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STUDY ON FOREST FIRE DANGER MODEL WITH REMOTE SENSING BASED ON GIS

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ABSTRACT: Forest fire is one of the main natural hazards because of its fierce destructiveness. Various researches on fire real-time monitoring, behavior simulation and loss assessment have been carried out in many countries. As fire prevention is probably the most efficient means for protecting forests, suitable methods should be developed for estimating the fire danger. Fire danger is composed of ecological, human and climatic factors. Therefore, the systematic analysis of the factors including forest characteristics, meteorological status, topographic condition causing forest fire is made in this paper at first. The relationships between biophysical factors and fire danger are paid more attention to. Then the parameters derived from remote sensing data are used to estimate the fire danger variables, According to the analysis, not only PVI (Perpendicular Vegetation Index) can classify different vegetation but also crown density is captured with PVI. Vegetation moisture content has high correlation with the ratio of actual evapotranspiration (LE) to potential ecapotranspiration (LEp). SI (Structural Index), which is the combination of TM band 4 and 5 data, is a good indicator of forest age. Finally, a fire danger prediction model, in which relative importance of each fire factor is taken into account, is built based on GIS.

KEY WORDS: forest fire danger index; models for danger prediction; inversion of remote sensing data; overlay analysis; geographical information system (GIS)

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1 INTRODUCTION

As an important component of the global terrestrial ecosystems, forest links the atmosphere, soil and water together through its powerful ecological function. In recent years, owing to the global warming and human influence, forest fire occur much more frequently. The annual fire loss of forest accounts for 1‰ of total forest area, especially in the frequently occurring countries being 2‰–8‰. Forest fire tends to be one of the main natural hazards due to high occurrence and wide spread. The huge losses of life and properties, the disadvantageous ecological results and the chains of disasters result from forest fire. Therefore, it is very valuable to predict the fire danger in quick, real-time and accurate ways. The researches on forest fire have been carried out in many countries including U. S. A, Spain and Australia etc. Most previous reports focus on the weather forecast of forest fire danger level, fire real-time monitor, fire behavior simulation, and fire loss assessment and so on (ZHU, 1995; MATSON *et al*., 1987; FLANNINGAN *et al*., 1986).

Since forest fire danger research is an integrated

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and systematic project, both the vast amount of environmental data and continuous information of forest status are required. Remote sensing techniques provide the potential technology support of fire danger prediction on spatial/temporal scale, as well as the satellite remote sensing data are used to evaluate the fire danger factors. A geographical information system (GIS) takes advantage of a computer's abilities to store and process great volumes of data. The fire danger models can be obtained from the overlay analysis of the data layers in the database. Therefore, an effective way to predict the fire hazard depends on the researches on the relationship between danger factors and remote sensing and the high precise and practical models for fire prediction with remote sensing and GIS.

2 SYSTEMATIC ANALYSIS OF THE FOREST FIRE DANGER FACTORS

Forest fire is a kind of gusty natural catastrophe with complex environment and diverse danger variables. Generally, the beginning and spreading of a forest fire is affected by the following factors: forest characteristics, meteorological status, fire source and topographic conditions and so on. The fire danger level depends on the interaction between the above factors.

2.1 Forest Characteristics and Fire Danger

Because forest is the material base of fire, the fire danger is closely related to the nature of flammable materials, i.e. the vegetation type, moisture content, canopy density and forest age etc.

2.1.1 Vegetation type and moisture content

Different vegetation types have different flammabilities. Owing to the high resin or essential oil content in the trunks, branch, leaves and litters, fire is easy to begin in the forest composed of pure coniferous trees. With a large amount of moisture and thick leaves, the evergreen broad-leaved forest has strong resistance to the fire. According to previous studies, the flammabilities of different vegetation types are ranked in descending order: weeds-shrubs, Chinese pine forest, pine deciduous broad-leaved and coniferous mixed forest, moss-spruce forest, broad-leaved mixed forest and evergreen broad- leaved forest.

The moisture content of forest, i.e. the humidity of flammable materials affects both the ignition and intensity of fire. Basically, the more moisture content is, the lower possibility of fire is.

2.1.2 Canopy density

The canopy density of forest is directly related to the amount of flammable litters and the microclimate. The forest with low canopy density is not only dry but also overgrown with weeds, fire is easy to break out thereby. By the virtue of less radiation, low temperature and evaporation, high humidity and more moisture content in litters, in the forest with high canopy density, fire can be resisted. While in the medium density forest, the rich combustible and dry internal environment aid the wide spread of the fire once it starts. Once the density reaches 0.6- 0.7, the fire tends to start due to dense crown.

