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Spatial-temporal Patterns of MODIS Active Fire/Hotspots in Chiang Rai, Upper Northern Thailand and the Greater Mekong Subregion Countries During 2003-2015

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Abstract

For the past decade, smoke-haze pollution from forest fires and open burning has been a yearly recurring problem over Chiang Rai and other provinces in Upper Northern Thailand, along with other countries in the Greater Mekong Sub-region. Remote-sensing active fire/hotspot data are currently used for monitoring the forest fires and open burning in the sub-region. This study aimed to extend the current monitoring work by performing spatial and temporal analysis to examine the patterns, either globally or locally, of MODIS active fires/hotspots during the critical smoke-haze pollution periods from January to April in 2003–2015. Fire radiative power was used as a weight attribute for each active fire/hotspot. Administrative unit maps were used for aggregating data and creating spatial weight matrices. Results indicated that for all the years over the investigated period and based on detected locations, active fires/hotspots were overall clustered spatially across provincial, interprovincial, and international scales. Their density patterns were locally variable for each year, but the high concentrated zones, in terms of both fire counts and fire radiative powers, were consistently bounded in the hilly and mountainous areas, confirming that the forest fires and open burning problem keeps recurring in certain areas. When aggregated by administrative unit, the administrative boundaries with high active fires/hotspots, in terms of both fire counts and fire radiative powers, were spatially clustered, either globally or locally, but there was only an increasing trend of the clustering intensity in fire radiative powers, implying that the forest fires and open burning problem have become more severe in particular areas. These findings could be useful for further reviewing and strengthening current measures and plans of fire and smoke haze pollution management.

Keywords: Spatial; Temporal; Pattern; MODIS; Fire; Hotspot

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Introduction

For the past decade, Chiang Rai and other provinces in Upper Northern Thailand have experienced smoke haze pollution to various degrees during burning seasons from January to April. [1]. As a result of forest fires and open burning within Chiang Rai and other provinces in the Upper Northern Thailand, plus other countries in the Greater Mekong Sub-region, especially Myanmar and Laos, the levels of ambient particulate matter have been found to exceed both the daily and the annual safety standards for prolonged periods [2,3]. This has induced adverse impacts to the environment, public health, and socio-economic developments, and caused disturbances to the lives of millions of local people.

To monitor the problem, remote sensing data has been extensively used [4]. As satellites pass over the earth, they take a snapshot of the ground. Each image pixel whose temperature brightness exceeds a pre-defined threshold value, is flagged as an active fire/hotspot [5]. Among various forms of remote sensing active fire/hotspot data, those from MODIS (Moderate-resolution Imaging Spectroradiometer) satellites appear to be freely available, easily accessible, and hence very useful for exploratory applications. In the current monitoring work, MODIS active fire/hotspot data are geographically mapped over administrative units to explore their spatial distributions over each day or week. Nonetheless, the current monitoring works do not take the spatial and temporal interactions among MODIS active fires/hotspots into consideration, so the underlying insights on patterns of forest fires and open burning within the area cannot be discerned.

As demonstrated in previous studies, applying geo-statistics on historical fire occurrence data could lead to a further understanding and insights of the fire patterns in an area of interest [7–10]. However, this study is the first to extend the current monitoring work in Upper Northern Thailand and other countries in the Greater Mekong Sub-region by applying geo-statistics to examine the spatial and temporal patterns, either global or local, of MODIS active fires/hotspots during the critical smoke-haze pollution periods from January to April in the past decade (from 2003 to 2015). The results are significant as a reference for the future monitoring work at various levels.

Data and methods

1) Data

Data in this study were collected from various sources. Firstly, the standard quality data of MODIS active fires/hotspots (MCD14ML Collection 6) during the burning seasons from January to April in 2003–2015 were obtained from NASA Fire Information for Resource Management System (FIRMS). Each active fire/hotspot included attributes of longitude and latitude of the center of the fire pixel, date of acquisition, confidence measured in percent (%) to gauge the quality of fire detection, version (collection and source), and fire radiative power measured in megawatts (MW). In this study, the active fires/hotspots with confidence less than 30%, as low-confidence fires, were screened out, and then the rest were yearly aggregated for further analysis. Secondly, the sub-district boundary maps of Chiang Rai and other provinces in Upper Northern Thailand were acquired from Thailand's Department of Provincial Administration where the township, district, and county boundary maps of Myanmar, Laos, and China's Yunnan, were acquired from the Database of Global Administrative Areas (GADM), respectively. Isolated areas or islands were excluded from the analysis.

