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A MODIS Time Series Data Based Algorithm for Mapping Forest Fire Burned Area

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Abstract: Burned area mapping is an essential step in the forest fire research to investigate the relationship between forest fire and climate change and the effect of forest fire on carbon budgets. This study proposed an algorithm to map forest fire burned area using the Moderate-Resolution Imaging Spectroradiameter (MODIS) time series data in Heilongjiang Province, China. The algorithm is divided into two steps: Firstly, the ′core′ pixels were extracted to represent the most possible burned pixels based on the comparison of the temporal change of Global Environmental Monitoring Index (GEMI), Burned Area Index (BAI) and MODIS active fire products between pre- and post-fires. Secondly, a 15-km distance was set to extract the entire burned areas near the ′core′ pixels as more relaxed conditions were used to identify the fire pixels for reducing the omission error as much as possible. The algorithm comprehensively considered the thermal characteristics and the spectral change between pre- and post-fires, which are represented by the MODIS fire products and the spectral index, respectively. Tahe, Mohe and Huma counties of Heilongjiang Province, China were chosen as the study area for burned area mapping and a time series of burned maps were produced from 2000 to 2011. The results show that the algorithm can extract burned areas more accurately with the highest accuracy of 96.61%.

Keywords: Burned area mapping; Moderate Resolution Imaging Spectroradiameter (MODIS); Global Environmental Monitoring Index (GEMI); Burned Area Index (BAI)

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1 Introduction

Fire is one of the most important natural disturbance processes in many ecosystems, ranging from grassland to forest ecosystem (Ramsey *et al*., 1999; Lhermitte *et al*., 2010; Kasischke *et al*., 2011). Being considered as an important land-management tool (Maxim *et al*., 2010), fire would modify the structure and the composition of the vegetation. Among all kinds of ecosystems, forest ecosystem has been affected by the fire greatly globally due to the change of its environment factors such as biomass, air composition and water circulation (Kashian *et al*., 2006).

Many researchers have identified forest fire as one of the major factors of carbon budgets and worldwide green-house gas emissions (Goetz *et al*., 2006; Vander *et al*., 2006; Chuvieco, 2008) as well as the global warming (Amiro *et al*., 2006; Kasischke and Turetsky, 2006). Forest fire in boreal forest is particularly sensitive to the temperature increasing and climate warming which is considered to be the most significant driving factor of the fire range dynamic (IPCC, 2007). On the other hand, climate warming will affect traditional fire cycles, make the fire recurrence time shorter, and increase the fire size

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and severity (Gillett *et al*., 2004; Flannigan *et al*., 2005).

Burned area mapping, particular in a long time period, is a critical factor to investigate either the impacts of forest fire on carbon budgets or the relationship between climate change and forest fire. Unfortunately, traditional data of forest fire are field-collected and statistical-recorded, which are difficult to manipulate over a large area. The development of the remote sensing technique provides a labor-efficient method for the land surface process research, especially to map the burned area accurately using the remote sensing in higher spatial and temporal resolutions (Maxim *et al*., 2010; Jose *et al*., 2012).

According to the different phases of burning, two types of methods could be used to map the burning area using remote sensing data: active fires (Monaghati *et al*., 2009; Wang *et al*., 2010) and burn scars (Louis, 2009; Jose *et al*., 2012) and both methods are complex and challenging (Zhang *et al*., 2011). The method through the active fire could generally be observed by the thermal characteristics and the mid-infrared bands are appropriate to perform a real time monitor on the hotpots. The main purpose of active fire monitoring is to detect the location and the time of the fire happened. Although the burned area can be estimated from the active fire monitoring by counting fire pixels, the result is unreliable (Kasischke *et al*., 2003; Giglio *et al*., 2005) due to its big omission errors. Burn scar is the area affected by a fire event, which can be obtained by the change of spectral reflectance and vegetation index between pre- and post-fires (Carl, 2006; Roy *et al*., 2008). The disadvantage of mapping burned area through burn scars is that some events, such as flooded areas, forest clear cuts, and harvested croplands, are difficult to be distinguish from burned scars due to their similar spectral characteristics as fires.