2.1.3 Forest age

The forest resistance to fire is corresponding to the ages of stand. In young growth forest, especially coniferous forest, the crown stretches to the land surface. Once the surface fire begins, the crown will be ignited. With forest growing, the resistance to fire enhances by the reason of natural pruning and increasing trunks and big branches. The resistance to fire of mid-aged forest is stronger than that of old forest since there are sparse crown density and more weeds and litters under forest crown. The related researches demonstrate that the occurring possibility of fire is sorted by descending order: young growth> old forest> mature forest> mid-aged forest and show an exponent function distribution.

2.2 Meteorological Status and Fire Danger

The beginning and spreading of forest fire depend on meteorological conditions, especially the precipitation, air temperature, relative humidity and winds.

2.2.1 Precipitation

Since the precipitation makes not only the air humidity and moisture content of inflammable matters increase directly but also vegetation evapotranspiration lower, the fire danger will lessen. Generally, 1 mm precipitation hardly increases the humidity of litters, while 2- 5 mm rainfall reduces the fire danger. The precipitation more than 5 mm make the moisture of combustibles saturated so that the fire does not begin. On the contrary, the dry weather increases the possibility of fire. According to statistics, during the spring fire prevention period in the Da Hinggan Mountain fire would break out if continuous drought days exceed ten days. An extraordinarily severe fire would occur if the drought lasted more than 20 days.

2.2.2 Air temperature and relative humidity

The relative humidity can affect the moisture content. The lower relative humidity is, the drier air is and the bigger evaporation is. The less the moisture content of inflammables is, the higher the fire danger is. It is reported that fire hardly starts while average relative humidity is above 75%. Once the humidity reaches 55% - 75%, forest fire is possible to occur. The relative humidity below 55% is closely related to a great fire.

There is some certain relationship between air temperature and fire danger. According to the survey in Heilonjiang Province, the average monthly temperature is - 10℃- 0℃, which means that fire possibly begins, 0℃- 10℃ brings about more occurrence of forest fire because the snow is melting and wind is strong. When the temperature is 11℃- 15℃, the plants return green thereafter the fire possibility decreases. The vegetation grows well at the temperature of 19℃- 20℃ and the fire is rare.

2.2.3 Wind

Wind is a main environmental factor in the occurrence and extension of forest fire. There is a good saying, that is, "Fire takes advantages of wind power and winds aid the fire spread." Wind can increase the evapotranspiration rate, decrease the moisture content in the forest as well. Furthermore, because the high wind speed provides a large amount of oxygen for ignition source, not only the radiation transfer is strengthened but also the fire will extend further.

2.3 Topographic Condition and Fire Danger

Topography is the base of geographical environment, which makes water and thermal resources reallocate. The beginning and spreading of forest fire is affected indirectly by topographic condition. The impacting factors are listed as follows:

2.3.1 Sea-level elevation

With the elevation rising, air temperature decrease while precipitation increase obviously. Not only the vegetation types change but there is more moisture content in trees. Therefore, the fires are rare.

2.3.2 Slope

Slope is considered the critical factor of fire danger. Steep slopes not only make the runoff drain away quickly, inflammables are easily dry thereby, but also increase the rate of fire spread. Thus, the fire danger level is high. In addition, wet airflow passing the summit of a mountain will become foehn so that the fire tends to be more severe there.

2.3.3 Aspect

Due to aspects, the heat and water status are different corresponding to different position. Therefore, the rate of fuel drying and speed of the fire are controlled. It has been stated that the occurrence of fire decreases at different aspects in the following order: south slope> west slope> east slope> north slope.

2.4 Human Factors and Fire Danger

Except for the natural factors, fire is affected by artificial factors, especially the potential ignition sources, which can be represented by the road density and population density.

2.4.1 Road density

Roads in forest are potential routes of fire resulted from human ignition source. The more intense the human activities are, the more the forest fire hazards are. The previous reports indicate that the buffer distance of 50 m for main roads and a distance of 150 m for pathways are built. The fire tends to occur more often in these buffer zones.

2.4.2 Population density

The population density is the critical factor for the allocation of settlements and working sites and intensity of human activity, thereby it affects the distribution of fire sources. The higher the population density is, the higher the fire hazard is. In the spring farming season, there are many productive fire sources such as the grass on wasteland and arable land, the fire-making for fertilizers and the fire on the pasture land etc. The life fire sources in winter result from camping, games, and woodcutting.

