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Using Satellite Fire Detection to Calibrate Components of the Fire Weather Index System in Malaysia and Indonesia

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ABSTRACT / Vegetation fires have become an increasing problem in tropical environments as a consequence of socioeconomic pressures and subsequent land-use change. In response, fire management systems are being developed. This study set out to determine the relationships between two aspects of the fire problems in western Indonesia and Malaysia, and two components of the Canadian Forest Fire Weather Index System. The study resulted in a new method for calibrating components of fire danger rating systems based on satellite fire detection (hotspot) data. Once the climate was accounted for, a problematic number of fires were related to high levels of the Fine Fuel Moisture Code. The relationship between climate, Fine Fuel Moisture Code, and hotspot occurrence was used to calibrate Fire Occurrence Potential classes where low accounted for 3% of the fires from 1994 to 2000, moderate accounted for 25%, high 26%, and extreme 38%. Further problems arise when there are large clusters of fires burning that may consume valuable land or produce local smoke pollution. Once the climate was taken into account, the hotspot load (number and size of clusters of hotspots) was related to the Fire Weather Index. The relationship between climate, Fire Weather Index, and hotspot load was used to calibrate Fire Load Potential classes. Low Fire Load Potential conditions (75% of an average year) corresponded with 24% of the hotspot clusters, which had an average size of 30% of the largest cluster. In contrast, extreme Fire Load Potential conditions (1% of an average year) corresponded with 30% of the hotspot clusters, which had an average size of 58% of the maximum. Both Fire Occurrence Potential and Fire Load Potential calibrations were successfully validated with data from 2001. This study showed that when ground measurements are not available, fire statistics derived from satellite fire detection archives can be reliably used for calibration. More importantly, as a result of this work, Malaysia and Indonesia have two new sources of information to initiate fire prevention and suppression activities.

The fire problems experienced in Indonesia and Malaysia are 1) the sheer number of fires that can occur at a given time, 2) that some fires escape control measures and burn economically or environmentally valuable land or forests, and 3) smoke pollution (UNDP 1998a). A fire danger rating system can inform decisions about fire prevention, mobilization, and suppression activities (Stocks and others 1989, Andrews and Bradshaw 1992). Reviews of the 1997/98 fire and smoke disaster in Southeast Asia recommended that a fire danger rating system be implemented (HTTF 1997, UNDP 1998b). Implementation of such a system was expected to provide early warning information to stimulate proactive management activities for preventing the spread of fire and reducing its impacts.

The Canadian Forest Fire Danger Rating System (CFFDRS) is used for exactly that kind of proactive fire management in Canada. Various components of the CFFDRS combine the inputs of risk, weather, fuels, and topography to predict fire weather, fire occurrence, and fire behavior. The core of the CFFDRS is the Canadian Forest Fire Weather Index System (CFFWIS). It is composed of three codes that rate the moisture

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content of the fuels and three indices that indicate the relative fire behavior (VanWagner 1987). The success of the CFFWIS provides an opportunity for Southeast Asian countries to incorporate an existing system into their fire management (Stocks and others, 1989). However, to be useful, the CFFWIS must be calibrated to the local climate, fuels, and fire problems. Without such calibration, errors in the system could result in unexpected fire problems (Fogarty and others 1998).

The problem of smoke pollution has been addressed by calibrating the Drought Code from the CFFWIS for use as a predictor of haze events in western Indonesia (Field and others 2004). The Drought Code is defined as a numeric rating of the average moisture content of deep, compact organic layers (Merrill and Alexander 1987). That study used the relationship between the climate, the Drought Code, and ground-based visibility to calibrate four classes that each trigger different fire management activities (Field and others 2004).

The problem of the large number of fires that can occur at a given time is influenced by the dryness of the fuels and the presence of an ignition source. One element that we can monitor is the relative dryness of fine plant litter. This is the component of the vegetation biomass that is most readily flammable (Pyne 1984). Within the CFFWIS, the Fine Fuel Moisture Code (FFMC) is defined as a numeric rating of the moisture content of litter and other cured fine fuels (Merrill and Alexander 1987). It is also considered a good indicator of the ease of ignition (Muraro 1975). The most direct approach to calibrating the FFMC is by testing ignitions under many different weather conditions (Simard 1970, Lawson and others 1993). A more indirect but still reliable approach is to use historical fire occurrence data for calibration (Van Wagner 1987). Fire occurrence is defined as the number of fires started in a given area over a given period of time (Merrill and Alexander 1987).

The province of Alberta, Canada, performed a calibration study when adopting the CFFWIS (Kiil and others 1977). Researchers found that the FFMC had the highest correlation to fire occurrence among four different components of the Fire Weather Index System. A recent study in Saskatchewan, Canada, also found a high correlation between FFMC and fire occurrence (Anderson and Englefield 2001). This was true for both people-caused and lightning-caused fires.

Other problems occur when large clusters of fires occur in a spatial region and persist over time, possibly burning economically or environmentally valuable land or forests. These large and persistent fires may be a consequence of deliberate land clearing of that scale, or a result of fires that have escaped control measures. Typically, land-clearing fires are controlled by fuel breaks (Colfer 2000). If a fire escapes beyond the fuel breaks, control measures may include application of water from tanker-trucks, or digging ditches and clearing fuel breaks using shovels or excavators. Once a fire has started, it may escape control for a variety of reasons. These reasons usually include the dryness and amount of fuel that combine to create fire intensity or rates of spread that are difficult to suppress with the resources available. Within the CFFWIS, these factors are monitored daily using the Fire Weather Index. The FWI component is considered to be a good general indicator of all kinds of fire activity (Van Wagner 1987).

The province of British Columbia, Canada, adopted the Canadian Forest Fire Weather Index System in 1974. As part of that implementation, the FWI component was calibrated based on fire load (BC Ministry of Forests 1983). Fire load is defined as the number and magnitude of all fires requiring suppression action during a given period within a specified area (Merrill and Alexander 1987). The British Columbia calibration derived a Fire Load Index by combining the relationship between the Duff Moisture Code and fire occurrence, and the relationship between the FWI and fire size (Turner 1973). This index and interpretation were calibrated for two different climatic regions within the province. Further evolution of the CFFWIS in British Columbia included identifying a third climatic zone and relating classes of individual components to the size of all active fires, total area burned, economic costs, and fire severity (BC Ministry of Forests 1983).

The Alberta calibration study mentioned above also included the FWI (Kiil and others 1977). In that study, the FWI was correlated to suppression difficulty. Suppression difficulty is defined similarly to fire load (the number of fires and fire size measured at discovery, at initial attack, and when under control). The study concluded that FWI is a good predictor of suppression difficulty, but cautioned that the relationship was influenced by human settlement and fire management patterns at the time. Furthermore, fire size is strongly influenced by the seasonal condition of fuels (Kiil and others 1977).

