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RS AND GIS-BASED FOREST FIRE RISK ZONE MAPPING IN DA HINGGAN MOUNTAINS

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ABSTRACT: The Da Hinggan Mountains is one of the most important forest areas in China, but forest fire there is also of high frequency. So it is completely necessary to map forest fire risk zones in order to effectively manage and protect the forest resources. Two forest farms of Tuqiang Forest Bureau (53°34′–52°15′N,124°05′–122°18′E) were chosen as typical areas in this study. Remote sensing (RS) and Geographic Information System (GIS) play a vital role and can be used effectively to obtain and combine different forest-fire-causing factors for demarcating the forest fire risk zone map. Forest fire risk zones were described by assigning subjective weights to the classes of all the coverage layers according to their sensitivity to fire, using the ARC/INFO GIS software. Four classes of forest fire risk ranging from low to extremely high were generated automatically in ARC/INFO. The results showed that about 60.33% of the study area were predicted to be upper moderate risk zones, indicating that the forest fire management task in this area is super onerous. The RS and GIS-based forest fire risk model of the study area was found to be highly compatible with the actual fire-affected sites in 1987. Therefore the forest fire risk zone map can be used for guidance of forest fire management, and as basis for fire prevention strategies.

KEY WORDS: forest fire risk zone; RS; GIS; Da Hinggan Mountains

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1 INTRODUCTION

Forests are one of the major natural resources that perform important environmental and recreational functions (COSTANZA and GROOT, 1997). It is well known that forests can absorb atmospheric carbon, maintain a certain degree of humidity in atmosphere, regulate rainfall, moderate temperature, and restrain soil erosion, etc. (AURELIA, 2003). So, the health of a forest in any given area is a very important indicator of the ecological conditions. But fire is the greatest enemy of the stands. Annual fires may decrease the growth of the grasses, shrubs and forests, which may result in increased soil erosion (IFFN, 2000). Forest fire is already a dominant disturbance factor in almost all forest vegetation zones throughout the world (IFFN, 2000), and is considered to be a potential hazard with physical, biological, ecological and environmental consequences (RAJEEV *et al.*, 2002). According to the statistics on forests in 47 nations (accounting for 53.9% of world forest areas) by Food and Agricultural Organization of the United Nations, the average fire area every year was 6.73×10^6ha from 1881 to 1990, accounting for 0.47% of world forest areas (KONG *et al.*, 2003).

Frequent occurrence of fire is one of the reasons for the degradation of forests in China (KONG *et al.*, 2003). From 1950 to 1997, the number of forest fires and the total burned areas have risen dramatically, with 14.3×10^3 forest fires occurred in China, and the burned forest area reached 8.22×10^6ha (SHAO, 2000). The forest in Da Hinggan Mountains is the largest forest resources in China. Unfortunately it is highly prone to suffering forest fire. From 1987 to 2002, 410 forest fires took place in the study area. Hereinto, 154 fires were caused by human activity, and 256 fires by natural forces such as lightening strike. On May 6, 1987, an intensive forest fire occurred and devastated more than 1.33×10^6ha of natural forest. So, more and more

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foresters have realized the importance of developing methodologies for monitoring and predicting the potential factors influencing the occurrence of fire.

Forest fire risk zones are locations where fires are likely to start, from which they can easily spread to other areas (RAJEEV *et al.*, 2002). Several countries like Canada, Australia and U.S.A. have developed highly sophisticated Forest Fire Danger Rating Systems (FFDRS), while in developing countries these systems are often very difficult to implement, since they are based on a lot of meteorological data (IFFN, 2000). Many researchers at home and abroad used different models to predict the forest fire risk, based on a lot of meteorological data and fire frequency data (LAZAROS *et al.*, 2002; GRISHIN and FILKOV, 2003; AMPARO and OSCAR, 2003; WILLIAM *et al.*, 2000; JIANG *et al.*, 1995; FU and DAI, 2001). But fast development of satellite remote sensing has opened up opportunities for qualitative analyses of forest at all geographic and spatial scales. It has also been effectively used in the study of forest fire monitoring and detection by many researchers (CHUVIECO and CONGALTON, 1989; EMILIO and RUSSEL, 1989; RAJEEV *et al.*, 2002; ZHANG *et al.*, 2003). Understanding the behavior of forest fire, the factors that influence fire behavior, is essential for forest fire risk zone mapping (CHUVIECO and CONGALTON, 1989; CHUVIECO and SALES, 1996). In this paper, an attempt was made to prepare a forest fire risk zone map in order to help forest management officials and foresters to minimize or prevent forest fire risk activities and take proper action when fire breaks out.

