A SPATIO-TEMPORAL ANALYSIS ON THE FOREST FIRE OCCURRENCE IN CENTRAL KALIMANTAN, INDONESIA

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ABSTRACT

Fire is a disaster that causes adverse effects to forests, ecosystems and human life in Central Kalimantan, Indonesia. Enhancing technologies that monitor fires could reduce the occurrence of these disasters. In order to develop a robust fire monitoring system, a deep understanding of fire behaviour is needed. This study focuses on the investigation of spatial and temporal factors influencing forest fires in Central Kalimantan from 2005 to 2012. Data analytic modelling methods in geographic information system tools are applied to analyse data retrieved from MODIS satellite images coupled with ecological and weather information. Based on this analysis and an extensive literature review, this study proposes a new framework that illustrates the interactions amongst factors that contribute to forest fire. This framework shows that weather and ecological conditions play an important role in the development of forest fire. It also shows the influence of fire related to human activities to the development of fire. Understanding the characteristics and behaviour of fire is however only the first step in the effort to minimise fire occurrence in Central Kalimantan. The future work of this study is to use fire characteristics and behaviour obtained from remote-sensing analysis as input to predict fire occurrence.

Keywords: remote sensing, GIS, spatio-temporal analysis, forest fire

1 INTRODUCTION

Forest fires have become an increasingly serious problem in Indonesia (Dolcemascolo 2004). Located in the southern part of Borneo Island, 20% of Central Kalimantan is covered with peatland. As most of this peatland is degraded, it has become a flammable area with regular occurrence of fires (Page et al. 2009). Fires in degraded peatland areas are difficult to extinguish and can last for days or weeks (Usop et al. 2004). Consequently they can create a significant disturbance to the environment (Gao et al. 2016; Harrison et al. 2009; Hoscilo et al. 2011)

In Central Kalimantan the local authorities lack mechanisms to prevent and minimise the occurrence of fire. Their capability is limited to daily hotspot information from remote sensing instruments to monitor the occurrence of fire. Unfortunately, this information does neither indicate which hotspot will develop into forest fires nor identify existing fires. There is a need for a mechanism that can provide information on potential fire before it happens, to enable local authorities to prevent the occurrence or minimise the risk of fire.

Enhancing the technologies and infrastructures used to monitor and manage forest fire could prevent the continuance of forest fires disturbance (Dennis et al. 2005; Herawati & Santoso 2011). However, to be able to develop a robust forest fire detection system, it is necessary to have an understanding of fire behaviour and factors that contribute to the occurrence of fire. Factors that influence fire behaviour include human activities that involve using fire in the forest, climatic conditions and ecosystem conditions. A wide range of technologies has been used to study the characteristic of fires around the world. Remote sensing technology on satellites offers many opportunities to understand the spatial and temporal dataset influencing forest fire occurrences (Chuvieco & Kasischke 2007; Giglio et al. 2013; Wang & Feng 2010). Fire evidence from an archive of satellite-based data can be used as a basis to predict the occurrence of fires (Dlamini 2010). A range of research that utilises satellite-detected fire data has been conducted around the world, including the examination of fires in Central Kalimantan (Tansey et al. 2008; Wooster et al. 2012). However, none of the studies considers remote-sensing analysis in the development of forest fire prediction systems in Central Kalimantan.

The focus of this study is to investigate the spatial and temporal factors influencing forest fire in Central Kalimantan based on the evidence of satellite-detected fire data. Ecosystem factors, including land cover and fire history, and weather conditions are discussed in this study along with the influence of fire-related human activity. This study introduces a new framework that conceptualises factors contributing to forest fire and gives information about detection of future fire. This framework is built by applying the data analytic modelling method in the geographic information system (GIS) tools to find the conceptual relation between fires and the influencing factors from a set of time series data. Influence factors found in this investigation will be used as input in the modelling of a forest fire prediction system. To be able parametrise the influence factors, a text mining experiments will be conducted on the literatures relevant to forest fire in Central Kalimantan. Fire experts will also be engaged to verify the accuracy and validity of the model.

2 RELATED WORKS

The purpose of this section is to review related works: firstly, on the use of remote sensing images on forest fire; and, secondly on factors that influence forest fire in Central Kalimantan.