The Saskatchewan, British Columbia, and Alberta studies relied on ground-based measurements of fire characteristics, such as area burned. Such fire reports are usually not available in Indonesia and Malaysia, but satellite fire detection (hotspot) records are readily available. The hotspot records have been used as proxy of fire records in relation to biomass burning and

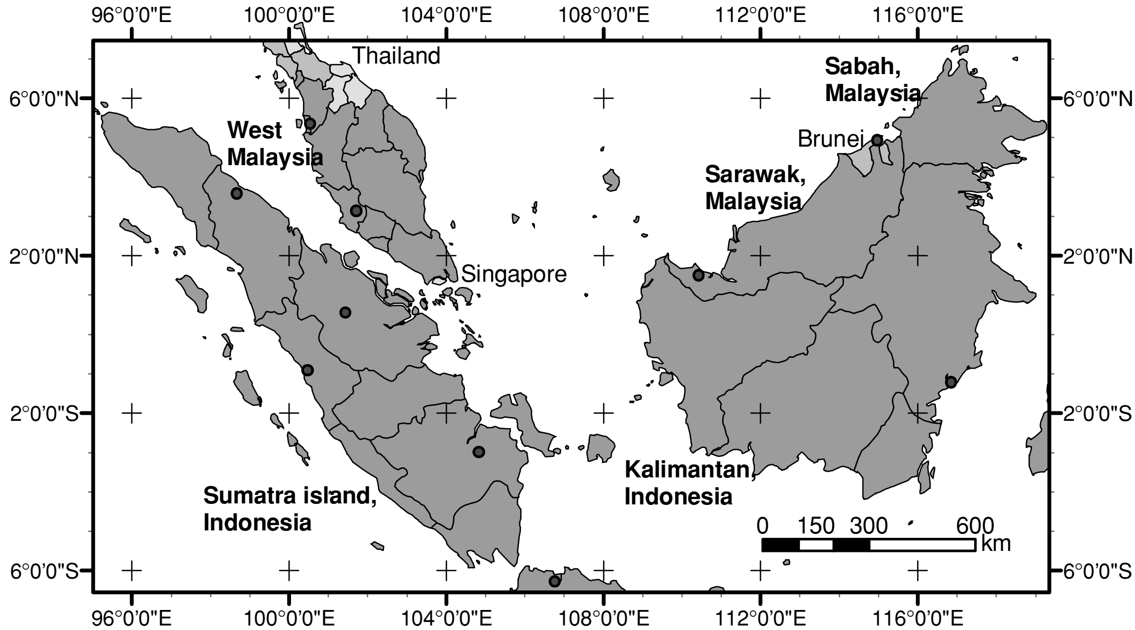


Figure 1. Study area of western Indonesia and Malaysia.

emissions (Duncan and others 2003). The general public, fire managers, and fire policy makers in Indonesia and Malaysia use these hotspots as qualitative indicators of fire occurrence (HTTF 1997, Hiroki 1999–2001). The public and managers perceive that more hotspots equate to more fire problems; for example, the number of hotspots per province is reported on nightly news broadcasts in Indonesia. An increasing number of hotspots within a province could be due to large intentional land clearing, a large fire being out of control, or because of a number of coordinated small controlled burns (Arino and Melinotte 1995). If the high number of fires in a province persists over numerous days, the perception is that fires have escaped controls. Despite potential difficulties, the multiyear hotspot databases provide an opportunity to characterize the relationship between CFFWIS components and the fire problems in Indonesia and Malaysia.

The purpose of this study was to calibrate the FFMC and the FWI components of the CFFWIS to the climate and two fire problems experienced by western Indonesia and Malaysia. Our first objective was to describe the frequency distribution of daily FFMC and FWI values as a consequence of the local climate. The second objective was to measure the problem of the number of fires as the relative hotspot occurrence, and measure the problem of regions of persistent fires as hotspot load. The third objective was to determine the relationships between FFMC and FWI values, the climate, and the fire problems to calibrate classes for a fire danger rating system.

Methods

Study Area

The study area lies between 6°S and 8°N latitude and 95°E and 120°E longitude (Figure 1). The total land area was almost 135 Mha. This area of western Indonesia and Malaysia has consistent climate, vegetation types, and cultural burning practices (Collins and others 1991).

Data Collection

The CFFWIS is based on daily weather records. Weather surfaces of each CFFWIS component were calculated from 1994 to 2001 daily weather data acquired from the National Climatic Data Center (available at http://www.ncdc.noaa.gov). This center implements significant quality control and archival service on synoptic weather data from the Global Telecommunications System. The CFFWIS indices are usually calculated on 12:00 local standard time observations of temperature, relative humidity, and wind speed. Daily mean values of these parameters were used because noon observations were not available in the dataset. Twenty-four-hour rainfall, totaled at 0000 UTC (0700 or 0800 local time in the study area) was used in place of rainfall totaled at noon. The year 1999 was not used because rainfall data were unavailable between January and October. Data from the year 2001 were used for validation purposes. Grids of each CFFWIS component were created using Spatial Fire Management System software (Lee and others 2002) using inverse distance weighting interpolation with adjustments to temperature and relative humidity based on altitude. There were no modifications made to the Spatial Fire Management System software or the calculations of the indices. Each grid cell was 10 × 10 km.

Fire detection data were acquired from the World Along Track Scanning Radiometer (ATSR) Fire Atlas (Arino and Melinotte 1995, Arino and others 2001). The thermal 3.7-μm channel of the ATSR sensor is sensitive to radiation emitted at temperatures ranging from 500 to 1000°K. With a 3-day revisit cycle, fire detection was carried out on nighttime data, which prevents false detection due to solar reflection. This way, the detection capability ranged from fires of 0.1 ha at 600°K to 0.01 ha at 800°K, for a background temperature of 300°K. The algorithm triggered a ‘‘hotspot’’ if the thermal channel was greater than 312°K, the saturation point for the channel. We assumed a constant underestimation of fire activity by the hotspots, that should not, therefore, affect the class boundaries. These data were previously used to study the interseasonal variability in biomass burning and emissions (Duncan and others 2003). For each hotspot detected, the date, time, and location in latitude and longitude were reported for a 1 × 1 km pixel. Based on the location of each hotspot, fire weather values were assigned from the 10 × 10 km FFMC and FWI grids.

Data Sampling for Hotspot Occurrence

An increasing number of hotspots indicates more fire problems (HTTF 1997, UNDP 1998a, Hiroki 1999–2001). Unfortunately, for statistical analysis, the raw hotspot data could not be used to estimate hotspot occurrence because one hotspot does not equal one fire. Each hotspot could be the result of more than one fire within a 1 × 1-km ATSR cell, or a large fire could result in multiple hotspots over many cells over many days. (Fire occurrence is defined as the number of fires started in a given area over a given period of time [Merrill and Alexander 1987].) Furthermore, the raw hotspot data has spatial and temporal autocorrelation characteristics that violate the assumption of independence in most common statistical tests. For example, a village may coordinate a number of field-clearing burns (Arino and Melinotte 1995).

To address these autocorrelation problems, we estimated hotspot occurrence from the presence of a hotspot in a randomly sampled area on a randomly sampled date. Four samples were collected from the population of hotspots available. In each sample, plot areas (3° × 3°) and dates were randomly generated 50,000 times (Figure 2). If a hotspot was present in the plot area and on the generated date, it were included in the sample. If more than one hotspot were present, one was randomly selected. The data were available for 1995 to 2001. A total of 20,900 hotspots were available and 1512 to 2763 hotspots were collected in each sample. Since less than 10% of the population was collected, the probability that those data points were autocorrelated was low.