2 STUDY AREAS

Two forest farms (Yuying and Fendou) of Tuqiang Forest Bureau (52°15′-53°34′N, 122°18′-124°05′E), in Da Hinggan Mountains, Heilongjiang Province, were chosen as a typical area(Fig. 1). The total area was about 120×10^3ha, and it was the severely burning region in 1987. The area of burned blanks was about 108×10^3ha, accounting for 90.2% of the study area, hereinto, the area of severely burned forest accounted for 44.4%. The climate is cool and dry. The mean annual temperature is -4.94℃, and the extreme lowest temperature is -53℃. The average annual precipitation is 432mm. The forest belongs to the most northern part of the global boreal forest biome. The local species composition is very poor, dominated by *Larix gemelini*, *Pinus sylvestris* var. *mongolica* or *Betula platyphylla.* The topography consists of rolling hill, with slopes ranging from 3° to 40° and elevations ranging from 420m to 920m. Most of the hills are facing to north-south. The main geologic formation is granite. With geological and topographical factors, podzolic soil is the dominant type in the upper hill, while *Stagni-Perudic Cambosols and Spodic Bori-Perudic Cambosols* are dominant in the middle, and *Hemi-Orthic Histosols* domains the down hill.

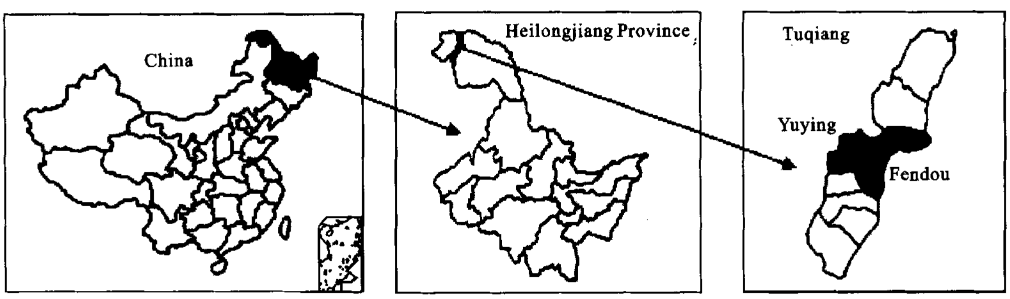

Fig. 1 Location sketch of the study area

3 FACTORS RESPONSIBLE FOR FIRES

The main factors that affect the problem of forest fires mainly comprise climate, topography, type of combustible vegetation, distribution of settlement, density of population, density of road-net, water system and fireproofing forest-belt, etc. (ZHANG *et al.*, 2003; RAJEEV *et al.*, 2002). In this paper, the study area is small, so the differences of many fire risk factors such as annual precipitation, wind speed, are not obvious. Therefore, based on principles of regional particularity, synthesis, representation, and maneuverability, combined with the fact of the study area and the available data, four types of fire risk factors were selected: type of vegetation, climate, topography, proximity to settlement.

Different types of veget^t^on has different combustibilities. The forest vegetation in the study area in 2000 were classified into 9 classes: coniferous forest, broadleaf forest, needle-broadleaf mixed forest, nursery, harvested area, swamp, grass, water, and built-up. The first three vegetation types are especially susceptible to fire, while water is the important factor preventing the spread of forest fire.