Although some accidental causes (e.g. thunderbolt) can lead to fire, we only take account into the forest nature and its pregnant environment variables as the driving factors of fire hazard.

3 GEOGRAPHICAL CHARACTERISTICS OF THE STUDIED AREA

The Changchun Jingyetan National Forest Park is selected as the studied area. The studied area lies between 125° 26′ 15″ E and 125° 30′ 00″ E, 43° 45′ 00″ N and 43° 47′ 30″ N, which has temperate semi-continental monsoon climate, i.e. four distinct seasons. The average annual temperature is 4.7℃, and the average maximum temperature and minimum temperature are 28.3℃ and − 22.4℃ respectively. The absolute maximum temperature can reach 38℃ while the minimum temperature is − 34.9℃. The mean annual precipitation is 645.3 mm. The raining season is in July and August, making up 67% of the annual precipitation. The relative humidity is 69%, while the average evaporation is 392.5 mm. The direction of wind is almost southwest in summer whereas the northwest wind often occurs in winter. The studied area is located in the transitional zone between eastern mountain and the Songliao Plain, where sea-level elevation is 220–406 m. The vegetation type is forest steppe, i.e. the transition type of deciduous broad-leaved forest in the Changbai Mountains to temperate steppe in the Songnen Plain, which is primarily composed of artificial cultural conifers such as *Pinus tabulaeformis*, *Pinus sylvestris* var *mongolica*, and *Pinus koraiensis*. The forest coverage area is 5006 ha, of which the conifers area is 3400 ha, broad-leaved forest area is 1606 ha, young growth and shrubs 82.7 ha and grassland 249.1 ha. The forest cover is 54.36%.

The studied area was disturbed by more than 80 fires during 1950–1984, which has made 13.8 ha of forest burned. Although the studied area has not hit by fire in recent ten years, it is ranked as a high-hazard area for forest fires.

4 METHOD OF FIRE DANGER PREDICTION

As remote sensing data and GIS previously stated, the relevant factors in fire danger rating system include vegetation weather data, relief and human activity etc. The use of a GIS approach has made it possible to evaluate the fire danger. Meanwhile, the remote sensing data are valuable for acquiring the fire danger factors in real-time.

4.1 Fire Danger Factors from Remote Sensing

The remote sensing techniques are employed to obtain dynamic fire danger factors, i.e. forest status such as vegetation type, age of stand and moisture content etc.

4.1.1 Vegetation type classification with remote sensing

Researches on the vegetation classification derived from remote sensing data have been widely reported in the literature. In the study, the Landsat TM band 3 and 4 data are collected to define the perpendicular vegetation index (*PVI*), which is used in classifying procedures.

$$PVI = (TM_4 - a_1 \times TM_3 - a_0) / \sqrt{(1 + a_1^2)}$$

where a_0 and a_1 are the coefficients in soil line equation i.e. $TM_4 = a_1 \times TM_3 + a_0$, TM_3 and TM_4 represent the reflectance of *TM* band 3 and 4 respectively.

4.1.2 Vegetation moisture content monitoring from remote sensing

There are a few basic approaches to monitor water content of vegetation with remote sensing as follows: (1) the vegetation water stress models stemmed from temperature difference between canopy and air are utilized to estimate moisture content; (2) the analysis of multi-temporal vegetation index (e.g. NDVI), the relationship between vegetation moisture content and vegetation index are developed; (3) the vegetation canopy evaporation data extracted from thermal infrared remote sensing reflect the water stress condition of the canopy.

NOAA-AVHRR data are suitable for monitoring the vegetation moisture content. The below expression is proposed by IDSO and JACKSON(1977)

$$LE^{24} = Rn^{24} - B \times (T_c - T_a)$$

NIEUWENHUIS (1985) modified the above equation and developed a new model in which radiation difference is replaced by evaporation.

$$LE^{24} = LEp^{24} - Br^{\times} (T_c - T_c^{*})$$

$$LE^{24}/LEp^{24} = 1 - Br^{\times} (T_c - T_c^{*})$$

where B, Br are experimental coefficients ($Wm^{-2}k^{-1}$), Ta is the air temperature, Tc^{*} represents the canopy temperature in optimum soil moisture, Rn is net radiation, LE and LEp are the latent heat flux or evapotranspiration and its potential value respectively (Wm^{-2}).