If fires are occurring independent of fuel moisture, then they are most likely to occur on days with the most common FFMC values. To account for the effect of climate on fires, the distribution of FFMC in an average year was determined. The possible range of FFMC values is from 0 to 101 and increases as the moisture content of fine fuels decreases (Van Wagner 1987). The climate distribution was calculated from the same weather data used to calculate the fire weather grids. Only records from the most reliable stations were included, specifically, those with greater than 75% rainfall completeness, plus one additional station to ensure that the study area was covered. The result was 31 weather stations and 42,043 records. The frequency of occurrence of each FFMC integer at each station was calculated on an annual basis (e.g., number of days in a year that FFMC = 78). The annual occurrence, the average among the 31 weather stations, was then used to calculate a cumulative probability.

The frequency of fires occurring in each initial FFMC class was calculated for each sample. The initial FFMC classes were based on the climate distribution, so that each initial class accounted for 10% of the days in an average year (10 classes in total). This accounted for the effect of climate. The null hypothesis was that the means would be equal because the fires occurred independent of FFMC. This hypothesis was tested using a Tukey’s test (Sokal and Rolf 1995).

Data Clustering for Hotspot Load

More hotspots within a province indicates a worsening situation (HTTF 1997, Hiroki 1999–2001). The raw hotspot data have spatial and temporal autocorrelation characteristics that violate the assumption of independence in most common statistical tests. We capitalized on these autocorrelation characteristics to

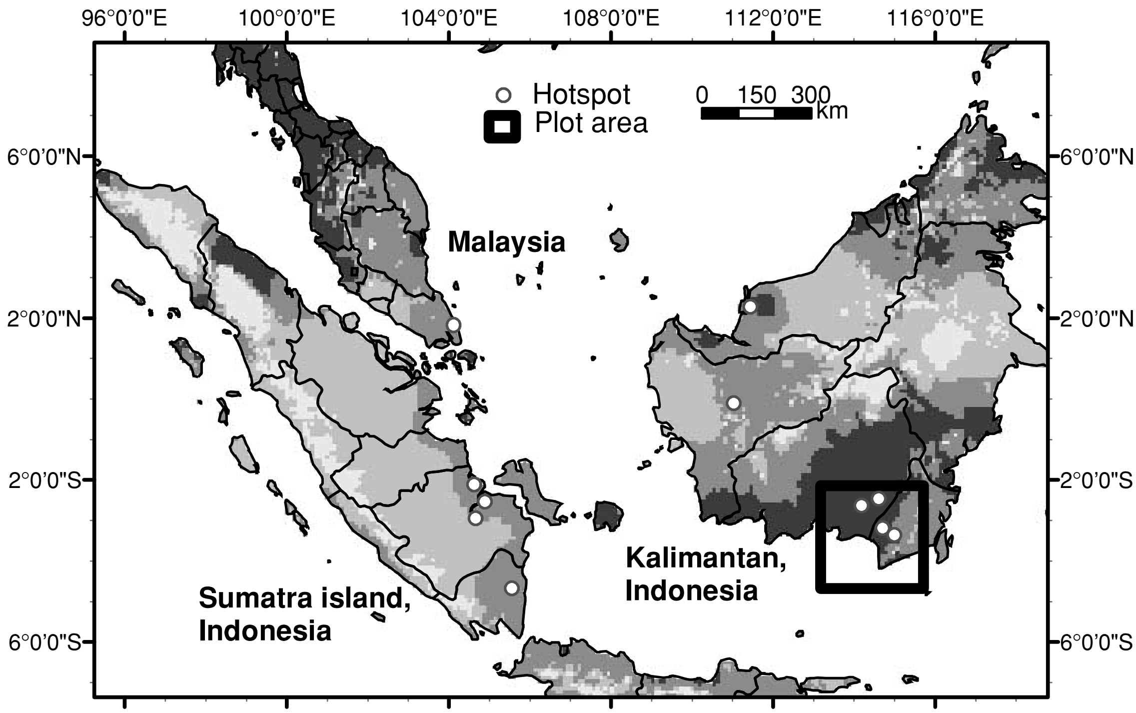


Figure 2. Example of a 3 × 3° plot area and hotspots for a randomly selected date. One of the four hotspots within the plot area was randomly selected to be part of the sample. Fifty thousand plot area and date combinations were generated for each sample. Four samples were collected. The gray-scale background represented a 10 × 10-km grid of FFMC values for the same date.

define hotspot clusters that represent a fire problem created by multiple ignition points that burn through a variety of fuel types in a heterogeneous landscape (Goldammer 1988). These hotspot clusters were assumed to be continuous in space and time. This assumption was made despite gaps between hotspots. The gaps may have been caused by the interaction between fires and the detection system. For example, fires may not be detected because of smoke or cloud cover obscuring the satellite's ability to sense the temperature of the earth surface (Arino and Melinotte 1995). Other fires may not have hotspots because they are moving rapidly; for example, although the fire was detected in one location on one day and detected some distance away on a subsequent day, the burned area between the two points may go undetected. Hotspots may occur in the same location over many days when a fire is moving slowly. Peat fires are a good example of a fire that may burn within a single grid cell over many days. Repeated burning also occurs; for example, an initial litter fire may kill the shrubs and trees, triggering leaf-fall and a renewed fuel bed.

Cluster analysis grouped the raw hotspot data into hotspot clusters as units for analysis (Figure 3). Cluster analysis is a statistical tool for organizing observed data into meaningful structures based on some measure of similarity or distance (Mirkin 1996). We used a nonhierarchical technique, K-Means, to partition the hotspots into hotspot clusters (SAS Institute Inc. 1999). The algorithm initiated with centroids tentatively defined along the scaled dimensions of date, latitude, and longitude. Hotspots were assigned to the cluster with the closest centroid, where ''closest'' was defined as the smallest Euclidean distance in scaled date, latitude, and longitude (Mirkin 1996). Hotspots that were very close to each other were assigned to the same cluster, and hotspots that were far apart were in different clusters. Each centroid was updated based on means calculated from the cluster members (Mirkin 1996). The process was repeated to reduce the least-squares criterion until no further changes occurred in the clusters (convergence > 0.95). The procedure used to generate the hotspot clusters was constrained so that a cluster could not last longer than 4 months. This constraint eliminated false hotspots caused by industrial activity that otherwise would create clusters of multiyear duration. Clusters with one or two hotspot members were also eliminated from subsequent