2.1 The Use of Remote-Sensing Images on Forest Fire

The emergence of sensor, remote-sensing techniques and satellite imagery has contributed to the continuous monitoring of the Earth’s condition through spaceborne sensors. This development has motivated researchers worldwide to use remote sensing to study forest fire occurrence in different ecosystems. The images from satellite remote sensing have become a major data resource to detect active fires (Wooster et al. 2013); for fuel and fire mapping (Boschetti et al. 2015); and to examine post-fire effects (Keeley 2009). In this section, a brief review on the use of - Advanced Very High Resolution Radiometer (AVHRR) instruments carried by National Oceanic and Atmospheric Administrator (NOAA) satellites and Moderate Resolution Imaging Spectroradiometer (MODIS) instruments aboard the Terra and Aqua satellites for active fires detection is presented.

The original purpose of NOAA-AVHRR was not to detect fires, but since it was launched in 1978, the instrument has provided digital images that can be used to detect fires. AVHRR pixels identify active fires by detecting the increase in AVHRR 3.7 µm channel brightness temperature measurement over that of the corresponding 11 µm value (Robinson 1991; Wooster & Strub 2002). Although the pixels saturate when the temperature is sufficiently high and this can lead to false alarms, the information of AVHRR daily coverage has provided useful material on identification of fire patterns in the various regions of the world (Flannigan & Haar 1986; Nakayama et al. 1999; Wooster & Strub 2002). However, it was found that sometimes the contextual algorithm delivered false fire detection due to cloud factors, cooler temperatures around the hot area and limitation of scale (Flasse & Ceccato 1996; Pu et al. 2004; Setzer & Verstraete 1994).

As part of NASA's Earth observing system, two fire channels in MODIS instruments were launched in 1999 and 2000 (Kaufman et al. 1998). The MODIS instrument is equipped with infrared (IR) spectral channels that are specifically designed to detect fires anomalies. Contextual algorithm was performed in the fire detection (Giglio et al. 2003), using the 4 µm and 11 µm thermal bands of the electromagnetic spectrum. The purpose of this algorithm is to identify pixels with one or more fires that are actively burning at the time of the satellite overpass and assign every pixel at spatial resolution of 1 km into one of the following classes: missing data, cloud, water, non-fire, fire or unknown (Giglio et al. 2003; Justice et al. 2002). Through the significant improvement of the algorithm, the better saturation level and accuracy in geolocation, MODIS instruments have provided more reliable detection in active fires compared to the earlier and other sensors. A range of successful research has reported on utilising active fire data from MODIS instruments in fire management and for characterisation fire activities (Boschetti et al. 2015; Dlamini 2011; Maeda et al. 2009; Tansey et al. 2008).

Satellite remote sensing has become the major data resource for forest fire detection research. However, research that utilises satellite-based data often used traditional liner and parametric fire occurrence models (Wooster et al. 2012). This method often does not account for uncertainty. The geospatial data also sometimes delivers uncertainty in the represented spatial relationship due to positional error, feature classification error, resolution, data completeness, currency and logical consistency (Kraak & Ormeling 2011). Another uncertainty that is sometimes unexploited, noted by Lozano et al. (2008), is the relationship between fire occurrence and environmental factors. This relationship is often non-parametric and when human activities are involved, the problem becomes more complex and dynamic. Methods that would handle uncertainty and enable various domains of evidence to be explicitly connected are therefore required for accurate analysis in forest fire detection research.

2.2 Factors Influencing Forest Fire in Central Kalimantan

Forest fire in Central Kalimantan arises from natural causes or human activity. Climatic and ecological conditions around the dry season are two natural influences in fire occurrences. Human activities in the forest also play an important role in triggering fire occurrences. A brief review of the literature discussing forest fires in Central Kalimantan is presented in this section.

Forest fires in Central Kalimantan mostly happen during the dry season. A range of studies has found that there is a close relationship between rainfall and fire incidents in Central Kalimantan (Ceccato et al. 2010; Putra & Hayasaka 2011; Yulianti & Hayasaka 2013). The number of fires increases when rainfall is below normal. Rainfall influences the fuel moisture content, especially in peatland. During the dry season, when rainfall is below average, the dryness of peat is increased and, in this condition, peat is very susceptible to burn (Usop et al. 2004).

Ecological conditions also contribute to the development of fires, especially in areas of peatland. When a fire eventuates in this area, it is difficult to extinguish (Putra & Hayasaka 2011; Usop et al. 2004; Yulianti & Hayasaka 2013). Siegert et al. (2001a) and Usop et al. (2004) found that during the dry season the degraded peatland experiences a decline in its water table, which in turn makes it easier for the area to catch fire. In the degraded areas, forest does not exist anymore, only shrubs are left. Shrubs can dry easily and become potential flammable material, especially in the dry season. When fires are ignited in this area, it easily spreads to neighbouring areas (Graham et al. 2014; Page et al. 2009).

