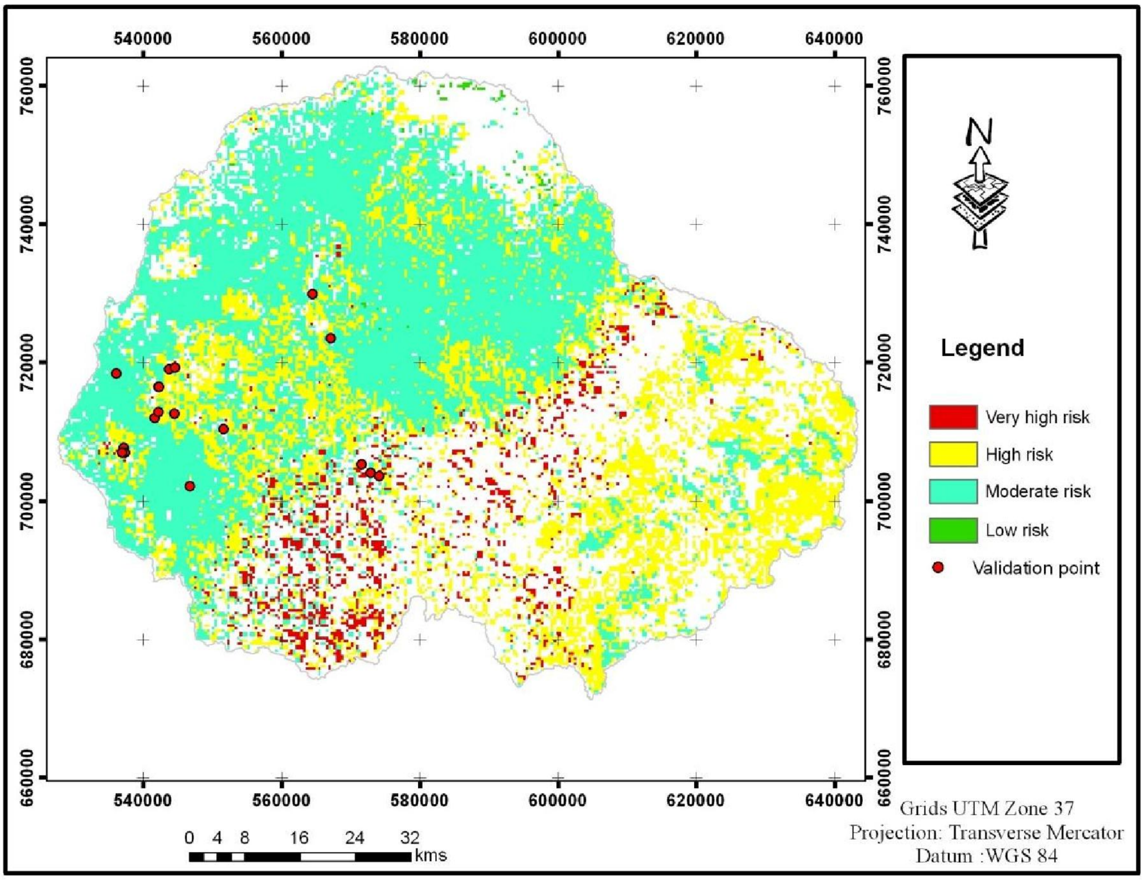


Fig. 5. Forest fire susceptibility map with validation points.

Rapid spread of fire upslope is made possible with the wind, which supplies more oxygen to the fire front and affects the rate at which fuels dry ahead of a fire front (Goldammer & de Ronde 2004). An increase in the speed of wind results in an increased rate of fuel drying and consequent increase in the spread of fire. In the present study area, most of the fire scars are distributed on steeper slopes than on gentle slopes. The study area is characterized with slopes of > 60° over a wide portion of the forest cover. Thus, the study area is highly influenced by the effect of slope, and more susceptible to forest fire.

Aspect does not have an effect on the ignition. However, it has influence on the rate at which fuels dry and consequently affect fire behaviour. The gradients facing east and west receive more heat during the day time. As a consequence, east and west aspects are drier compared to aspects facing north and south (Goldammer & de Ronde 2004). Aspect also has a role in species distribution, as certain vegetation types are found on certain aspects (Chuvieco 1999), mainly influenced by the vegetation composition. Frequent fires are expected on aspects exposed to sun for long hours in the study area. Forests in the eastern and western aspects are exposed to the direct effect of sun, and have high occurrence of fire. The northern and southern aspects provide more moisture, less exposed to sun, and hence drying of fuel is slow, which results in less occurrence of fire.

Areas in the highest elevation have no fire incidence. The general trend indicates that temperature reduces and humidity increases with increased elevation (Rothermel 1983). The moisture content of fuel is high in elevated areas, which reduces the flammability, and thus reducing chance of fire incidence. In the study area, forest habitats more susceptible to fire based on the elevation classes are in the ranges of 1000 to 2000 m altitude. Most of the forest cover in the study area was found in these elevation classes.

Areas near to settlements are of very high fire-risk zones by considering a combination of factors such as high human disturbances, favourable vegetation types (mostly grass and shrub), steep slopes and western and eastern aspects. There are several settlements inside the study area. Most of the fire originated from intentional activities of human beings such as careless use of fire for forest clearing purposes. Lack of environmental awareness of the settlers has also been a reason for frequent occurrence of fire in the study area.

Roads and foot paths facilitate poaching and illegal transport of forest products. On the other hand, roads are critical in improving forest management and emergency response of forest and wildlife managers and other officials. The study area as a whole does not have motorable road network for the authorities to control illegal forest harvesting and to control and manage forest fire. Hence, the present study area experiences frequent forest fire, which results in high loss in forest cover of the area. Very high fire-risk susceptible areas are those in the slopes with grass and shrub vegetation; lower altitudinal areas, dominated by eastern and western phasing aspects and near to settlements and foot paths. High susceptible categories are generally falling in some part of the grassy and shrub land areas on higher slopes and moderate elevation areas. Moderate fire-risk susceptible areas are largely dominated by moist forest. Low fire-risk areas are forest cover found away from settlements, foot paths and at higher elevations. Human population pressure and the corresponding demands for agricultural land, grazing land, built-up and forest products are earmarked as major causes for forest cover loss (Guild *et al*. 2004). Non-coherent decisions, weak land-use policies and governmental institutions and agencies have also led to the transformation of natural habitats to other land-use/land-cover classes in the area as reported elsewhere (Foody 2003).

The results of the present study have revealed that within the period of twenty years (1986-2006), forest cover of the present study area has deteriorated due to anthropogenic impacts. The cover change and fire-risk area mapping from remotely sensed imagery and GIS have helped to determine the extent of forest cover change, and mapping the fire-risk areas. Most changes are effected due to transformation of forest in to other land-use types and recurrent forest fire. Early identification of fire-risk areas will help in the prevention of fire outbreak. Thus, the fire-risk susceptibility map of the area can be used by forest officials to develop and improve forest fire fighting strategies.

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