The climate conditions determine the vegetation in a region, and play a dominant role in creating fire-prone areas and increasing dramatically the total burned areas. It has been estimated by forestry scientists. Air temperature, relative humidity and wind are main weather factors, which can determine the possibility of forest fire ignition (ZHANG and HUO, 1995). ZHANG and HUO (1995) ever analyzed the correlation and found that air temperature and wind speed have positive linear correlations with the beginning spread speed of fire through large numbers of ignition examinations at laboratory and outdoor, while relative humidity has a negative linear correlation. In addition, phenology is also a fire risk factor. During the period of withering vegetation, the possibility of fire ignition and spread will be increasing, and vice versa. So, the drier and windier the climate is, the more fire-prone the site will be. Climate of the study area is cool, dry and windy, making it vulnerable to forest fires. But the difference of climate is not obvious, and overlaps with the topography to a certain extent, so climate is not discussed in this study, just regarded as a reference factor.

Topography is an important physiographic factor among fire risk factors, which is related to wind behavior, and then affects the fire proneness (RAJEEV *et al.*, 2002). Topography can affect the emergence and spread of forest fire, through changing airflow and local microclimate (ZHANG *et al.*, 2003). Topography mainly comprises altitude, slope and aspect. At a mountainous area, with the increase of altitude and precipitation and the decrease of air temperature and evaporation, humidity is increasing and the possibility of fire ignition is decreasing. Aspect directly affects the amount of solar radiation, and then the temperature at different aspect is quite discrepant. At sunlight aspect, solar radiation is larger than others, so air dryness degree is larger, and forest fire will take place more easily. With the increase of slope, soil erosion is getting more severe, and the combustibles are easier to dry, so the spread speed of forest fire is faster.

Proximity to settlements is more prone to fire, because the practices of the inhabitants can lead to accidental fire. Very few settlements are located in the study area, but they still may be the cause of some forest fires.

4 METHODS

The digitization, analyses, disposal and management of all data were completed in GIS. Fig. 2 is the flow chart about the processing.