For the purpose of this study, all collected data were organized into three datasets according to three overlapping study areas for the analysis at provincial, interprovincial, and international scales: Chiang Rai only (CRI), Chiang Rai and other provinces in Upper Northern Thailand (UNT), and Chiang Rai, and other provinces in Upper Northern Thailand, and Myanmar, Laos, and China's Yunnan in the Greater Mekong Sub-region (GMS) respectively (Figure 1).

All datasets were mainly stored in the comma-separated values (CSV) format and/or the shapefile format with the Asia South Equidistant Conic projected coordinate system (EPSG 102029). They were mainly managed and processed by using QGIS version 2.18.15 (Open Source Geospatial Foundation Project) and R version 3.4.3 (R Foundation for Statistical Computing).

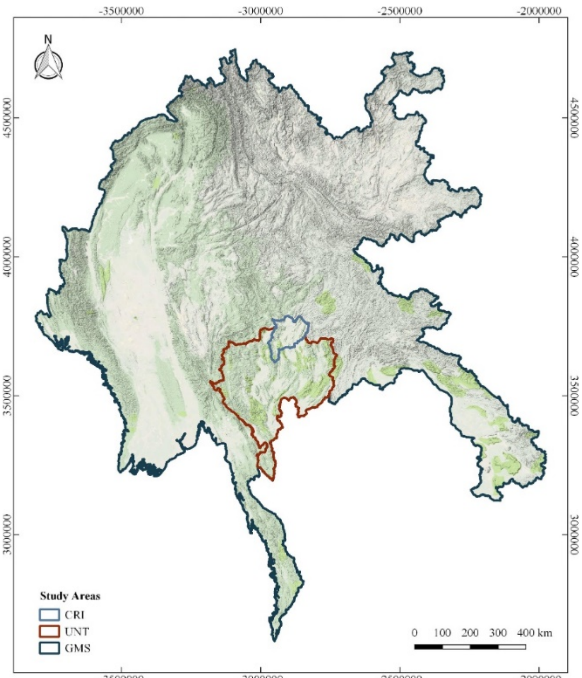

Figure 1 Three overlapping study areas for the analysis at provincial, interprovincial, and international scales: Chiang Rai only (CRI), Chiang Rai and other provinces in Upper Northern Thailand (UNT), Chiang Rai, other provinces in Upper Northern Thailand, and Myanmar, Laos, and China's Yunnan in the Greater Mekong Sub-region (GMS), respectively.

2) Method

The MODIS active fires/hotspots in each of the CRI, the UNT, and the GMS study areas were subjected to exploratory analysis using descriptive statistics to examine the overall trend. Then, they were subjected to spatial and temporal analysis using geo-statistics, including nearest neighbor index, Moran's I, and Anselin Local Moran's I to detect and quantify types and degrees of yearly density and spatial patterns over a 13-year period of time. In this study, the finding pattern is statistically significant when $p < 0.05$. The fire radiative power, as a quantification of biomass burning, was used as a weight attribute for each active fire/hotspot. It has been demonstrated in small-scale experimental fires that integrating this variable over the lifetime of a fire provides an estimate of the total fire radiative power, which for forest fires should be proportional to the total biomass combustion [11]. The administrative unit maps were used for aggregating data and creating spatial weight matrices based on the contiguity of edges and corners. All geo-statistics settings were kept the same for each study area in order to make the results comparable within the same study area over the investigated period.

