Paper presented at the 22nd Asian Conference on Remote Sensing, 5 - 9 November 2001, Singapore.

Forest Fire Hazard Model Using Remote Sensing and Geographic Information Systems: Toward understanding of Land and Forest Degradation in Lowland areas of East Kalimantan, Indonesia

Mulyanto Darmawan
Graduate School of Agricultural and Life Sciences, The University of Tokyo,
Email: darmawan@affrc.go.jp
Masamu Aniya
Professor, Institute of Geoscience, University of Tsukuba, Japan,
Email: aniya@atm.geo.tsukuba.ac.jp
Satoshi Tsuyuki
Associate Professor, Graduate School of Agricultural and Life Sciences, The University of Tokyo, Japan
Email: tsuyuki@fr.a.u-tokyo.ac.jp

Keywords : Forest Fire Hazard, Fuel type, GIS, Soil Erosion Hazard, Land and Forest degradation

ABSTRACT. A heavy scale of forest fire occurred during the year of 1997/1998 in Indonesia, which burnt millions hectares of the tropical rain forest. The Indonesian East Kalimantan province was the most severely affected by this forest fire, which have destructed a natural forest and induced accelerated soil erosion. A repetitive forest fires in this province lead to bring a land and forest degradation process. This study develops a forest fire hazard model using remote sensing technique integrated with Geographic Information Systems (GIS). It also attempts to establish a method for land and forest degradation hazard mapping in lowland area of East Kalimantan based on analyzing of forest fire hazard with respect to soil erosion hazard. The following variables were derived for a study area: vegetation fuel type, terrain, road, and bare soil. Those variables were weighted according to their impact on the forest fire hazard or accelerating soil erosion. Supervised classification and NDVI analysis are applied to Landsat TM to derive a fuel type. Tasseled cap transformation, the simplified end member technique and the GIS neighborhood analysis was carried out to identify bare soil areas, which consist of maximum approximating of a pure bare soil on 3 by 3 pixel size. The final result offers a model of forest fire and soil erosion hazards. The models of forest fire hazard show reliable from perspective of the proportion of areas affected by high burnt areas of forest fire in 1997/1998. A derived land and forest degradation map has been offered. Based on this map it is possible to identify and monitor areas affected by forest fire or to evaluate the pattern of land and forest degradation.

1. INTRODUCTION

Land and forest degradation process is considered to be one of the major environmental problems, which lead to a variety of environmental disasters and adversely affecting human life. In the tropical rain forest region, where rainfall is substantially high and vegetation cover is seriously damage due to repetitive forest fire event, both land and forest degradation is usually occur (Dent, 1992).

After a big forest fire in 1981/1982 and others fire during 1991 to 1994 again in 1997/1998 a heavy forest fire occurred in Indonesia. The Indonesian East Kalimantan province was the most severely affected by this fire, which not only damaged approximately 5.2 million ha of forest in the entire East Kalimantan province (Hoffman et al., 1999) but also has accelerated soil erosion (Kustiawan, 1999). Repetitive forest fire in East Kalimantan indicates that fire become an important natural phenomenon, which is characterized by a high level of vegetation stress during the drought season. Human activities, for such shifting cultivation and plantation, and the severe drought associate with a very strong El Nino event, occur every 3or5 year, potentially have become a major factor contributing forest fire in this province. Therefore, the understanding of the areas susceptible to forest fire need to be closer attention in this province, includes a reliable method for land and forest degradation hazards mapping.

Remote sensing has significant advance over a conventional method to map forest fire hazard, because of its continuity coverage over large areas. A GIS takes advantage of its capability to combine different source of information for modeling or mapping. However, for the optimum utilization of remote sensing and GIS to forest fire hazard model, the characteristic of remotely sensed data and GIS analysis, which are closely related to fuel type, terrain and human access, that have been known as a factor affecting spreading of fire need to be studied. However, this type of research is generally lacking in the tropical region compared to other regions.

2. OBJECTIVES AND STUDY AREA

The objective of this research is to develop a model of forest fire hazard using remote sensing and Geographic Information Systems in East Kalimantan, Indonesia. In addition, this research also attempts to establish a reliable method for land and forest degradation hazard in lowland environment of East Kalimantan, Indonesia.

An area along Samarinda and Balikpapan cities of East Kalimantan, Indonesia (Fig. 1) is selected as a study site. The area extend around 2,100 km^2 between 116^o 45' to 117^o 13' E and 0^o 45' to 1^o 8.5' S. The area is part of the Mahakam Lowland environment, which was covered by thick primary forest and recently began to be degraded rapidly due to combination of human activities and forest fire. The climate is typically tropical rain forest type with a mean annual rainfall of approximately 2,000-3,000 mm and an average range of monthly temperature less than 5^o C. Rainy period occurs between November to May while dry season from June to October.