Human activity also plays a significant role as a contributing factor to forest fires in Central Kalimantan (Jaya et al. 2007; Siegert et al. 2001a; Tacconi 2003). Human forest activity, that is, land clearing, timber exploitation and hunting, has a greater causal effect on the occurrence of forest fires than environmental or climatic factors. Fire can also spread from unmanaged or abandoned land. This category of area mostly experiences accidental fires due to the negligent behaviour, for example, cigarette butts or unprotected cooking fires (Thoha et al. 2014).

Since forest fires are not new problems in Indonesia, especially in Central Kalimantan, extensive research into identification of the causes of fires and impact after fire has occurred has been undertaken using different approaches. Qualitative approaches (Dennis et al. 2005; Vayda 2010; Tacconi et al. 2007) and simple statistical methods, such as finding the correlation between different factors, (Putra & Hayasaka 2011; Wooster et al. 2012; Yulianti & Hayasaka 2013) are the methods that were used most commonly to understand forest fire behaviour and its impact in Central Kalimantan. However, these methods have limitations in delivering comprehensive understanding about the relationship between anthropogenic fire and climate and ecology conditions. The implementation of modelling tools will provide a useful way of dealing with the complex problems of forest fire in Central Kalimantan.

3 METHODS

This research was based on gathering information from local community knowledge, from interviews with experts, and a review of existing research. Based on the information gathered, the variables that are used in the spatial and temporal analysis were determined. This analysis aimed to provide information on the behaviour of fires in different ecosystems and landscapes and also in different climate conditions.

A set of data about the topographic conditions was collected from the Kalimantan Forest Carbon Partnership (KFCP) dataset to be used in the spatial analysis. This dataset included land cover, peat condition, and burn area. Daily hotspot data from MODIS images were obtained for the period from 2005 to 2012. Data analytical modelling method in GIS tools was used to conduct spatial analysis using topographic and hotspot data.

A set of time series data about the climatic conditions, including humidity, rainfall, temperature, wind speed and direction, has been collected from the Bureau of Meteorology of Central Kalimantan for the period from 2005 to 2012. This period was selected because the El Niño phenomenon occurred four times between these years in 2005, 2006, 2009 and 2012. Basic analysis of detected active fires was undertaken through the calculation of hotspots occurring for each day of the period of investigation. This calculation was used to discover the temporal expansion of the fire activity and to explain the period of fire season in Central Kalimantan.

4 SPATIO-TEMPORAL PATTERNS: EVIDENCE FROM REMOTE SENSING DATA

Spatio-temporal analysis in this research used information about fire location and the development of hotspots obtained from MODIS. This information was used to investigate the factors influencing forest fire occurrence in Central Kalimantan. Spatial analysis of land cover, previous fire location and hotspot occurrence was conducted to show how the changes on landscape could contribute to fire occurrences.

Analyses of climate conditions including rainfall and the El Niño phenomenon was conducted to explain why fires only occurred at certain time in Central Kalimantan. Spatial analysis was also conducted on wind and hotspot dataset to figure out the location of fire spread.

Spatial analysis was conducted using land cover dataset and hotspots data from 2005 to 2012 on the KFCP area. Figure 1 illustrates the spatial occurrence of fires in this area as determined by the MODIS sensor with the pattern of land cover. Hotspots were detected mostly on shrub–mixed dryland farm and swamp shrub, 63% and 25% of the total number of hotspots, respectively. Both of these areas were degraded and very susceptible to fires. A disturbed or degraded area is an area where forest does not exist anymore, only shrubs grow on this area. In the dry season, shrubs dry out easily and become flammable material. Figure 1 also shows two areas that remained green and contained less hotspot occurrence – primary and secondary swamp forest. The number of fires in these two areas was quite low, less than 10% of the total number of hotspots that occurred on KFCP area. This happened because these forests still have the ability to absorb and store water, which kept the level of water table close or above the surface throughout the year (Hoscilo et al. 2011).