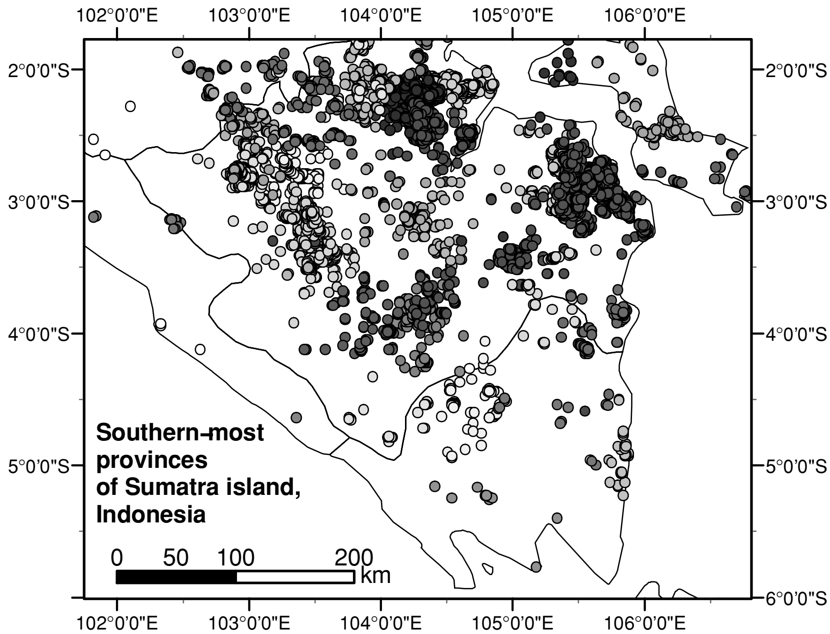


Figure 3. Example of clustering for a small area within the study area. Each dot represented one hotspot. Dots near each other and with similar color were assigned to the same cluster. Open circles represented hotspots that were not members of a cluster.

analysis, because they were likely to be manageable compared to the much larger clusters.

Hotspot load was estimated using the hotspot clusters as the unit of analysis. An increasing number of hotspot clusters, plus their increasing size, were interpreted as increasing hotspot load based on the previous work on fire load (Kiil and others 1977, BC Ministry of Forests 1983). The size of a hotspot cluster was determined from the maximum range of latitude or longitude of the member hotspots. FWI classes were assigned to each burning area based on the maximum FWI of hotspots members. This value was used to capture the worst fire weather conditions contributing to the hotspot load. The average FWI among the hotspot members was also tested; however, the results were unclear, possibly due to a skewed distribution. The data used for calibration were from 1995 to 2000. The total number of hotspots was 20,900 and resulted in 454 hotspot clusters.

If high hotspot loads are independent of fuel moisture, then they are most likely to occur on days with the most common FWI values. The FWI ranges from close to zero (rounded to zero in this study) and is unbounded on its upper end (Van Wagner 1987). Extreme fire weather conditions in Canada are associated with values above 21 to above 31, depending on the location. To determine the effect of climate on fires, the distribution of FWI in an average year was calculated using the same method as described for FFMC.

The average hotspot load was calculated for each FWI class. These FWI classes were based on the climate distribution, so that the four initial classes accounted for 75%, 10%, 10%, and 5% of the days in an average year. The inequality of the initial classes prevented formulation of a clear, statistically testable null hypothesis. The number of hotspot clusters and their sizes were compared between FWI classes to detect differences that could be captured by class boundaries. The initial classes that did not have distinct hotspot loads were combined to result in the calibrated classes.

Validation

The low density of weather stations in Indonesia and Malaysia was of concern because the weather may differ between stations, which may have created inaccuracy in the FFMC values associated with each hotspot. This may have been a source of error in defining the relationships between hotspot occurrence or hotspot load and fire weather. To test for this source of error, we graphically compared the relationship between hotspot occurrence and FFMC for all fires, and for those within 20 km of a weather station. Twenty kilometers was a conservative guideline because weather stations have been found to be reliable within 40 km and unreliable beyond 160 km (Turner and Lawson 1978). Twenty kilometers is also the radius that the Indonesia Meteorological Service uses to estimate the area accurately represented by its weather stations.

Seasonality may have also influenced the relationship between hotspot occurrence and FFMC. For example, fires may occur at lower FFMC values during waste removal from agricultural lands because elevated slash fuels are drier than fuels on the ground. We looked at how the proportion of hotspots occurrences in each Fire Occurrence Potential class changed over the course of a year. Monthly intervals were used to capture known agricultural seasons.

The class boundaries defined using 1995 to 2000 hotspots data were validated using independent data from 2001. We graphically compared the proportion of hotspots occurring in low, moderate, high, and extreme Fire Occurrence Potential classes. We also graphically compared hotspot load for low, moderate, high, and extreme Fire Load Potential classes. The validation dataset had 823 hotspots and 68 hotspot clusters.

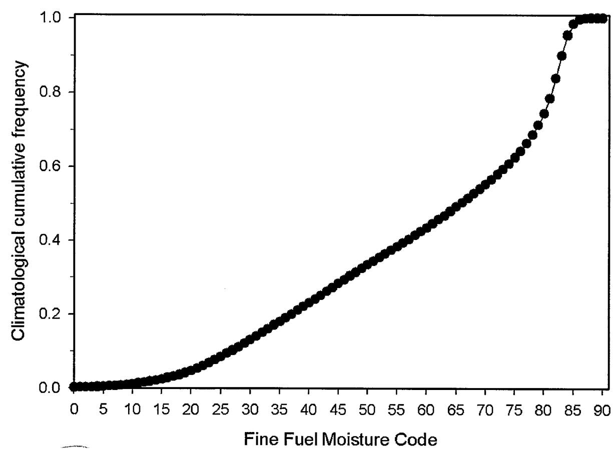


Figure 4. Cumulative frequency distribution of the Fine Fuel Moisture Code from 1994 to 1998 and 2000; 1999 was not available.

Results

Calibration of the Fine Fuel Moisture Code

The climate distribution of FFMC over a five-year-average indicated that low values were unlikely (Figure 4). The most frequently occurring values were between 80 and 85, with the maximum observed of 89. Therefore, if hotspot occurrence was independent of fuel moisture, most hotspots would have occurred when the FFMC was between 80 and 85. Based on the climate distribution, FFMC values were classified so that each class represented 10% of the days in an average year.

Hotspot occurrence was the lowest when FFMC was between 0 and 36 (Figure 5; Tukey's test; alpha = 0.05). Hotspot occurrence was the highest when FFMC was greater than 83 (Tukey's test; alpha = 0.05). Rather than most hotspots occurring between 80 and 85, as hypothesized above, the days with an FFMC of 84 to 89 had 37.6% of all hotspots, despite representing only 10% of days. An increasing FFMC from 36 to 84 corresponded to a generally increasing hotspot occurrence, increasing faster above an FFMC of 70. This change in slope corresponds with the theoretical ignition point of fine fuels at an FFMC of 70 to 73 (Muraro 1975). Therefore, we set our Fire Occurrence Potential classes based on the climate and hotspot occurrence as: low, 0–36; moderate, 36–69; high, 69–83; and extreme, >83.