Landsat Thematic Map (TM) images (on July 12,

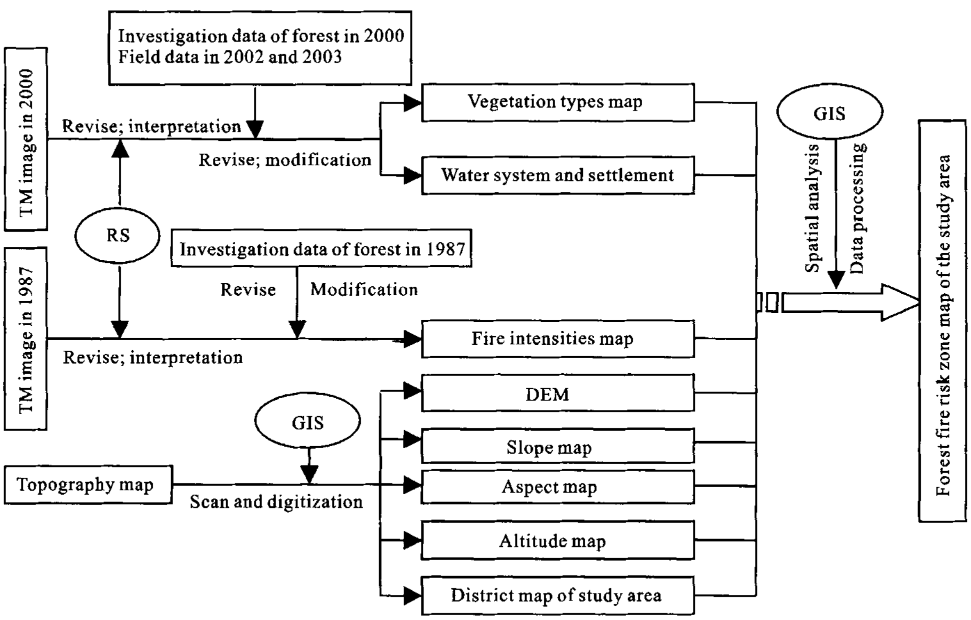

Fig. 2 Flow chart of the analysis processing

1987 and September 14, 2000), the investigation data of forest in 2000 were used for vegetation mapping in 2000 (Fig. 3). Forest fire intensities map in 1987 (Fig. 4) was derived from interpreting the satellite imagery (TM image on July 12, 1987). Because forest vegetation reflects strongly on the infrared portion of the spectrum, while a scorched area caused by fire shows considerable reduction of reflectance, the spectral curve of the forest after burning becomes flat, resulting in burnt areas having high contrast compared to the surroundings (MEI *et al.*, 2001). The forest fire intensities were classified into 4 categories: unburned (no sign of fire effects), lightly burned (older trees or even the most fire-susceptible species survived, with only stems scorched, and soil organic layer remained), moderately burned (all trees of fire-susceptible species killed, but older trees of fire-tolerant species leaved), severely burned (all trees killed) (KONG *et al.*, 2004). Slope, altitude and aspect were derived from digital topography maps (Fig. 5, 6, 7). Settlements were derived from TM image in 2000 (Fig. 8). The aspects were classified 4 categories: darkness aspect (North (337.5°–22.5°) and Northeast (22.5°–67.5°)), semi-darkness aspect (Northwest (292.5°–337.5°) and East (67.5°–112.5°)), semi-sunlight aspect (West (247.5°–292.5°) and Southeast (112.5°–157.5°)), sunlight aspect (Southwest (202.5°–247.5°) and South (157.5°–202.5°)). Corridors of 500m, 1000m and 1500m distance around the settlement were created and digitized as polygon data (Fig. 8).

The different classes in the thematic maps were labeled separately based on their sensitivity to forest fire as extremely high, high, moderate or low. In order to achieve effective conclusions through computation in the GIS analysis, the descriptive information was necessary to be converted into a forest fire risk index and a rating system (Table 1). A higher rating indicates the factor has a high degree of influence on the fire risk. Then suitable weights of factors were assigned using the AHP method. All the thematic maps (layers) were then integrated, and the forest fire risk index was calculated. The equation used in a GIS for the fire risk modeling is:

$$FFR=0.40V_i+0.15P_j+0.15S_k+0.15A_l+0.15H_m$$

where FFR is the forest fire risk index, V is the vegetation variable (with 9 classes), P indicates proximity to settlement (with 4 classes), S indicates slope factor (with 5 classes), A indicates aspect (with 4 classes) and

Table 1 Weights and ratings assigned to variables and classes

No.	Variable	Class	Rating	Fire sensitivity
1	Vegetation type (weight=0.40)	Coniferous forest	10	Extremely high
		Broadleaf forest	8	Extremely high
		Needle-broadleaf mixed forest	9	Extremely high
		Nursery	5	Moderate
		Harvested area	3	Low
		Swamp	4	Moderate
		Grass	7	High
		Built-up	6	High
		Water	0	Low
2	Settlement buffer (weight=0.15)	Corridor < 500m	10	Extremely high
		Corridor 500–1000m	7	High
		Corridor 1000–1500m	4	Moderate
		Corridor > 1500m	2	Low
3	Slope (weight=0.15)	Gently sloping (0–5°)	1	Low
		Moderately sloping (5–15°)	3	Low
		Strongly sloping (15–25°)	5	Moderate
		Steep (25–35°)	7	High
		Very steep (>35°)	10	Extremely high
4	Altitude (weight=0.15)	420–500m	10	Extremely high
		500–600m	9	Extremely high
		600–700m	7	High
		700–800m	5	Moderate
		800–900m	3	Low
		> 900m	1	Low
5	Aspect (weight=0.15)	Darkness aspect	2	Low
		Semi-darkness aspect	5	Moderate
		Semi-sunlight aspect	7	High
		Sunlight aspect	10	Extremely high

H indicates altitude variable (with 6 classes). The subscripts i, j, k, l, m indicate classes.

Finally, criterion-based analysis was carried out to create fire risk zone map (Fig. 9) and the comparison between the fire risk zone map and the actual fire-affected sites in 1987 was done (Fig. 10).