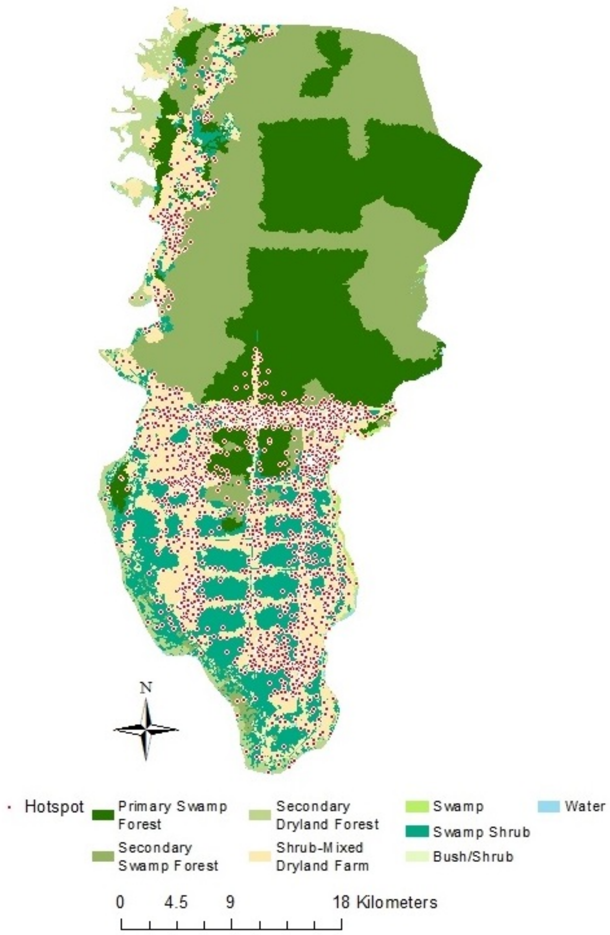

Figure 1. Land cover and hotspot occurrence

Based on the spatial analysis of the pattern on the burn area, it is clearly seen that fires mostly happened within the same area. Figure 2 shows areas that have experienced fire and areas that are never touched by fire. Fires have affected almost 20% of the area in KFCP site at least once and 30% have experienced repeated fire. Forest that previously burned became more fire-prone because the area contained opened-up forest with less tree canopy, subsequently lowering humidity and making the materials drier (Siegert et al. 2001b). The result of spatial analysis on hotspot and burn areas revealed that more than 80% of hotspots occurred in the area that had experienced fire in the past. This happens because this area contains a lot of flammable materials left from previous fires that can easily burn in subsequent fires. When the fires only ignite leaves, branches and surface non-tree vegetation, tree trunks usually remain unburnt (Hoscilo et al. 2011). These trunks become the fuels for subsequent fires.

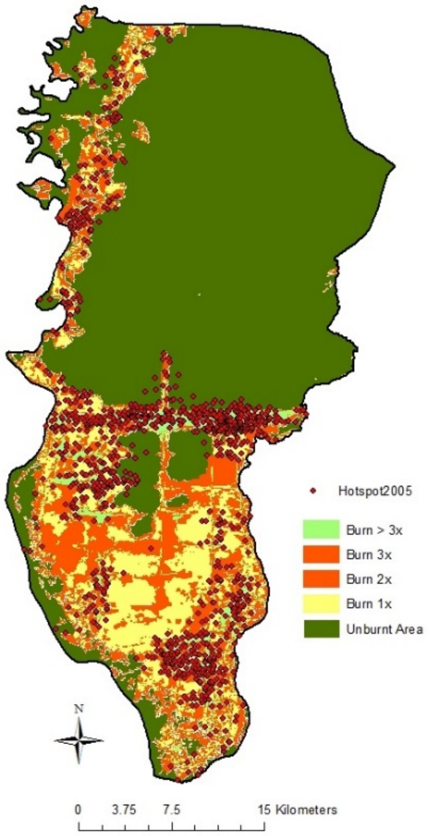

Figure 2. Fire history and hotspot occurrence

The type of land cover and the location of previous fires are not the only the factors that influence fire occurrence. Analysis of hotspot data from MODIS revealed that the fire season typically runs from early August to the end October (see Figure 3) with approximately 90% of annual hotspots occurring in this period of time. In 2005, 2006, 2009 and 2012 the number of hotspot occurrences reached a peak in September and slowly decreased towards the end of October, when it started to rain. However, the 2006 long drought in Central Kalimantan created a different trend; the rain season was delayed until the end of the year resulting in hotspots occurring until December.

Hotspots do not occur every year. Figure 3 shows that hotspots mainly occurred in the El Niño years and no hotspots were found in La Niña year. The El Niño phenomenon causes a reduction in the intensity of rainfall and also causes long drought. In 2005, 2006, 2009 and 2012 when a moderate and high El Niño occurred, it is recorded that for almost 30 consecutive days in August to September there was no rainfall. This led to the number of hotspots increasing rapidly to two or three times more than the previous month. Hotspots were unlikely to occur if there was rainfall. For example in October 2009, when it started to rain, the number of hotspot significantly decreased.