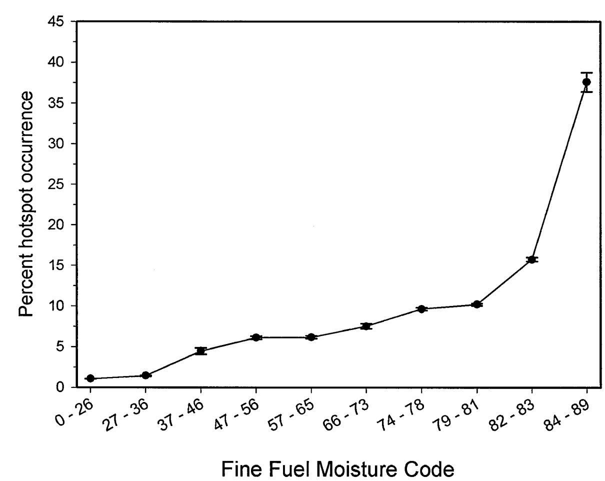


Figure 5. The average number of hotspot occurrences (mean ± standard error), proportional to the total, within each climate-based class of the Fine Fuel Moisture Code.

Calibration of the Fire Weather Index

The climate distribution of FWI over an average year indicated that low values were very common (Figure 6). FWI values above 6 accounted for less than 10% of an average year. The maximum observed was 33. If hotspot load was independent of the fire weather, many days with high hotspot load would occur when FWI was 0 or 1 and low hotspot load situations would occur when FWI was greater than 6. Because of the shape of the climate distribution, we could not define FWI classes with equal representation of the days in an average year, as we did with FFMC. Instead, classes representing 75%, 10%, 10%, and 5% of the days in an average year were used to account for the possible effects of the climate on the occurrence of high or low hotspot load situations.

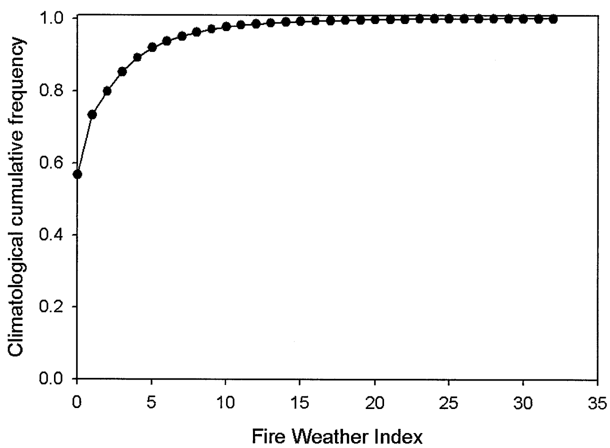


Figure 6. Cumulative frequency distribution of the Fire Weather Index from 1994 to 1998 and 2000; 1999 was not available.

The clustering analysis defined hotspot clusters that may be a single fire or multiple fires. A total of 454 hotspot clusters were identified (Table 1). The number of hotspots within each cluster tended to be lower than 12 (mode = 3, median = 11), although some were quite large (mean = 45, maximum = 469). Clearly, the number of hotspots per cluster was not normally distributed (kurtosis = 8, skewness = 2.7). The FWI values for the hotspot clusters were also not normally distributed (kurtosis = −0.717, skewness = 0.692). Despite the climate analysis showing FWI values of 0 and 1 to be most common, the median FWI value for the hotspot clusters was 6. The hotspot size ranged from 0.01 to 1.05° latitude or longitude with the mean at less than 0.5°. Therefore, analysis of these hotspot clusters was not indicative of variation within a local area, but of general trends across the entire study area.

Based on the combination of number and size of hotspot cluster, hotspot load was lowest when the FWI class was 0–1 (Figure 7). Although this range represented 75% of days in an average year, it accounted for only 24% of the total number of hotspot clusters, and they tended to be only one third the size of the largest hotspot clusters. The relative difference in hotspot load could not be tested using a Tukey's test because the data violated the assumption of similar variances (Sokal and Rolf 1995). Hotspot load was highest when the FWI class was greater than 6, although this class represented only 5% of days in an average year. This FWI class accounted for 49% of the total number of hotspot clusters, and they tended to average half the size of the largest cluster. The largest single hotspot cluster also had an FWI class above 6. Classes 2–3 and 4–6 each represented 10% of days in an average year. They also accounted for similar proportions of the number of hotspot clusters (14% and 12%) and had hotspot clusters more than one third the size of the largest cluster. Therefore, we set our Fire Load Potential classes, based on hotspot load, as: low, 0–1, moderate, 1–6, high and extreme, > 6. The range of FWI from 7 to 33 (the maximum observed value) represented a large range in weather conditions and potential fire behavior. Therefore, a class boundary between high and extreme was defined using the climatology (Figure 6). An FWI value of 13 or greater was rare in a normal year (probability of < 0.01), and primarily occurred under extreme drought conditions when extreme fire behavior has been observed. Therefore, we set our Fire Load Potential class of high at 6–13 and extreme at > 13.

Validation

The low density of weather stations in the study area could create inaccurate FFMC or FWI values. To test this, we compared the relationship between FFMC and all hotspot occurrences with the relationship between FFMC and hotspots occurring within 20 km of a weather station. The number of hotspots in each sample dropped dramatically (from 1512–2763 per sample to 37–62 per sample). There was general agreement that the proportion of hotspots occurrences increased as the Fire Occurrence Potential increased from low to extreme (Figure 8). The differences may have been due to local rainfall events being applied to large areas between weather stations, resulting in the underestimation of the FFMC values so fires were overrepresented in the moderate class and underrepresented in the extreme class. We also compared the proportion of fires that occur in each month, on average (Figure 9). Hotspot occurrence varied seasonally; the greatest proportion of fires occurred at the end of the dry season in August and September. Despite this seasonal variation, almost all fires occurred under high or extreme Fire Occurrence Potential conditions. The smaller peak in the high conditions of June was unexpected.

When hotspot occurrence data from 2001 were analyzed, the proportion of hotspots occurring increased as the Fire Occurrence Potential class increased from low to extreme (Figure 10). Analysis of hotspot load data from 2001 indicated an increasing hotspot load as the Fire Load Potential class increased from low to extreme (Figure 11). The results from 2001 were consistent with the calibration based on 1994–2000 data.

Table 1. Descriptive statistics for hotspot clusters

Statistic	Number of hotspots per cluster	Cluster size (degrees latitude or longitude)	Fire Weather Index value
Mean	45.3	0.455	8.99
Standard error	3.63	0.011	0.39
Median	11.0	0.47	6.0
Mode	3.0	0.50	0.0
Standard deviation	77.5	0.236	8.3
Sample variance	6004.0	0.056	68.9
Kurtosis	8.0	−0.628	−0.72
Skewness	2.72	−0.073	0.69
Range	466.0	1.04	32.0
Minimum	3.0	0.01	0.0
Maximum	469.0	1.05	32.0