5 RESULTS AND CONCLUSIONS

The forest fire risk zones were delineated four classes: low ($0<FFR\leqslant3$), moderate ($3<FFR<6$), high ($6\leqslant FFR<8$), extremely high ($FFR\geqslant8$) (Table 2). Because polygons of surface water bodies have zero weighting and intersect with the resultant map, these were classified separately on the final forest fire risk zone map, and were defined as none forest fire risk zone (Table 2, Fig. 9).

From Fig. 9, we can distinctly get the information of fire risk zone distribution: 1) "extremely high" and "high" fire risk zones are almost lying in the Midwest and East of the study area; 2) "moderate" and "low" fire risk zones are almost lying in Northeast and South; 3) none forest fire risk zones are almost lying in the central section and West. The areas under high fire risk zones are those areas where fire can be unintentionally caused by human activities, and where fire could thus certainly be averted by taking precautionary measures. A fire risk zone map should prove to be helpful to the Forest Department and the foresters, because it would enable the foresters to set up an appropriate fire-fighting infrastructure for the areas more prone to fire damage, in order to effectively prevent and decrease the likelihood of forest fire.

The fire risk in the study area reflects both the likelihood of ignition and the risk of spreading. The slope, altitude and aspect factors, which influence the risk of spreading, thus increase the fire risk in present model. An interesting feature of the model is that it explains the important fact that even if a forest type has a low risk weighting (such as harvested area), the probability of a forest fire occurring there can be moderate due to other factors.

Table 2 describes the resultant fire risk zones and the corresponding degree of fire risk. In the study area, 1.70% falls in the category of "extremely high" fire risk, followed by 58.63%, 38.67%, 0.63% and 0.37% respectively, in the categories "high", "moderate", "low" and "none". This result showed that the study area is prone to suffering forest fire all the time. So, forest fire management task in this area is super onerous.

Table 2 Classification of fire risk zones

Class of fire risk zones	Degree of fire risk	Area (ha)	Proportion to study area (%)
0	None (Water)	44.56	0.37
1	Low ($0<FFR\leqslant3$)	76.20	0.63
2	Moderate ($3<FFR<6$)	4688.89	38.67
3	High (($6\leqslant FFR<8$)	7108.01	58.63
4	Extremely high ($FFR\geqslant8$)	206.50	1.70

Through the comparison of all thematic layers, we can easily get the following conclusions:

(1) The regions which have "extremely high" degree of fire risk are almost the areas with coniferous forest, broadleaf forest, needle-broadleaf mixed forest, very steep or steep slopes, sunlight aspects, low altitude (<600m) and close to the settlements (<1000m).

(2) The regions which have "high" degree of fire risk are almost the areas with coniferous forest, broadleaf forest, nursery, needle-broadleaf mixed forest, grass, very steep, steep or strongly slopes, sunlight and semi-sunlight aspects, low altitude (<700m) and within a distance of the settlements (1000–1500m).

(3) The regions which have "moderate" degree of fire risk are almost the areas with built-up, swamp, harvested area, grass, broadleaf forest, gently sloping or moderately sloping, darkness and semi-darkness aspects, high altitude (>700m) and far from the settlements (>1500m);

(4) The regions which have "low" degree of fire risk are almost the areas with harvested area, swamp, grass, gently sloping, darkness aspects, and high altitude (>700m).

Finally, the fire risk zone map was compared with the actual sites affected by fire in 1987 (Fig. 10). It was found that the area of matched patches accounted for 60.21% of the total study area. That is to say, most of the patches predicted from the model were located in actual burnt areas in 1987 (Fig. 4, 10). This comparison shows that the approach and the fire risk zone map have high reliability, which can be used by foresters to make the fire prevention policy effective.