Previous researchers have found that fire can spread from one area to a neighbouring area under certain conditions (Graham et al. 2014; Usop et al. 2004). Fire could spread because it happened in open areas where strong wind blew, causing the fires to expand. Using data collected in 2012 from a ground investigation in the KFCP area, the relationship between wind direction and the hotspot locations was examined. This ground investigation was conducted using several criteria to determine the exact location and the causes of fire based, on daily MODIS data.

The first criterion was that if several hotspot data points were clustered at one location, only a single point within the cluster was investigated. The next criterion determined that all hotspots occurring in deep peat were investigated. If hotspots occurred within areas managed by local communities, especially cleared land and community assets, only a proportion of the hotspots were investigated. Hotspots occurring on planting sites were investigated. Hotspots occurring on mineral soils that were being cleared by deliberate burning were not investigated. Based on these criteria, the investigation discovered there were 25 hotspots that developed into fire in the study areas. The location of these hotspots was used to examine the occurrence of hotspots on the next day, based on wind direction. Wind speed and direction several hours before the occurring of hotspots were also used in this investigation.

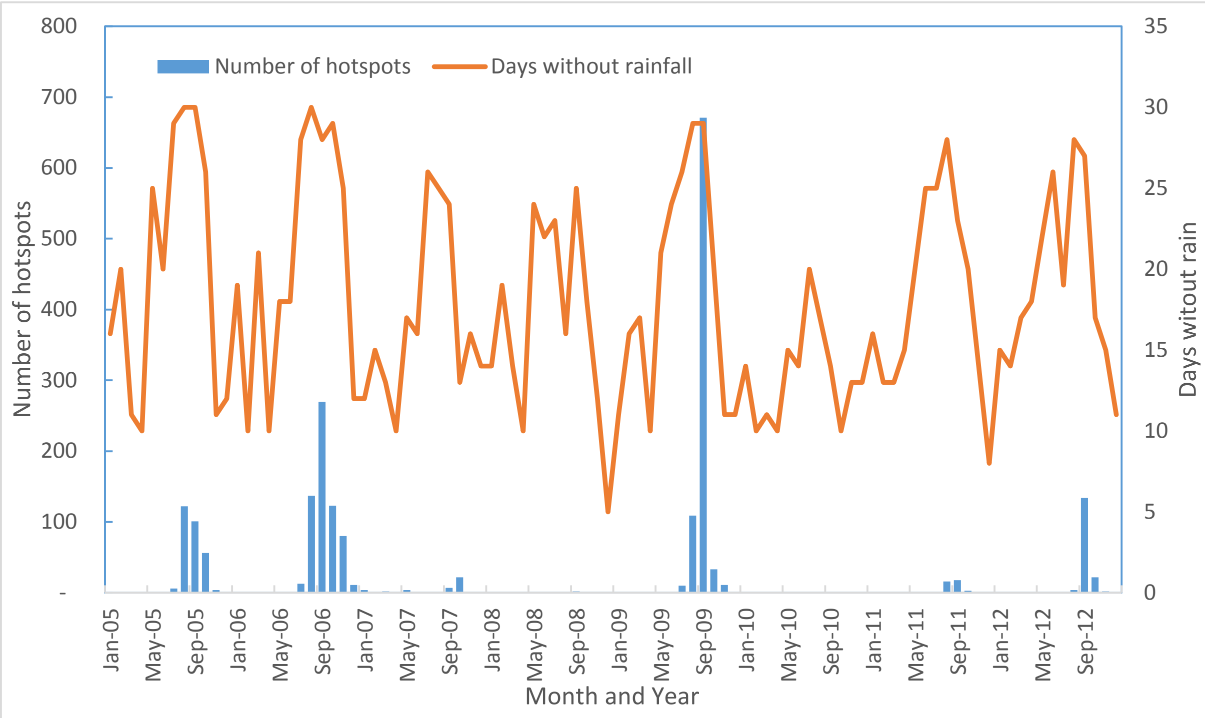

Figure 3. Comparison between days without rainfall and hotspot occurrence

The next investigation followed the four criteria used in the ground investigation with two additional criteria. The additional criteria were the linearity with wind direction and radius of fire. The examination of wind direction was used to determine hotspots that were not identified in the ground investigation as a fire or not. Because only one hotspot in a cluster of hotspots was investigated, there is a possibility that other hotspots in that cluster also turned into fires. Based on this assumption, the non-investigated hotspots were examined and labelled as fire. Based on the finding in the land cover analysis where fire can spread to neighbouring areas, non-investigated hotspots were examined to discover the linearity with wind direction. Wind speed and direction several hours before the appearance of hotspots were examined. If hotspots occurred inside of the radius of fire and they appeared linear with wind direction they were labelled as fire.