3. DATA AND METHODOLOGY

Landsat Thematic Mapper (TM) acquisition on 14 October 1996 and Digital Elevation Model (DEM) derived from topographic map 1:50,000 scales were used as the main data in this research. Several variables are derived from these data: vegetation fuel type, elevation, gradient, aspect, and bare soil image.

3.1. Forest Fire Hazard

A flow chart of research is shown in Figure 1. Selection of variables affecting forest fire hazard is important step of this research. It has been known that a basic factor affecting spread of forest fire as follow: fuel type, fire behavior and human activities (Wirawan, 2000). Therefore three groups of factors were identified: land use/cover related to fuel type, terrain related to fire behavior, and road related to human activities.

Traditionally fuel type is collected directly from the field with an intensive and accuracy measurement (Pickpord, 1995). Mostly they worked with local scale or in small areas. In case of forest fire hazard model it is required information of fuel type on large areas, and remote sensing has succeed to overcome this task (Chuvieco and Congalton, 1988). In this research a fuel type was derived from land use/cover map, which was analyzed previously by supervised classification of Landsat TM, and from the NDVI image.

Land use/cover was categorized into several fuel types with respect to its vulnerable and combustion properties. Land covers of water/cloud, settlement and bare soil were masked and excluded from the analysis, while agriculture farmland and plantation were retained because of these land use played a major cause of forest fire in East Kalimantan (Wirawan, 2000). Three categories of fuel type were derived as follow: (1) high fuel category type and vulnerable to fire, (2) high fuel type but less vulnerable to fire, (3) low fuel type category but can be a major cause of forest fire. The first categories include grassland, bushes, and disturbed forest, the second category includes mangrove, swamp trees, and natural forest, and the last category include agriculture farmland and plantation.

The second model was derived from Normalized Difference Vegetation Index (NDVI), which was calculated from ratio of near infrared again visible band of Landsat TM. Harsanugraha et al. (1998) used this index from NOAA-AVHRR with a range of 0.05 to monitor dry condition of land in Kalimantan. This value was found to be very coarse to be applied for Landsat TM, which has a spatial resolution of 30 m x 30 m compared to 1 km x 1 km of NOAA-AVHRR. Therefore a visual analysis is used to threshold the Drought Vegetation Index (DVI) ranges with respect to the vegetation type on the ground. The NDVI with increment of 0.15 was found representing of the drought vegetation change on the ground. The low level of green vegetation is found in high dry areas, and these areas are usually vulnerable to fire. This area was assigned score of 3 or high hazard, except for settlement or bare soil covers as no hazard. In otherwise, the highest level of green vegetation index corresponds to low drought index and was assigned score of 1 (low hazard), the moderate level corresponds to value between these hazards.

Terrain (elevation, gradient and aspect) was derived from DEM. Elevation of the study area was divided by increment of 50 m, and gradient was divided by increment of 15% ranges. Aspect was classified into east (45^o to 136^o), south (136^o to 225^o), west (225^o to 315^o), and north aspect (136^o to 45^o). It has been reported that fire behavior trends to be less severe at higher elevation due to high rainfall. Step gradient increased the rate of fire spread because of more efficient convective preheating and ignition, and gradient facing to the east receives more ultraviolet during the day, as consequence east aspect drier faster (e.g. Chuvieco and Congalton, 1989). In addition a buffer distance of 250 m, 500 m and 1000 m from road was created for all the study area.

The value of 1, 2, and 3 were assigned to each variable in order to indicate its level of fire hazard in GIS analysis (Table 1). The research attempts to model GIS analysis based on the assumption that in forest fire hazard the availability of fuel type is a key factor on fire spreading. A fuel type provides a burning resource or plays as source of ignition based on its combustion properties. In summary the GIS models applied for forest hazard as follow:

Model 1. All the variables have the same weight

FT + EL + GR + AS + BR ………………………………………………………… (1)

Model 2. Fuel type derived from land use/cover has a weight twice higher than the other variables

20 FT + 10 EL + 10 GR + 10 AS + 10 BR …………………………………………….(2)

Model 3. Fuel type derived from land use/cover has a weight higher followed by gradient

30 FT + 20 EL + 10 GR + 10 AS + 10 BR…………………………………….......(3)

Model 4. A model derived from Dried Vegetation Index and all the variable have the same weight