4.1.3 Forest age derived from remote sensing

It is demonstrated that Structural Index (SI) is very sensitive to the age of stand (CARLSON *et al*., 1989). SI not only is easy to be calculated and interpreted, but also minimum the effect of topographic shadow. SI is related to forest age well. In the study area, the relationships is defined as:

$$\text{Lg}\, Y = 1.304 + 1.127\text{Lg}(SI)$$

where Y is age of stand, SI is structural index and is equal to TM_4/TM_5, the relation coefficient $R = 0.96$.

4.2 Forest Fire Danger Database

The spatial database of forest fire danger factors is the base of fire prediction.

4.2.1 Data set

(1) Remote sensing data collected by Landsat TM and NOAA-AVHRR;

(2) Meteorological data, including air temperature, precipitation, wind, relative humidity derived from meteorological stations and real-time measurements;

(3) Thematic maps such as vegetation type administration division, road network and population density etc.

(4) Digital terrain model (DTM) stems from the digitized topographic map at scale 1:10000.

4.2.2 Data organization

In the study, we use IDRISI as software platform to establish the database. Each data layer was stored by 30 m × 30 m grid cell so that the further analysis would be accomplished. Meanwhile, owing to diverse forest fire danger factors and different rate to be used, the data were input to four modules, that is, forest dynamic data module, meteorological data module, topographic data module and human causes data module.

4.3 Fire Danger Prediction Model

4.3.1 Main ideas of the model

The beginning and spreading of forest fire depend on the coupling impacts of many variables. In the GIS database, every fire factor was defined as a data layer, which would be weighted according to its impact on increasing the fire hazard. Actually, the selected weights tend to take into account the relative importance of each variable (layer) as a factor for increasing the fire danger according to the literature and to the environmental characteristics of the study area. Each data was then divided into different levels, which were assigned a coefficient of 0, 1 and 2 based on a ranking of low, medium and high fire danger respectively. Finally, the fire danger level for each grid was obtained from the spatial overlay between data layers.

4.3.2 Forest fire danger prediction model

For each grid cell, the Fire Danger Index (FDI)

can be defined as:

$$FDI = \sum_{i=1}^{n} W_i X_i$$

where W_i is the weight of each fire factor (data layer), X_i represents the level value of each grid on each variable layer.

The weights of forest fire danger factors and the value of each danger level are given in Table 1.

Table 1 Weights and level of fire danger variables in the studied area

Original type	Fire danger level	Coefficients
1.1 Vegetation type (weight 100)		
Broad-leaved forest	Low	1
broad-leaved and coniferous mixed forest	Medium	2
Coniferous forest	High	3
Weeds-shrubs, grassland	Higher	4
1.2 Moisture content (weight 60)		
> 50%	Low	1
20% - 50%	Medium	2
< 20%	High	3
1.3 Age (weight 30)		
Young	Higher	4
Middle-aged	Low	1
Old	High	3
Mature	Medium	2
1.4 Canopy density (weight 30)		
< 0.3	Higher	4
0.3- 0.5	High	3
0.5- 0.7	Medium	2
> 0.7	Low	1
2.1 Precipitation(weight 35)		
Continuous drought	Higher	4
0.1- 2.0mm	High	3
2.1- 5.0mm	Medium	2
> 5.0mm	Low	1
2.2 Minimum relative humidity (weight 30)		
≥41%	Low	1
40% - 33%	Medium	2
32% - 26%	High	3
≤25%	Higher	4
2.3 Maximum temperature (weight 25)		
< 12.0℃	Low	1
12.1℃- 18.0℃	Medium	2
> 18.0℃	High	3
3.1 Slope (weight 25)		
< 8°	Low	1
9° - 15°	Medium	2
16° - 25°	High	3
> 25°	Higher	4
3.2 Aspect (weight 10)		
North	Low	1
NE, NW, East, West	Medium	2
SE, SW	High	3
South	Higher	4
4.1 Population density (weight 5)		
< 10 per/km^2	Low	1
10- 15 per/km^2	Medium	2
15- 40 per/km^2	High	3
> 40 per/km^2	Higher	4
4.2 Road density(weight 5)		
< 1m/ha	Low	1
1- 1.5m/ha	Medium	2
1.5- 3m/ha	High	3
> 3m/ha	Higher	4

5 CONCLUSION

Remote sensing provides sources of forest fire danger factors including vegetation type, moisture content, forest age etc., meanwhile GIS processing make it possible to create fire danger models. The fire danger prediction of the Jingyuetan National Forest Park was fulfilled through a practical model with high precise.

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