Datasets on wind direction, burn area, fires and hotspot location from 10–13 September 2012 are used to show the relationship between those data and determine the potential of fire. Based on the analysis shown in Figure 4, it can be seen that new hotspots are located in areas not far from the previous fire and are linear with wind direction. The fire itself happened from the morning of 11 September until the 13 September 2012. All the hotspots that occurred during this period were included in this examination. Figure 4 (b) and (c) shows that two clusters of hotspots occurred in areas surrounding the fires. It is also clearly seen that most of the hotspots occurred linearly with the wind direction. For example, there are clusters of hotspots that occurred south-west of the fire location and/or on the south direction of the fire. However, a hotspot also occurred far from the original fire and not linear with wind direction. It is possible that, this hotspot represents new fire ignition that arises from hot temperature or from human activities.

5 FRAMEWORK FOR FOREST FIRE IN CENTRAL KALIMANTAN

The new framework showing the broad relationship of fire to hotspot occurrence, climatic conditions and human activity is illustrated in Figure 5. The framework was developed using the understanding that fire is generated from flaming combustion that comes from heat and light and needs a particular proportion of fuel and oxygen to make it flame (Cochrane 2003). Heat is represented by a hotspot. A hotspot is a high temperature event that recording systems on weather satellites can identify (Langner & Siegert 2009). Each hotspot can be flagged as containing one or more fires, or other thermal anomalies (such as volcanoes, sun glint or gas flames on oil platforms). In Indonesia, hotspot data from NOAA-AVHRR and from the MODIS instruments on Terra/Aqua are mainly used to monitor hotspot occurrences.

Figure 5 shows hotspot occurrence triggered by climatic conditions, the ENSO index and human activities. Climatic conditions include temperature, amount of daily rainfall, the percentage of relative humidity and wind speed and direction. Human activity includes population density, livelihood of local people around the forest and how easily an area is accessed by people.

A study from Putra and Hayasaka (2011) found a strong correlation between the ENSO index and the amount of precipitation in Central Kalimantan. When the ENSO index increased, the amount of precipitation decreased. A robust relationship between the deficit of rainfall and the number of hotspots was also revealed in the Wooster (2012) study. Both of these studies showed that when the amount of precipitation is lower than normal, climatic conditions become drier, increasing the dryness of peatland and making this area susceptible to catching fire. Wooster (2012) also found a strong linear relationship between the ENSO index and the number of hotspots occurring in Central Kalimantan. The vast majority of hotspots (>80%) occurred within the period of an El Niño event.

Wind speed and direction also play an important role in hotspot development. Even though Usop et al. (2004) claimed that the relationship between fire spread on peatland area and wind speed is still unclear, the experiment in the section 4 of this paper found that hotspots spread to neighbouring areas and turn into large fires linear with the wind direction and speed.

Changes in the tropical land cover contribute to the ignition and spread of fire. Road construction, illegal logging, plantations and deforestation lead to structural change on the land cover. Cochrane (2003) shows that land cover that changed because of burning or logging becomes prone to fire after a few weeks without rain. This is because the fuel now available, such as dead trees, wood debris, leaf litter and branches, increases the opportunity for fire to start and spread.

Forest fire in Central Kalimantan is an anthropogenic fire. From ethnography and social science studies conducted by some researchers (Dennis et al. 2005; Tacconi et al. 2007; Vayda 2006), it is found that livelihood activities of local people in swamp and peat areas, such as agriculture, fishing and collecting wood, appear to be responsible for the ignition of fire and fire spread. These people mainly used fire to open and clear the land. Some unattended fires can be uncontrollable and spread to the forest.

Heat that is represented by hotspots, combined with dry conditions, can lead to forest fires, especially when fuel consisting of flammable materials is available around the hotspots. The flammable materials available depends on the vegetation type, soil characteristics and the land cover type of the forest. An area that covered with flammable materials is most prone to fires, especially if the forest fire weather index (FWI) is high and there are human activities present.