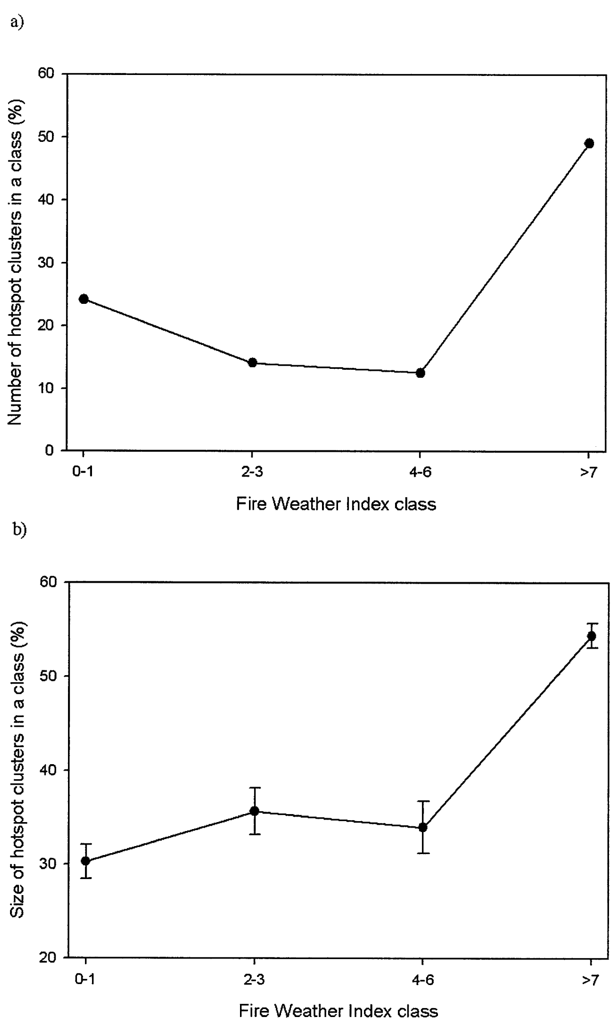


Figure 7. The hotspot load condition associated with each climate-based class of the Fire Weather Index (FWI): (**a**) component of the hotspot load estimated from the proportion of all hotspot clusters to fall within an FWI class; (**b**) component of hotspot load estimated from the size of hotspot clusters in a class (mean ± standard error) proportional to the maximum hotspot cluster size.

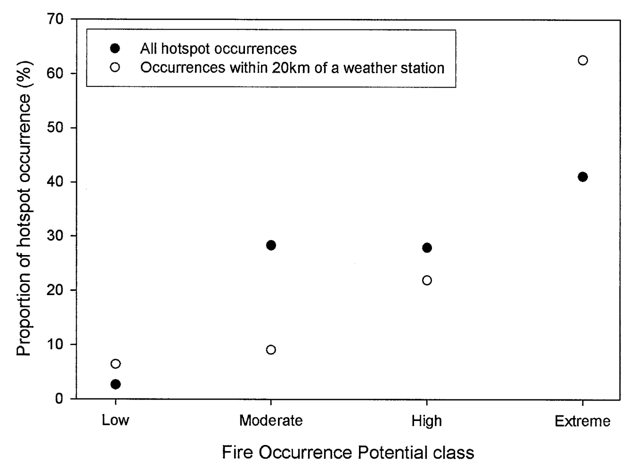


Figure 8. The relationship between average Fire Occurrence Potential and hotspot occurrence for all hotspots and for hotspots within 20 km of a weather station.

Discussion

This study found a positive relationship between increasing FFMC and hotspot occurrence. This relationship allowed us to define Fire Occurrence Potential classes for western Indonesia and Malaysia. The trend of an increasing proportion of hotspots occurring as Fire Occurrence Potential increased was consistent despite the seasonal drought and the use of an independent dataset. The seasonal pattern was consistent with the cultural practices. Crop rotation of herbaceous crops (e.g., rice, vegetables) generally occurs in late February through March, and August through September (Collins and others 1991). Woody slash burning generally occurs in August and September (Ketterings and others 1999, Saharjo and others 1999). The interpretation of the Fire Occurrence Potential classes was developed from the data analysis and from discussions with fire managers in Indonesia and Canada (Table 2). The classes and interpretations should

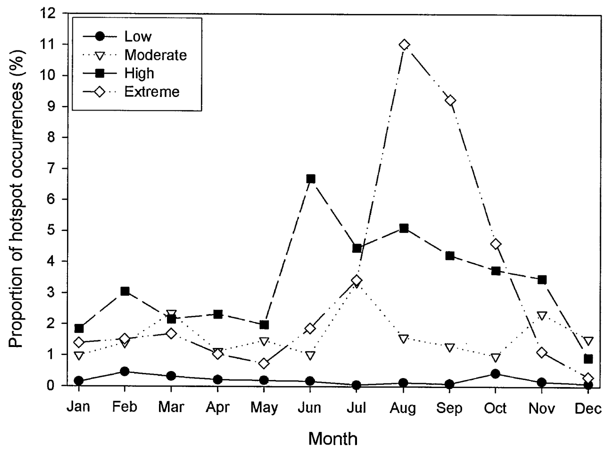


Figure 9. The proportion of hotspot occurrences (mean) within each Fire Occurrence Potential class on a monthly basis.

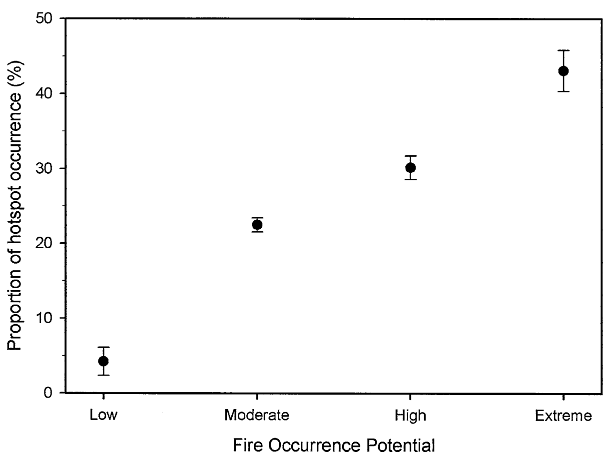


Figure 10. The proportion of hotspot occurrences (mean ± standard error) within each Fire Occurrence Potential class during the validation year of 2001.

be regularly reviewed and improved by experienced users.

Our results were consistent with studies relating ground observations of fire occurrence with FFMC in that relative hotspot occurrence estimated from satellite fire detection increased as FFMC increased. However, the Fire Occurrence Potential class boundaries were set at quite different values than are used in Canada. For example, the calibration study for the province of Alberta resulted in FFMC class boundaries of: low, 0–60; moderate, 61–80; high, 81–86; very high, 87–90; and extreme, 91+ (Kiil and others 1977). One factor creating these different results was the different climates. The maximum FFMC observed in western Indonesia and Malaysia from 1997 to 2000 was 89 (Figure 4). Under the Alberta calibration, extreme conditions would never occur. However, there are anecdotal reports of extremely dry conditions and easily ignited fuels. Likewise, the moderate class boundaries of 36–69 for western Indonesia and Malaysia may seem improbable to Canadian users. Under Canadian conditions, fires are unlikely to occur when the FFMC is less than 70 (Muraro 1975). The hotspot occurrences at FFMC values from 36 to 69 may be an artifact of the low density of weather stations, they may reflect the different drying conditions that occur in the tropical climate, or they may be a consequence of the intentional nature of the burning. The difference between the class boundaries for Alberta and Indonesia and Malaysia reinforces the importance of completing calibration studies.