DVI + EL + GR + AS + BR . ………………………………………………..……..(4)

Model 5. A model derived from DVI has a weight twice higher than the other variables

20 DVI + 10 EL + 10 GR + 10 AS + 10 BR ……………………………………..…..(5)

Model 6. A model derived from DVI has a weight higher followed by gradient

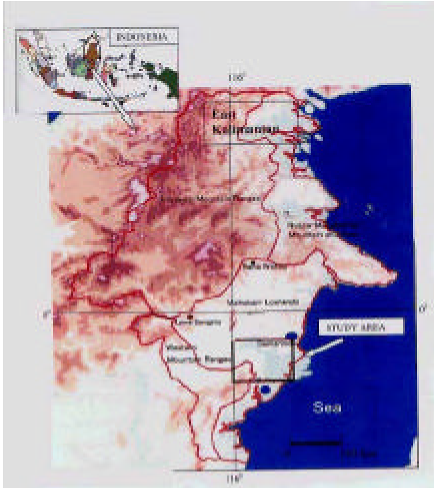
30 DVI + 20 EL + 10 GR + 10 AS + 10 BR……………………………………………..(6)

Where FT, DVI, EL, GR, AS, and BR represent fuel type, dried vegetation index, elevation, gradient, aspect and buffer road respectively.

3.2. Soil Erosion Hazard

A simplified end member technique and tasseled cap transformation were carried out to derive pure pixels, which consist of maximum approximating of bare soil. The procedures are as follow: the tasseled cap I (brightness) and II (greenness) were selected to construct a basis of the two dimensional feature spaces and the tendency peak of this scatter plot was identified. The corresponding pixels at the peak to Landsat TM and land use/cover map were verified. The average pixels correspond to vegetation, water, and bare soils were selected and a new image was computed which follows the technique described by Zhou et al. (1994). Fraction of bare soil on 3 by 3 pixel size was then calculated from the new image using the GIS neighborhood analysis of Erdas Imagine. Finally the study area was categorized according to the percentage of bare soil as follows: (a) bare soil less than 50 %, (b) bare soil between 50-60%, (c) bare soil between 70-80 %, and (d) bare soil more than 80%. The susceptibility level of soil erosion are increase from a to d.

Vegetation and gradient are important factors on soil erosion process, therefore analysis these factors with the percentage of bare soil provide a reasonable model for soil erosion. Vegetation type was derived from Landsat TM and classified as (1) homogeneous vegetation, such as natural forest and mangrove, (2) different association vegetation such as grassland, plantation, disturbed forest, and (3) agriculture farmland type. The susceptibility level of vegetation type in responds to the soil erosion increase from agriculture farm type to natural forest.



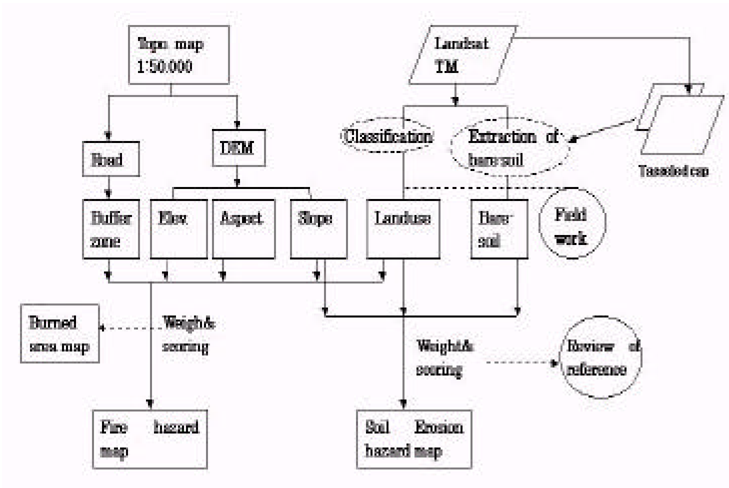


Figure 1. Study area

Figure 2. Flowchart of research

4. RESULTS AND DISCUSSION

The final result offers a model of forest fire and soil erosion hazard (Fig. 3 and 4). The hazard classes were defined based on the range of digital number (DN) between maximum minus minimum and divided by number of class. The value close to minimum DN indicates low hazard, while the one close to high DN indicates high hazard, the hazard value ranges from 1 to 255. The derived model is representing fire hazard condition in 1996 or one year before a heavy forest fire in 1997/1998, since remotely sensed data is in 1996. As forest fire becomes a natural phenomenon in East Kalimantan, this fire hazard model can be used as a prediction model.