2.1) Nearest neighbor index

This study calculated the nearest neighbor indices to determine whether the yearly spatial patterns of MODIS active fires/hotspots in each study area are globally clustered, dispersed, or random. The index is a ratio that compares the mean of the series of distances to nearest neighbor in the observed MODIS active fires/hotspots ($\bar{r}_A$), with such in the hypothetical random data with the same density ($\bar{r}_E$) [12]:

$$NNI = \frac{\bar{r}_A}{\bar{r}_E} = \frac{[\Sigma r/N]}{[1/2\sqrt{\rho}]} \quad \text{(Eq. 1)}$$

where *r* is the distance from a given MODIS active fire/hotspot to its nearest neighbor, *N* is the yearly sum of MODIS active fires/hotspots, and ρ is the density of the observed MODIS active fire/hotspot, expressed as the number of observations per unit of area. Note that the observed MODIS active fires/hotspots are towards global clustering when $NNI < 1$, dispersion when $NNI > 1$, and random when $NNI \approx 1$.

2.2) Moran's I

The spatial autocorrelations were measured to evaluate whether the yearly spatial patterns of the MODIS active fires/hotspots by administrative unit in each study area are globally clustered for similar values (either high-high or low-low) or dissimilar values (either high-low or low-high), in terms of fire counts and fire radiative powers. The evaluation was based on the Moran's I statistics [13]:

$$I = \frac{n \sum \sum w_{i,j}[x_i - \overline{X}][x_j - \overline{X}]}{(\sum \sum w_{i,j}) \sum [x_i - \overline{X}]^2} \qquad \text{(Eq. 2)}$$

where n is the total number of administrative units, $w_{i,j}$ is the spatial weight matrix of the administrative unit network, x_i and x_j are the yearly sums of MODIS active fires/hotspots in terms of fire counts and fire radiative powers, for administrative unit i and j (where $i \neq j$) respectively, and $\overline{X}$ is the mean of the yearly sums of MODIS active fires/hotspots in terms of fire counts and fire radiative powers over the administrative units. Note that the observed MODIS active fires/hotspots are towards global clustering of similar values (either high-high or low-low) when I is positive, and clustering of dissimilar values (either high-low or low-high) when I is negative.

2.3) Anselin Local Moran's I

The cluster and outlier analysis was to depict how the yearly spatial clustering for similar (either high-high or low-low) or dissimilar (either high-low or low-high) values of the MODIS active fires/hotspots, in terms of fire counts and fire radiative powers by administrative unit, vary locally in each study area. The depiction was based on the Anselin Local Moran's I statistics [14]:

$$I_i = \left[\frac{x_i - \overline{X}}{S_i^2}\right] \sum W_{i,j} [x_j - \overline{X}] \qquad \text{(Eq. 3)}$$

$$S_i^2 = \frac{\sum w_{i,j}}{n-1} - \overline{X}^2 \qquad \text{(Eq. 4)}$$

where n is the total number of administrative units, $w_{i,j}$ is the spatial weight matrix between administrative unit i and j, x_i and x_j are the yearly sums of MODIS active fires/hotspots in terms of fire counts and fire radiative powers for administrative unit i and j (where $i \neq j$) respectively, and $\overline{X}$ is the mean of the yearly sums of MODIS active fires/hotspots in terms of fire counts and fire radiative powers over the administrative units. Note that the local spatial patterns are classified into four types of association based on the observed value and the corresponding spatial weighted average: cluster of high values (HH), cluster of low values (LL), outlier in which a high value is surround primarily by low values (HL), and outlier in which a low value is surround primarily by high values (LH).

Results and discussion

The yearly sums of MODIS active fires/hotspots in each study area during the critical smoke-haze pollution periods over 2003–2015 are summarized in Table 1. They fluctuate greatly with no clear trend (Figure 2). Noted that severe droughts and related El Niño events in 2007 [15], and anomalously high rainfall in the pre-monsoon season and great floods in 2011 [16], could potentially be key drivers to the fluctuations.

Table 1 Average (min-max) of yearly sums of MODIS active fires/hotspots in the CRI, the UNT, and the GMS study areas during the burning seasons in 2003–2015.