The interpretation of Fire Occurrence Potential classes (Table 2) includes reference to different fuel groups (Dymond and others 2004). Fire managers intuitively understand that some fuel types have drier litter compared to others and are therefore more easily flammable. This intuition is supported by study results in Canada (Lawson and others 1993) and Indonesia (Marjenah and Toma 1999, Nicolas and Beebe 1999, Fogarty 2002). In general, the more protection the litter fuels have from solar radiation and wind, the more drying time is needed to reach the moisture content required for ignition.

Hotspot load generally increased as FWI increased. This relationship allowed us to define Fire Load Potential classes. About half of the hotspot clusters occurred under low or moderate Fire Load Potential conditions. These fire clusters probably represent the use of fire as a tool by knowledgeable villagers, where the fires are easy to control and tend to go out at the fuel breaks or at roads (Colfer 2000). However, the other half of the hotspot clusters occurred under unusually dry conditions (probability of 0.05) and over larger areas (average size 54% of maximum). The interpretation of the Fire Load Potential classes was developed from our study results and from discussions with Indonesian and Canadian fire managers (Table 3). The classes and interpretations should also be regularly reviewed.

The pattern of increasing hotspot load with increasing FWI was validated as consistent by the 2001 data. Despite 2001 being a normal year, with few days in the extreme class, there was a greater proportion of hotspot clusters in the extreme class compared to the high class. Hotspot clusters experiencing extreme conditions also tended to be the largest. Similar FWI classes have been applied to managing open burning

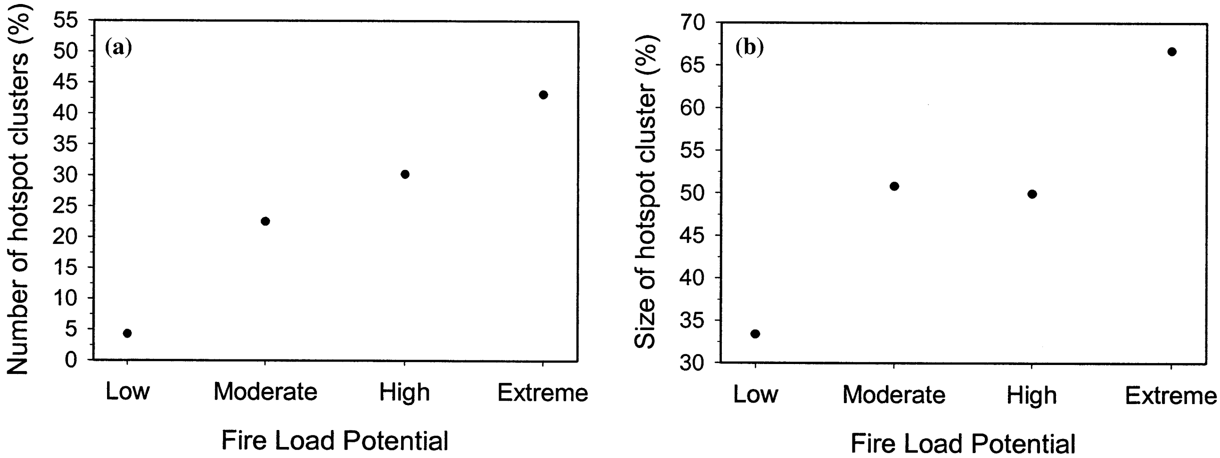


Figure 11. The hotspot load condition associated with each Fire Load Potential class during the validation year of 2001: (**a**) component of the hotspot load estimated from the proportion of all clusters; (**b**) component of hotspot load estimated from the size of a cluster in a class (mean) proportional to the maximum cluster size.

Table 2. Interpretation of Fire Occurrence Potential classes calibrated from the Fine Fuel Moisture Code (FFMC) for the fire danger rating systems of Indonesia and Malaysia[a]

Fire Occurrence Potential class	FFMC range	Proportion of an average year	Proportion of fires occurring 1994–1998	Interpretation
Low	0–36	0.20	0.025	Few fires will occur
Moderate	36–69	0.35	0.25	Ignitions may occur in Grassland or Slash fuel groups
High	69–83	0.35	0.26	Grassland and Slash fuel groups will easily ignite, potentially resulting in many fires
Extreme	>83	0.10	0.38	Open forest, Grassland, and Slash fuel groups will easily ignite, potentially resulting in many fires

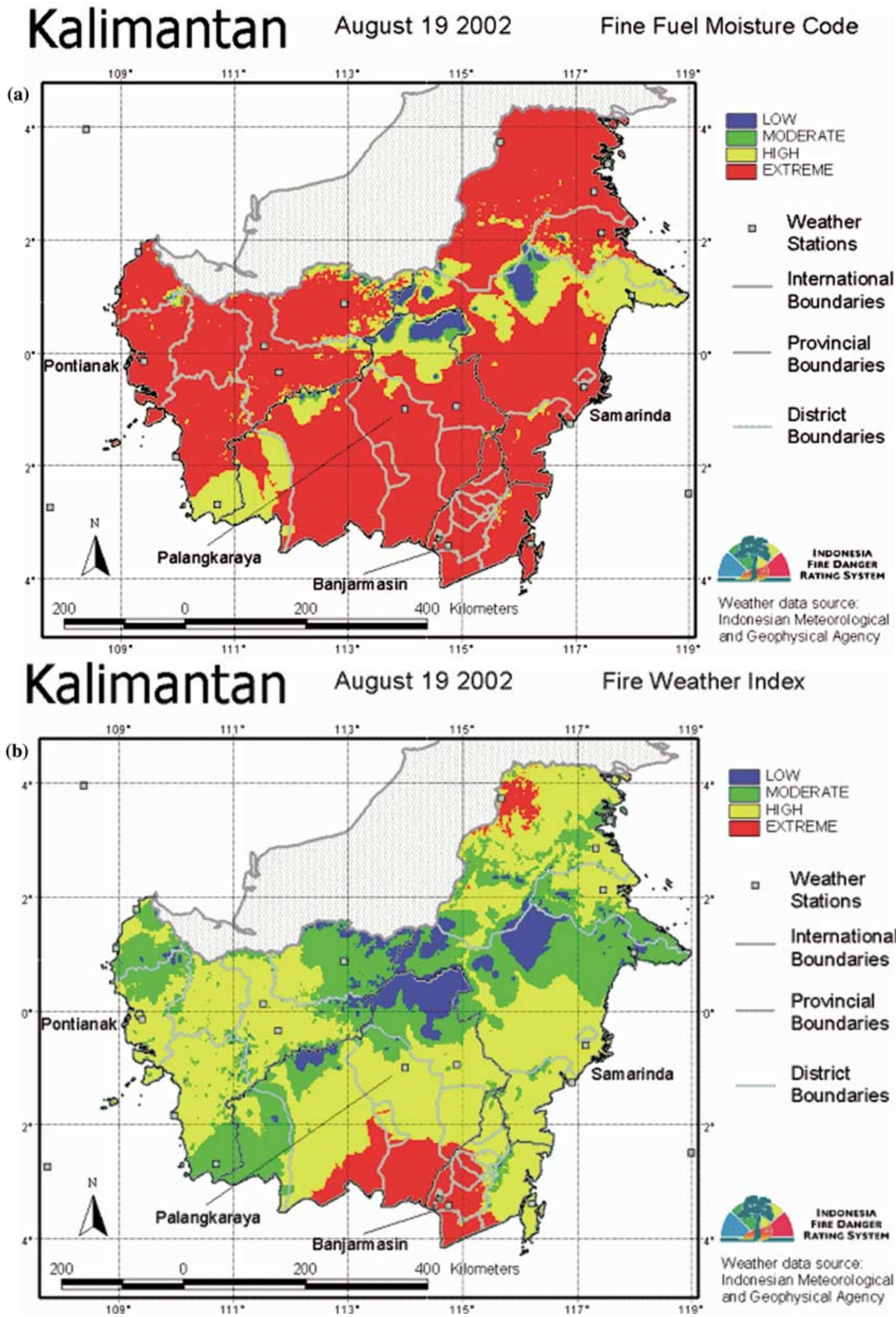
[a]Proportions do not sum to 1 because of averaging and rounding.