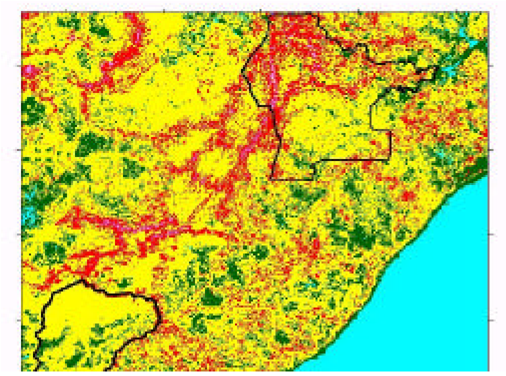


Figure 3. Forest Fire Hazard

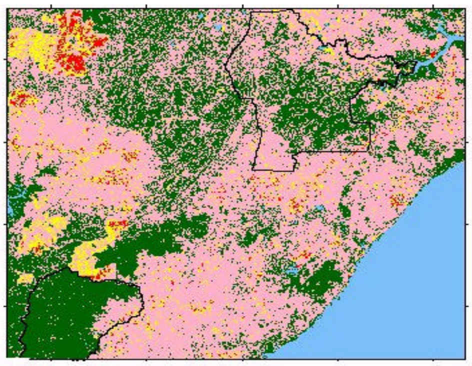


Figure 4. Soil Erosion hazard

A Comparison between the models and a reference data made it possible to assess the reliability or consistency of the model. A fire-damaged map of Integrated Forest Fire Management (IFFM) was used as the reference map of burnt areas of forest fires in East Kalimantan in 1997/1994. The fire-damaged areas of this map is measured based on land use class, which derived from ERS-1 SAR data (Hoffman et al., 1999). One of a few weakness of this map for reference is due to scale of interpretation between ERS-1 SAR of 1 km x 1 km and Landsat TM, which probably result on overestimating of burnt areas. However, this map was found the best available map for comparison. The reference map was registered to Landsat TM in order to make possible the GIS analysis. The reference map was classified into low, moderate, and high burnt areas correspond to 20-50% vegetation damage, 50-80% vegetation damage, and more than 80 % vegetation damage respectively.

An overall agreement of the model to the reference are varies as follow: 49 %, 53%, 46 %, 51 %, 53%, 53 % for model 1, model 2, model 3, model 4, model 5, and model 6 respectively. The result shows that the forest fire hazard model derived from the Drought Vegetation Index (model 4-6) show a better result than the model derived from land use (model 1-3). It means vegetation condition plays more important factors in forest fire hazard than vegetation type. Since the same species may present a complex hazard level according to their condition, fire hazard is more strongly on this factor than the vegetation species it self. Chuvieco and Congalton (1988) found similar result that fire behavior depends on morphology or structure of the vegetation than vegetation species in the Mediterranean region. No significant result found in case of increasing of the weight of vegetation condition or fuel type, followed by increasing of gradient (model 3 and 6). This is because increasing gradient on the model also increases the areas classified as very high hazard on steep gradient and steep gradients in the study area are commonly found on the elevation more than 150-m. Fire less severe at higher elevation due to higher rainfall.

The forest fire hazard models show more reliable from perspective of the proportion of the areas affected by burnt area as shown in figure 3. The proportion of the area classified as very high hazard was five times more compared with the area classified as low hazard in high burnt area of the reference map. While the proportion of the areas classified as low hazard was two times more compared to the areas classified as very high hazard in low burnt area.

A soil erosion hazard based on the percentage of bare soil derived from Landsat TM has been offered in this research. The result showed that 66 % of the areas classified as high hazard fall with the steep gradient (gradient > 30%), and 34 % with steep gradient (>45%), and no areas fall with plain gradient (Fig. 4). As bare soil on stepping terrain is always susceptible to erosion this soil erosion hazard model represent satisfy the distribution of bare soil on the study area and can be used as indicator for active soil erosion process.