Yearly sums of MODIS active fires/hotspots during the burning seasons in 2003–2015	Study area		
	CRI	UNT	GMS
Count	1279 (621–2075)	11865 (5032–17313)	116811 (75500–160045)
Percentage relative frequency	1.1% (0.7–1.4%)	6.7% (10–12%)	100%[a]

Remark: [a] Myanmar, Laos, and China's Yunnan Province accounted for 55.3% (50.7–61.2%), 30% (24.5–36.5%), and 4.7% (3.0–6.7%) of those in the GMS study area, respectively.

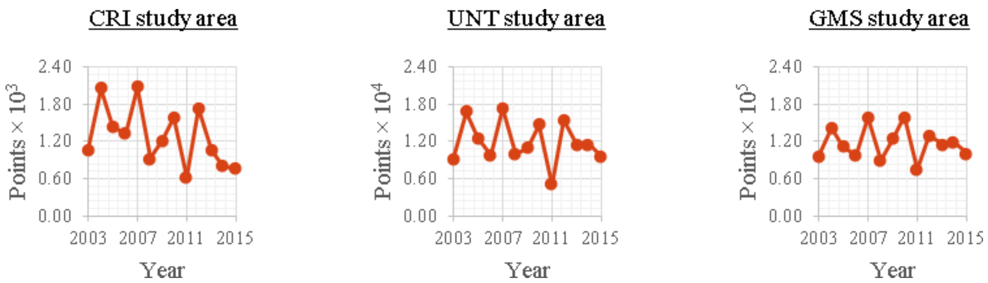

Figure 2 Yearly sums of MODIS active fires/hotspots in the CRI, the UNT, and the GMS study areas during the burning seasons in 2003–2015.

When geographically mapping the administrative units, the distributions of the yearly sums of the MODIS active fires/hotspots, in terms of fire counts and fire radiative powers, were skewed to the right: low values were found in most administrative units, whereas extraordinary high values were only found in some administrative units. By administrative unit, the yearly sums of MODIS active fires/hotspots, in terms of fire counts, varied between about 0-170 points with a median of 3 points for the CRI study area, 0–376 points with a median of 3 points for the UNT study area, and 0-5186 points with a median of 9 points for the GMS study area, while the yearly sums of MODIS active fires/hotspots, in terms of fire radiative powers, varied between approximately 0–6867.4 MW with a median of 43.9 MW for the CRI study area, 0–24343.9 MW with a median of 44.7 MW for the UNT study area, and 0-360613.4 MW with a median of 177.0 MW for the GMS study area. Note that zero observations might be as a result of satellite under-detection, possibly due to the fires being obscured by smoke, clouds, canopy cover, and/or the fires were not active when the satellites passed over [17]. Previous accuracy assessment of MODIS active fires/hotspots validation against field surveys in Chiang Mai (one province in the UNT study area), Thailand, reported a high accuracy of 97.67% for the 2007 fire season [18].

The yearly spatial patterns of MODIS active fires/hotspots in each study area were determined by using the nearest neighbor index. The calculated indices were between about 0.61-0.78 for the CRI study area, 0.65–0.77 for the UNT study area, and 0.55–0.62 for the GMS study area. Note that all *NNIs* < 1 and statistically significant ($p < 0.05$), indicating that the observed MODIS active fires/hotspots exhibited spatial clustering globally for all years over the period of investigation. When plotting the corresponding test statistics (Z_{NNI}), they apparently fluctuated with no clear trend in each study area (Figure 3).

In this study, Moran's *I* were used to evaluate the yearly spatial patterns of the MODIS active fires/hotspots, in terms of fire counts and fire radiative powers, by administrative unit in each study area. Unlike *NNI* that determines spatial patterns based only on the locations of active fires/hotspots, *I* evaluates spatial patterns based on both the sum of MODIS active fires/hotspots within a given administrative unit, and the administrative unit network simultaneously. The estimated statistics for fire counts by administrative unit were between approximately 0.19–0.33, 0.48–0.55, and 0.41–0.60 for the CRI, the UNT, and the GMS study areas, respectively, while those for fire radiative powers by administrative unit were between approximately 0.20–0.34, 0.53–0.67, and 0.35–0.61 for the CRI, the UNT, and the GMS study areas, respectively. All *I*s were positive and statistically significant ($p < 0.05$), indicating overall spatial clustering of similar values of, either high-high or low-low for all years over the period of study. The corresponding test statistics (Z_I) are plotted in Figures 4 and 5 in which the higher Z_I suggests a higher clustering intensity. Interestingly, those for fire radiative powers by administrative unit in the CRI and the GMS study areas apparently showed an increasing trend, suggesting the spatial clustering is getting more intensified over the years. In other words, the forest fires and open burning problem has become more severe in certain areas.