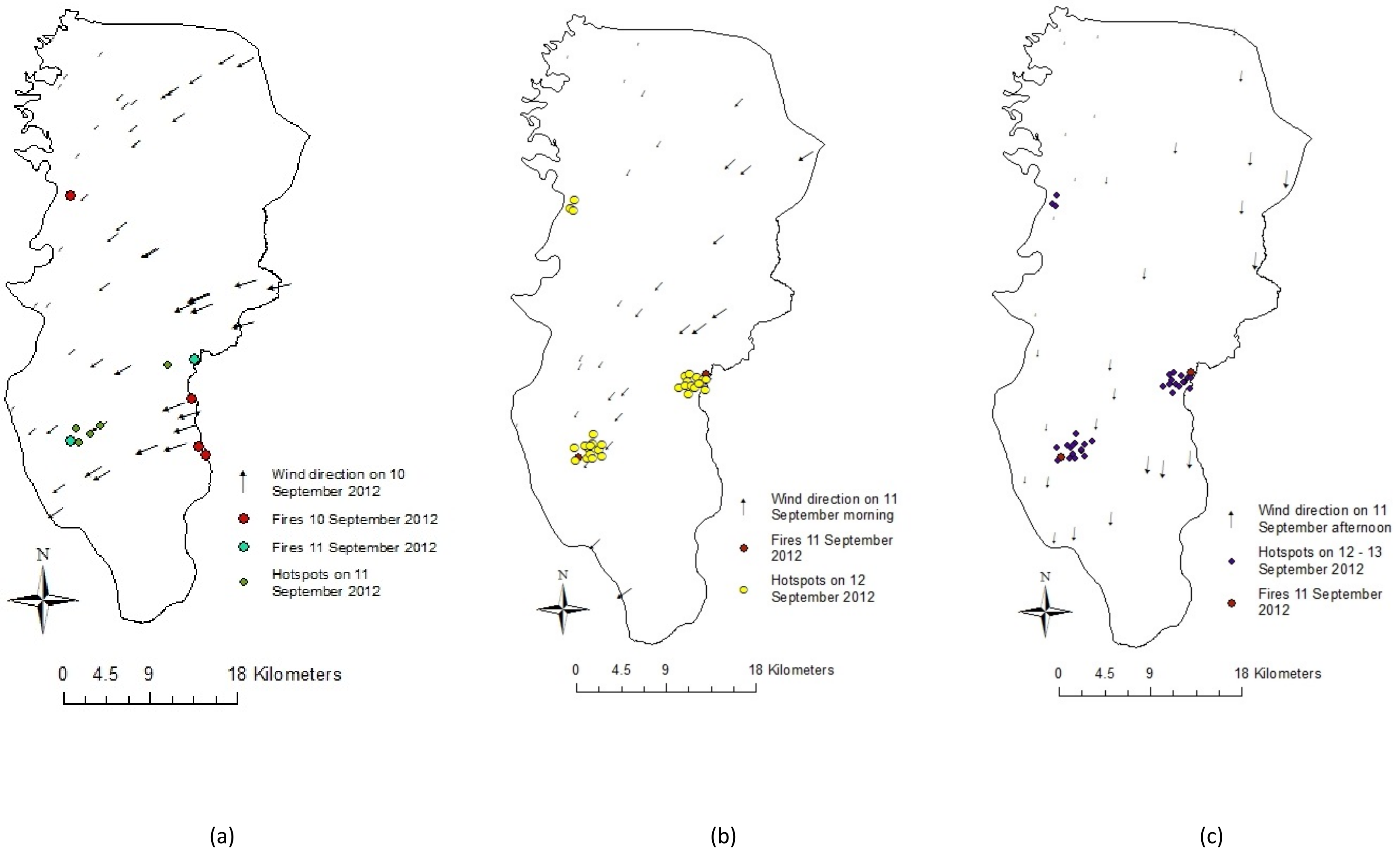

Figure 4. *Spatial analysis of wind direction and wind direction. (a) result from analysis on 11 September, (b) result from analysis on 12 September morning (c) result from analysis on 12 September afternoon*