In this paper, RS and GIS were used to analyze the forest fire risk zone mapping and forest fireproofing work at moderate and small geographic and spatial scales, which adapted to the developing trend of forest fireproofing in the world. Integration of RS and GIS can update the vegetation type map rapidly and accurately, and also can obtain lots of original data of forest resources, and then create thematic maps of different forest fire risk factors. So, it can help forest management officials and foresters to obtain the dynamic changes of the forest fire risk in time, and improve the

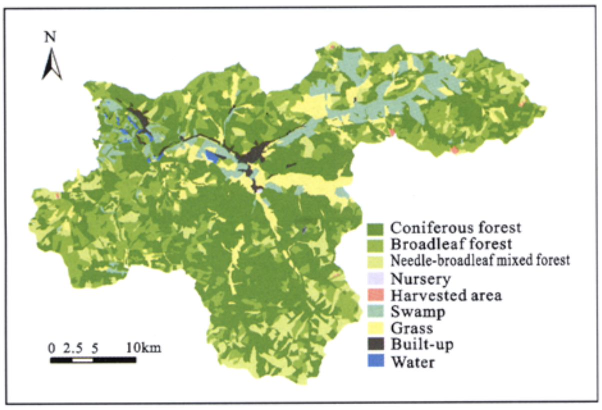

Fig. 3 Vegetation types map of the study area

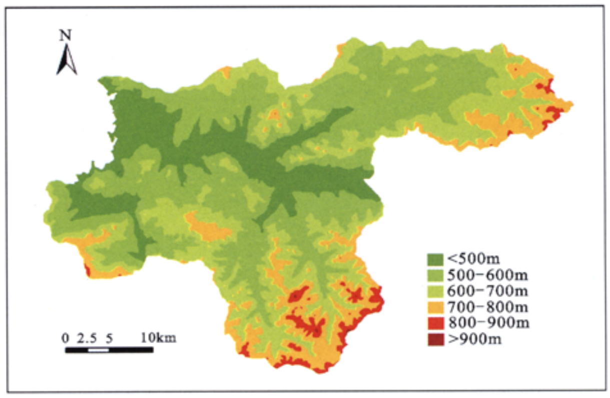

Fig. 6 Altitude map of the study area

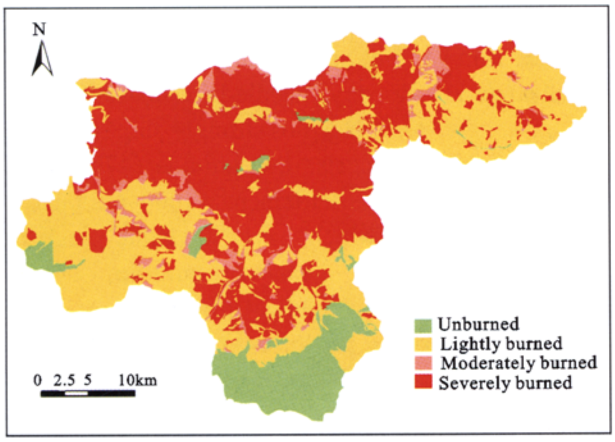

Fig. 4 Fire intensities map of the study area

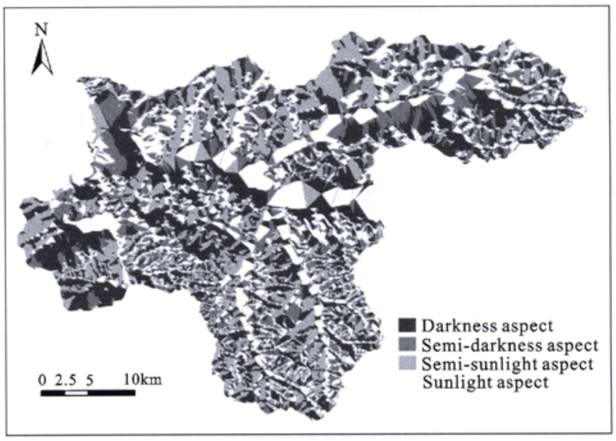

Fig. 7 Aspect map of the study area