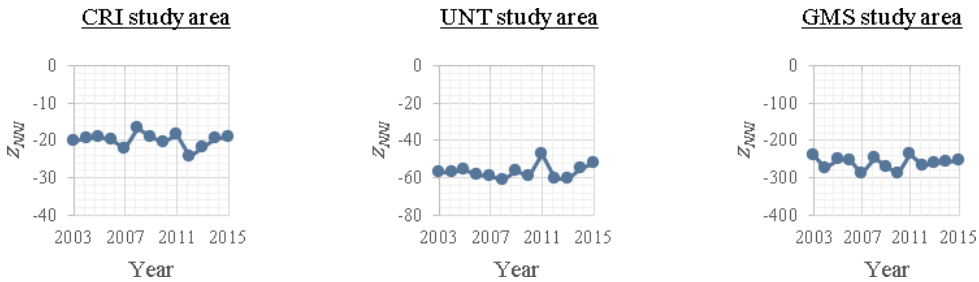

Figure 3 Yearly corresponding Z_{NNI} for the nearest neighbor indices of the MODIS active fires/hotspots in the CRI, the UNT, and the GMS study areas during the burning seasons in 2003–2015.

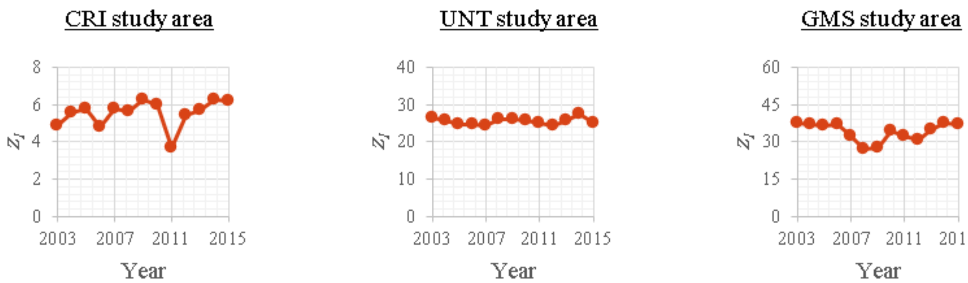

Figure 4 Yearly corresponding Z_I for the Moran's I of the MODIS active fires/hotspots, in terms of fire counts by administrative unit in the CRI, the UNT, and the GMS study areas during the burning seasons in 2003–2015.

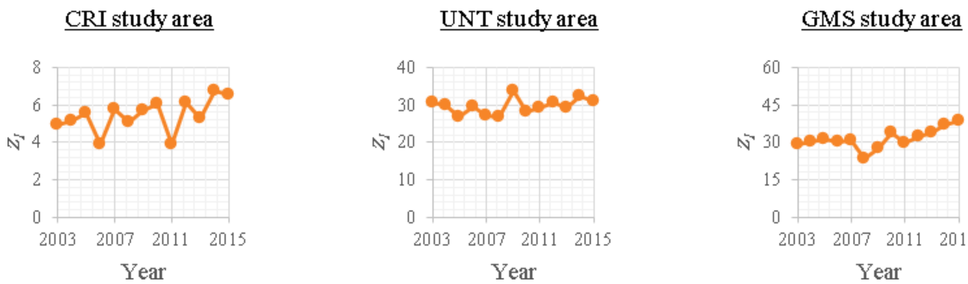

Figure 5 Yearly corresponding Z_I for the Moran's I of the MODIS active fires/hotspots, in terms of fire radiative powers by administrative unit in the CRI, the UNT, and the GMS study areas during the burning seasons in 2003–2015.