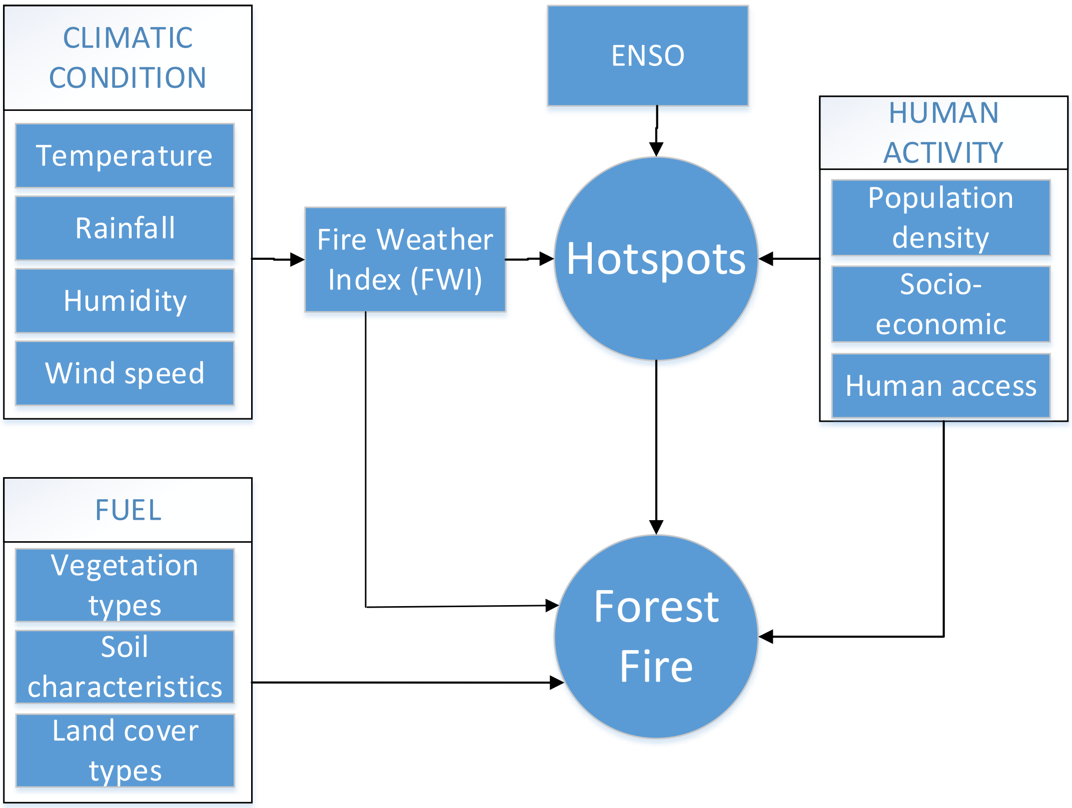

Figure 5. *Conceptual diagram of factors contributing to forest fire occurrence*

6 CONCLUSION

Fire is one of the disasters that causes adverse effects to forests, ecosystems and human life in Central Kalimantan, Indonesia. Remote-sensing active fire data has proven to be useful in helping to understand the spatial and temporal characteristics of fire in this area. In general, it has found that land cover is a big contributor to the likelihood of hotspot occurrence and fire spread. Non-forest areas such as shrub–mixed dryland farm and swamp shrub are the two land cover types that are suitable for hotspot occurrence. The fire season happens mostly in the dry season, from June to October and is compounded with the long drought that happens in El Niño years.

Based on the remote-sensing active fire data analysis and an extensive literature review, a contextual model of factors that contribute to forest fire occurrence has been introduced in this study. It shows that fire occurrence is influenced by the characteristics of land and weather conditions. In addition, it is also necessary to consider human activities involving the use of fire as an important contribution to fire occurrence in Central Kalimantan.

However, understanding these characteristics and human behaviour is only the beginning in the effort to minimise fire occurrence in Central Kalimantan. Increasing the use of technological tools to recognise dangerous fire activities at an early stage will help to anticipate future disasters and minimise losses.

7 FUTURE WORK

The future work of this research is to try to implement the details of fire characteristics and behaviour available from remote sensing analysis as input information for further analysis in modelling fire occurrence. A fire model that takes into account the results of satellite-based analysis will develop to give further information about the behaviour of anthropogenic fires in Central Kalimantan.

However, domain knowledge of fire behaviour in peatlands is still largely in the form of narratives and unmeasured qualities, such as human activities contributing to the escalation of a hotspots into forest fires. To be able parametrise the variables and find the relationships between each variables, a method in text mining will be conducted through all the literature that has relevance to forest fire in Central Kalimantan. The results from the text mining process will be used to develop the structure of the fire model. When the structure of fire model is built, experts in forest fire science will be interviewed and asked to evaluate and verify the validity of the fire model. The final step of this research is to evaluate the fire model using actual data obtained from satellite-based analysis.

Furthermore, this model is also expected to be able to provide information about early fire occurrence. The information about early fires will help fire agencies and other decision makers in making tactical and critical decisions in the forest fire management systems.

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