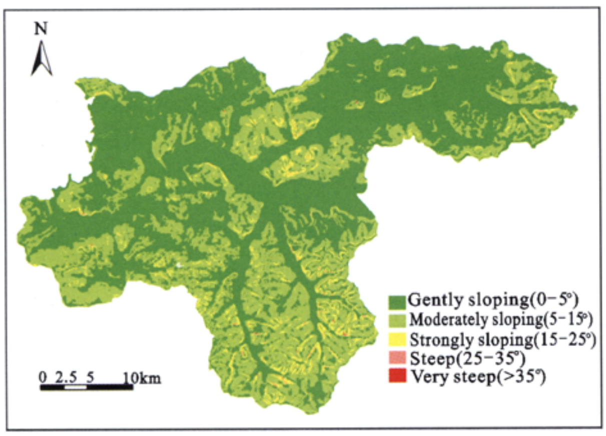

Fig. 5 Slope map of the study area

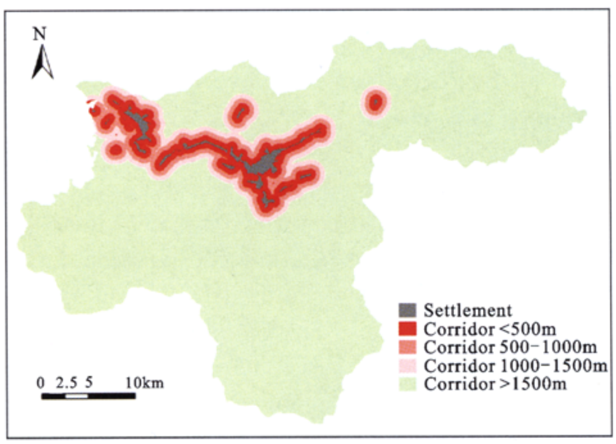

Fig. 8 Settlement buffer map of the study area

level of forest fireproofing. Certainly, the work of forest fire risk zone mapping is only an evaluation or predication of the potential possibility of the forest fire emergence, while many forest fires are caused by human activity, so it is impossible to predict every forest fire. In addition, limited to the imperfect of research data, some forest fire factors such as climate were not analyzed in this paper, so it maybe affects the evaluation result to a certain degree.

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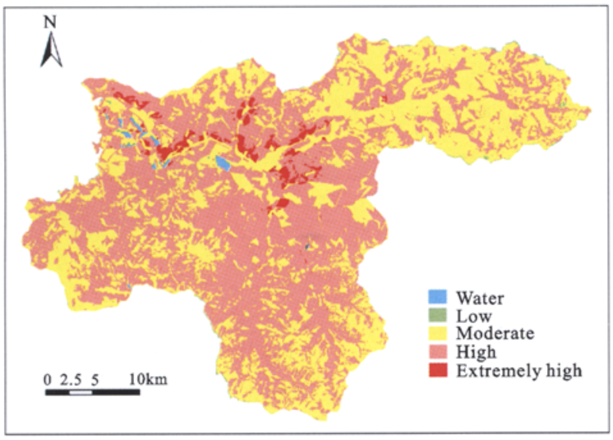

Fig. 9 Forest fire risk zone map of the study area

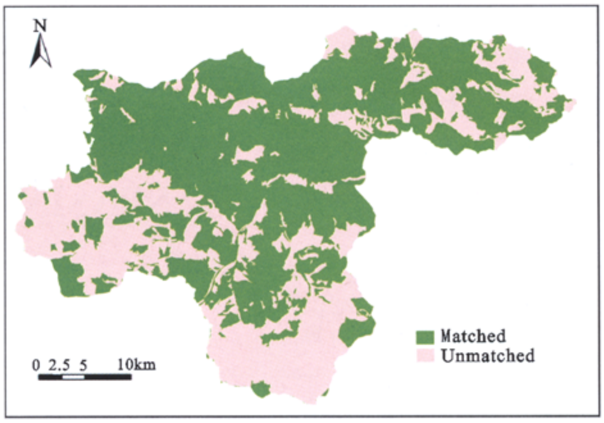

Fig. 10 Matched result between fire risk zone and fire intensities

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