This study also used Anselin Local Moran's I to depict the yearly local spatial clusters of high-high or low-low values and local spatial outliers of high-low or low-high values of the MODIS active fires/hotspots, in terms of fire counts and fire radiative powers, by administrative unit in each study area (Figures 6 and 7). Interestingly, the spatial clusters of high-high values were found to be predominant in each study area, while the spatial clusters of high-low values were only found occasionally. Note that the yearly local spatial clusters and outliers of fire counts were slightly different from those of fire radiative powers. Even though the local clustering patterns in each study area were spatially and temporally variable, some administrative units were consistently classified as hot spots over the investigated period, indicating that the forest fires and open burning problem keeps recurring in certain areas. This may lead to questions about the suitability of mitigation measures which have been implemented so far.

Overall, the applied geo-statistics in this study were able to detect and quantify types and degrees of historical density and spatial patterns of MODIS active fires/hotspots in Chiang Rai, other provinces in Upper Northern Thailand, and other countries in the Greater Mekong Sub-region. Although these tools rarely provide reasons for why the patterns occur, they provide prerequisites to understanding the complicated spatial and temporal processes underlying the distribution of MODIS active fires/hotspots, as surrogates of the forest fires and open burning in the Sub-region. For example, as mentioned before, the extreme fire occurrences in 2007 could be partially explained by severe droughts and related El Niño events, while the sudden drop of MODIS active fires/hotspots in 2011 could be partially explained by an anomalously high rainfall in the pre-monsoon season. The concentrated or clustering zones of MODIS active fires/hotspots in terms of fire occurrences and fire radiative powers in the hilly and mountainous areas, seem to be correlated with increased uncontrolled and controlled burning due to agricultural activities, forest harvesting, forest management, and so on. Other local variations are possibly the result of legislative and non-legislative plans and measures to promote or demote haze-free and/or zero burning practices [18]. Hence, future work may investigate the links between the detected density and spatial patterns in this study, and the potential underlying processes, in detail, especially on the increasing clustering intensity of fire radiative power as a quantification of biomass burning in the CRI and the GMS study areas. Moreover, it would be also interesting to examine the correlation between the patterns of MODIS active fires/hotspots and the patterns of smoke-haze related health impacts in the Sub-region.

Additionally, as seen in the results, the patterns varied locally across the geographical scales from provincial to interprovincial and international, since the applied spatial statistic tools are highly sensitive to the spatial characteristics of each dataset. The dominant concentration of clustering at a provincial scale may not be detected when changing the spatial scale to a wider geographical scale. Hence, to obtain a complete picture of the forest fires and open burning in the sub-region, the analysis must be performed at all locations and at spatial scales that correspond to the current fire and smoke haze pollution management. The analysis may be performed at finer temporal scales (e.g., monthly) or compare between wet and dry sea-sons to provide policy and decision makers with the useful information needed for tracking and monitoring the problem of forest fires and open burning. However, it must be ensured that the analyzed data are large enough to have sufficient statistical power for obtaining reliable results.