Table 3. Interpretation of Fire Load Potential classes calibrated from the Fire Weather Index (FWI) for the fire danger rating systems of Indonesia and Malaysia[a]

Fire Load Potential class	FWI	Proportion of an average year	Proportion of hotspot clusters occurring	Average of cluster size compared to maximum size (%)	Interpretation
Low	0–1	0.75	0.24	30	Fire clusters may occur, but they are relatively small and of short duration
Moderate	1–6	0.20	0.26	35	Fire clusters are more probable and may be larger than under low conditions
High	6–13	0.04	0.19	39	Fire clusters are probable and may be larger than under moderate conditions
Extreme	>13	0.01	0.30	58	Severe drought conditions and dangerous burning conditions exist. Fire clusters are highly probable, and may become large

[a]Proportions do not sum to 1 because of averaging and rounding.

in the province of Prince Edward Island, Canada (PEI Department of Agriculture and Forestry 1999). The FWI classes are low (0–1), moderate (2–8), high (9–15), very high (16–21), and extreme (> 22). Burning permits are valid when the FWI is low and are never valid when the FWI is high or extreme. Under moderate conditions, burning is restricted, such as, if it is necessary to burn slash under moderate FWI conditions, permit holders must ensure that the surrounding ground is wet.


Kalimantan
August 19 2002
Fine Fuel Moisture Code
(a)
LOW
MODERATE
HIGH
EXTREME
Weather Stations
International Boundaries
Provincial Boundaries
District Boundaries
Pontianak
Samarinda
Palangkaraya
Banjarmasin
200 0 200 400 Kilometers
Indonesia Fire Danger Rating System
Weather data source: Indonesian Meteorological and Geophysical Agency
Kalimantan
August 19 2002
Fire Weather Index
(b)
LOW
MODERATE
HIGH
EXTREME
Weather Stations
International Boundaries
Provincial Boundaries
District Boundaries
Pontianak
Samarinda
Palangkaraya
Banjarmasin
200 0 200 400 Kilometers
Indonesia Fire Danger Rating System
Weather data source: Indonesian Meteorological and Geophysical Agency

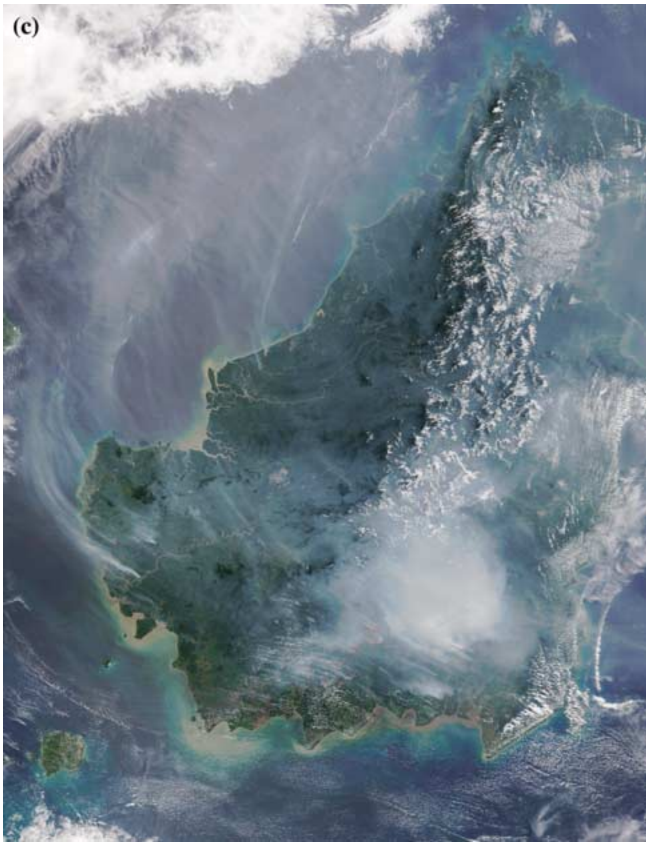


Figure 12. Fire information for Kalimantan provinces for August 19, 2002: (**a**) Fire Occurrence Potential classes; (**b**) Fire Load Potential classes; (**c**) satellite image from the Moderate Resolution Imaging Spectroradiometer sensor (courtesy of the Earth Observatory website: earthobservatory.nasa.gov).

A major communication tool of the Indonesia fire danger rating system is daily maps produced by the Indonesian Bureau of Meteorology and Geophysics (www.bmg.go.id). For example, the Fire Occurrence Potential (Figure 12a) and the Fire Load Potential (Figure 12b) maps for Kalimantan provinces on August 19, 2002. A satellite image with hotspots and smoke plumes (Figure 12c) provides fire information from the same day. Although fires occur in many locations over the landscape, the smoke plumes appear to originate within areas of high and extreme Fire Load Potential. From this comparison, the Fire Occurrence Potential and Fire Load Potential maps appear to provide a reliable and useful source to inform fire managers.

Conclusion

The Fire Occurrence Potential classes represent the Fine Fuel Moisture Code calibrated to Indonesian and Malaysian climate and hotspot occurrence. The most hotspots (38%) occurred under extreme Fire Occurrence Potential conditions. The Fire Load Potential classes represent the Fire Weather Index calibrated to Indonesian and Malaysian climate and hotspot load. The greatest amount of hotspot activity (30% of hotspot clusters with an average size of 58% of the maximum) occurred under extreme Fire Load Potential conditions. The Fire Load Potential and the Fire Occurrence Potential, as part of the currently operational fire danger rating systems for Indonesia, Malaysia, and Southeast Asia, will provide information that is fundamental to fire prevention, mobilization, and suppression activities. This calibration is to be used for general prevention, planning, and mobilization purposes. The local Fire Occurrence Potential and Fire Load Potential conditions depend on many site-specific factors that cannot be anticipated at the island or national level.

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