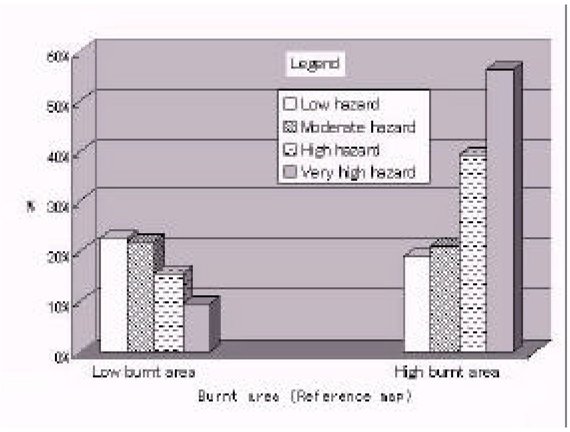


Figure 3. Forest fire hazard over the burnt area map

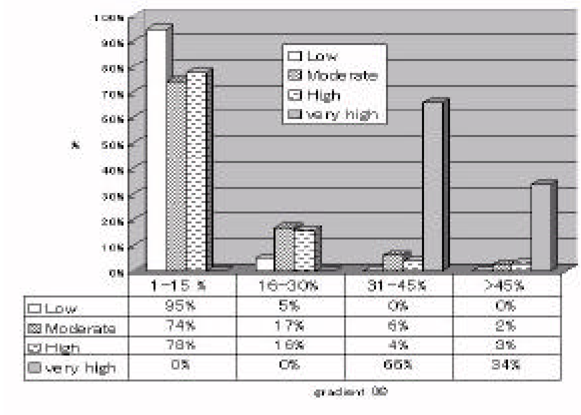


Figure 4. Soil erosion hazard and gradient

The GIS index analysis was applied to derive land and forest degradation map (fig. 7), which combines the forest fire and soil erosion hazards into single index of degradation areas (Table 2). The priority was given to the areas has susceptible to forest fire, since the study area is threatened by routine forest fire and it may accelerates soil erosion. Based on this map it is possible to identify and monitor areas affected by forest fire or to evaluate the pattern of land and forest degradation in the study area. According to this map, the area around Bukit Suharto National Park (up right) has threatened to be degraded area compared to Sungai Wain National Park (left below).

5. CONCLUTION

This research helps to understand the basic factors affecting forest fire hazard in lowland area of East Kalimantan using remote sensing. An area affected by forest fire can be predicted through deriving a forest fire hazard model using Geographic information systems. A method of land and forest degradation hazard mapping has been offered through index analysis of the forest fire and soil erosion hazards. Some factors were not considered, such weather data which area also known as factor having strong influence in forest fire should be considered in the next studies.

Acknowledgments

We would like to express our gratitude to Mr. Haruo Sawada, Forest and Forest Products Research Institute (FFPRI) Tsukuba-Japan and Mr. Kanehiro Kitayama, Kyoto University, for their useful comment and discussion on the research draft and for allowing using the remote sensing lab facilities.

Table 1. Index Value for Forest Fire Hazard

Variable	Value	Hazard class
Fuel type		
Wetland	1	Low
Natural Forest	1	Low
Plantation	2	Moderate
Farm land	2	Moderate
Grass land	3	High
Log over forest	3	High
Elevation		
> 150 m	1	Low
100 – 150 m	1	Low
50 – 100 m	2	Moderate
0 – 50 m	3	High
Gradient		
0 – 15 %	1	Low
16 – 30 %	2	Moderate
> 30 %	3	High
Aspect		
South ($135^0 – 225^0$)	1	Low
North ($315^0 – 45^0$)	1	Low
West (225^0 – 315^0)	2	Moderate
East (45^0– 135^0)	3	High
Road		
> 100 m	0	No hazard
500 – 1000 m	1	Low
250 – 500 m	2	Moderate
0 – 250 m	3	High

Table 2. The Relationship between Forest Fire and Soil Erosion Hazards to Land and Forest Degradation

Forest Fire Hazard	Soil Erosion Hazard			
	Low	Moderate	High	Very High
Low	Low	Moderate	Moderate	High
Moderate	Moderate	Moderate	Moderate	High
High	Moderate	High	High	Very High
Very High	High	High	Very High	Very High

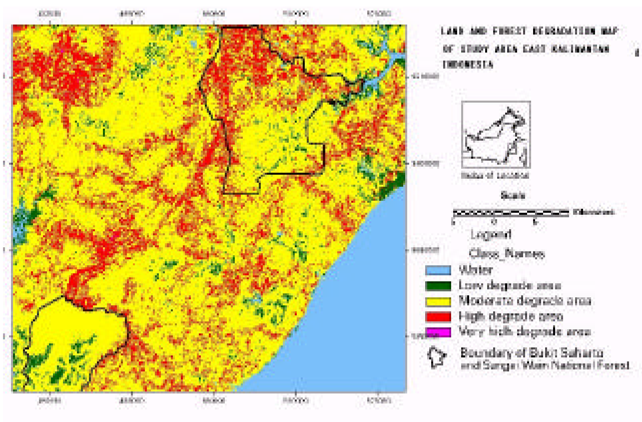


Fig. 7 Land and Forest Degradation Map

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