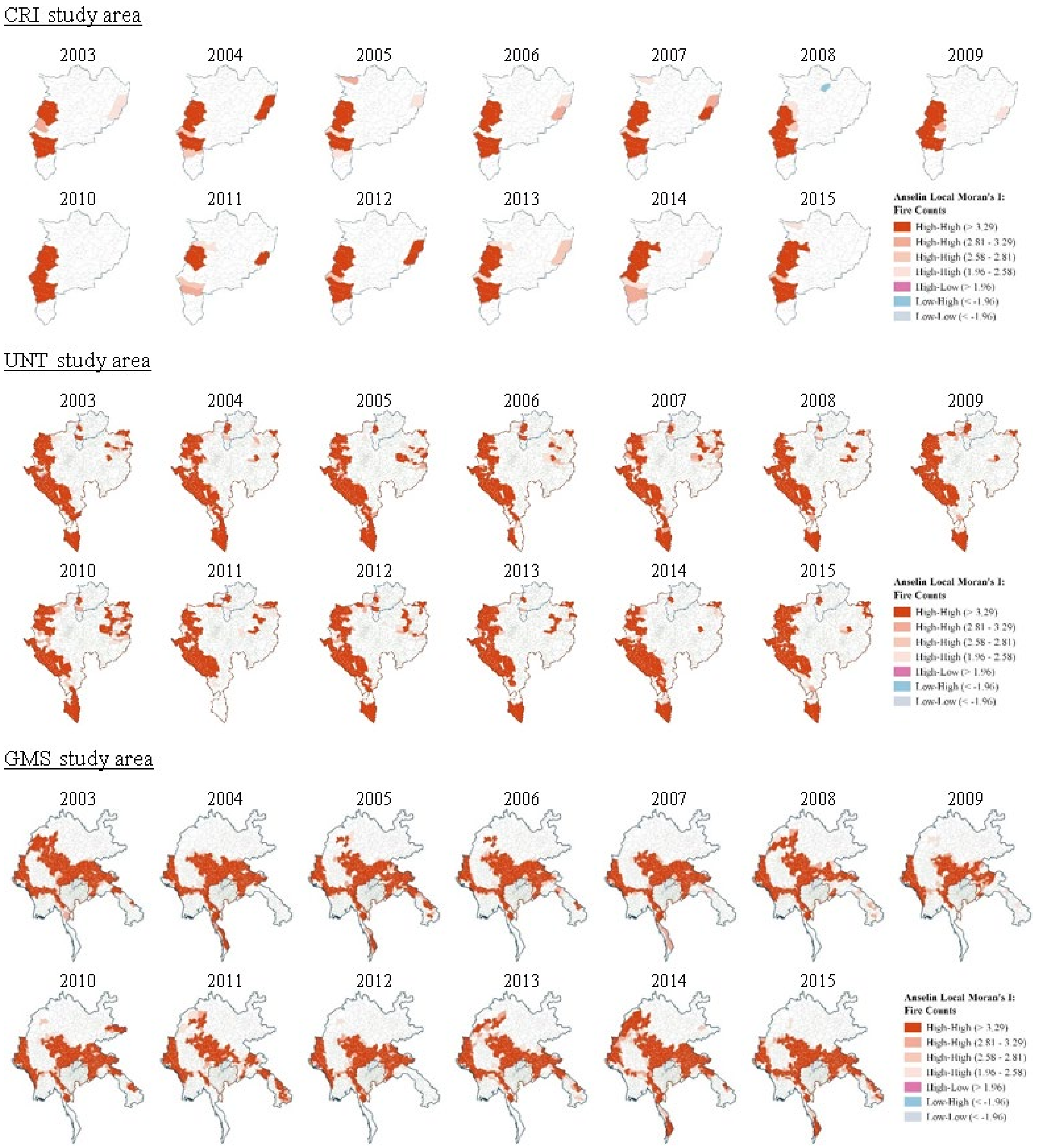

Figure 6 Yearly local spatial clusters of high-high or low-low values and local spatial outliers of high-low or low-high values (I_i) of the MODIS active fires/hotspots, in terms of fire counts, by administrative unit the CRI, the UNT, and the GMS study area during the burning seasons in 2003–2015.

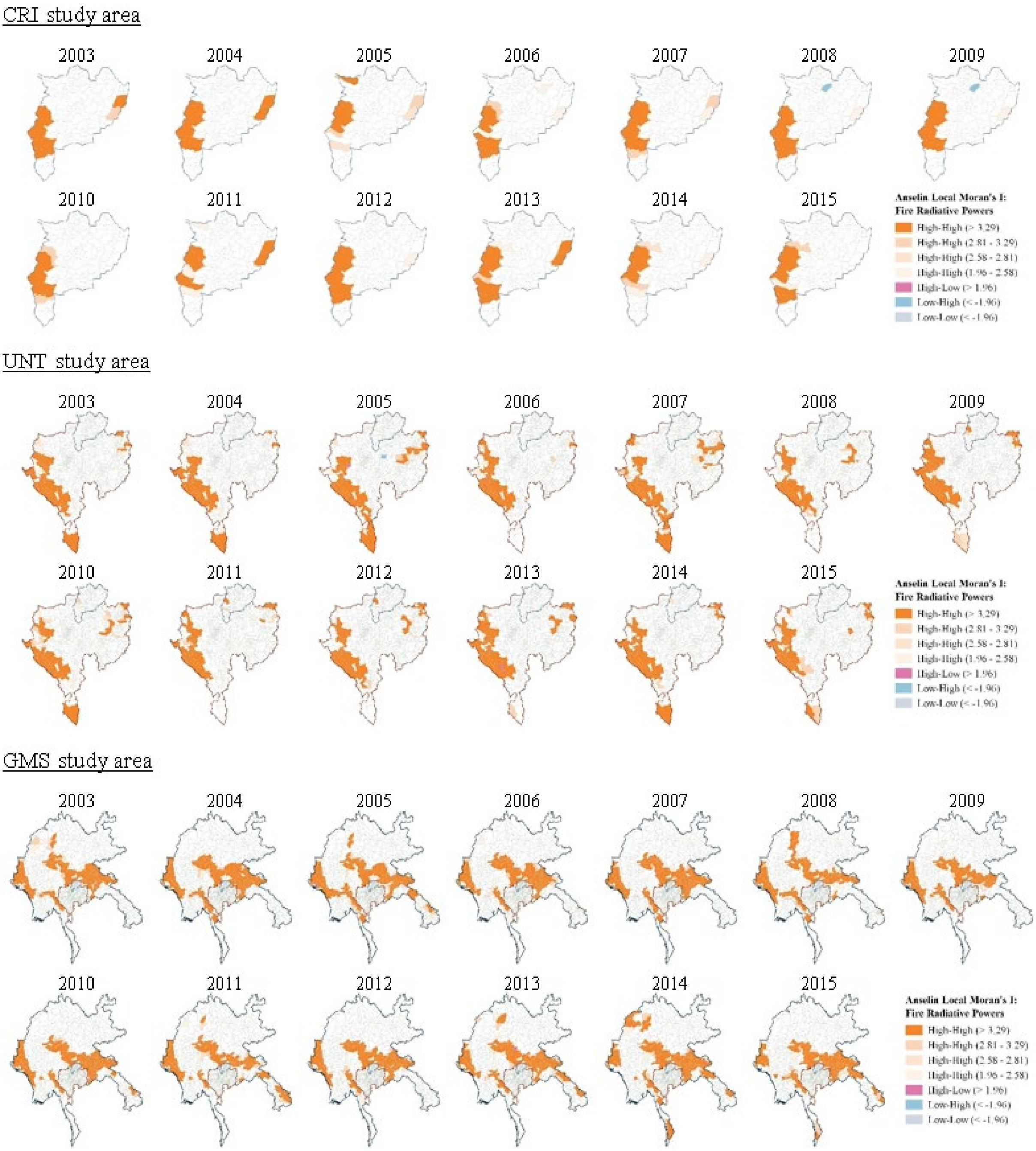

Figure 7 Yearly local spatial clusters of high-high or low-low values and local spatial outliers of high-low or low-high values (I_i) of the MODIS active fires/hotspots, in terms of fire radiative powers, by administrative unit the CRI, the UNT, and the GMS study area during the burning seasons in 2003–2015.

Conclusions

The spatial and temporal analysis of remote-sensing active fire/hotspot data is the indispensable source of information for the fire and smoke haze pollution management. Various spatial statistics tools used in this study successfully detected and quantified the spatial and temporal patterns, either globally or locally, of MODIS active fires/hotspots in three overlapping study areas across provincial, interprovincial, and international scales. The results provide insights into the forest fires and open burning distribution in the Greater Mekong Sub-region, which could be useful for further reviewing and strengthening current measures and plans of fire and smoke haze pollution management. The applied spatial statistic tools and framework could serve as a model for future assessments of the forest fires and open burning and other related problems.

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