At the regional or global scale, to obtain a long time series of burned area map, the moderate spatial resolution with high temporal resolution remote sensing data is considered as the best alternative (Emilio *et al*., 2008). Currently, the most widely used remote sensing data are Advanced Very High Resolution Radiometer (AVHRR) images (Sukhinin *et al*., 2004; Pu *et al*., 2007; Vafeidis *et al*., 2007) and Moderate-Resolution Imaging Spectroradiameter (MODIS) images (Roy *et al*., 2002; 2008). Although the AVHRR provides continuous observation for burned area analyses, but some studies have identified several sources of potential errors in burned area discrimination from this sensor, mainly due to its radiometric instability, cloud obscuration and transmission problems (Martín and Chuvieco, 1995; Barbosa *et al*., 1999; Pereira, 1999). Most of these problems have been notably reduced in the MODIS sensor, which offer greater spectral, spatial, and radiometric resolution than the AVHRR.

The objective of this study is to propose an algorithm to extract time series of burned area maps based on the MODIS data. This algorithm will consider both the thermal abnormal when fires take place and the spectral difference between pre- and post-fires to extract the burned area more accurately at the regional scale. The continuous burned area maps extracted from this research could be used as base maps for the studies in forest fire monitoring, forest management, and forest sustainability

2 Materials and Methods

2.1 Study area

The area selected for this study is located at the frontier between Russia and China, including three counties (Mohe, Tahe and Huma) of Heilongjiang Province, China (Fig. 1). Under the control of continental monsoon climate, the study area has distinct four seasons with long, extremely cold and dry winter and short, mild and moist summer. The annual average temperature is low and there is a large difference of temperature between day and night. The dominant wind direction is northwest, and in spring there are more windy days with the winds over five grade than any other seasons.

The major land cover type in the study area is vegetation (Fig. 1) and the forest type is coniferous forest in the southern part of boreal forest with the dominate species as *Larix gmelinii*. The large amount of vegetation cover and the climate condition as gale and drought in the study area make this area easy to be fired. In order to monitor forest fire dynamics and investigate the long term ecological process after burning, it is critical to develop a method to identify and map the burned area at a large scale in continuous domains.

2.2 Data sources

2.2.1 MODIS data

In this study, we used the Terra/Aqua 250m MODIS atmospherically-corrected Level 3 8-Day composite

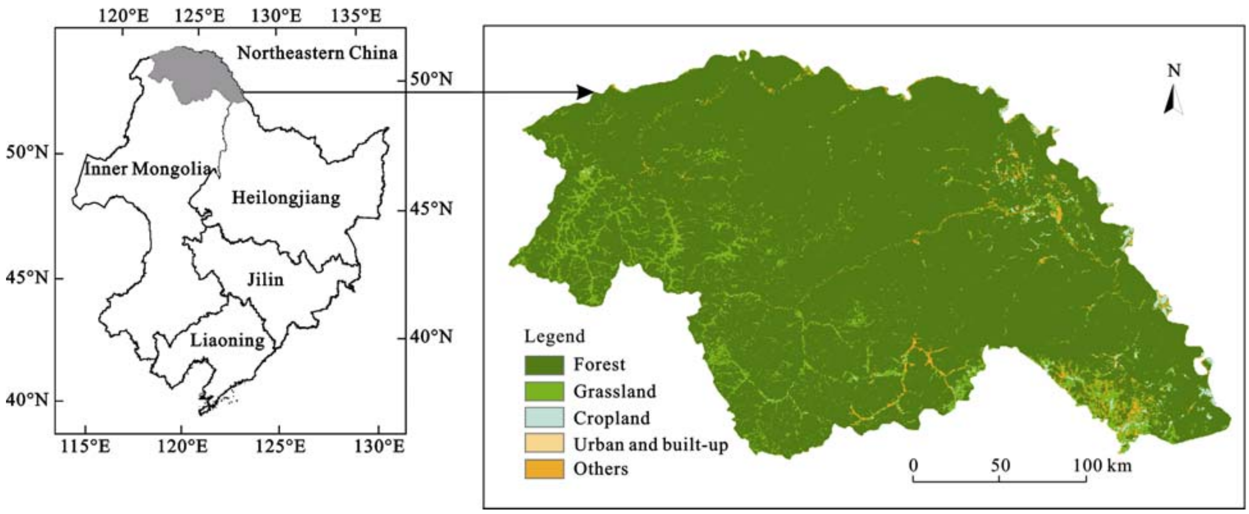

Fig. 1 Location and land cover map of study area in 2000

Surface Reflectance products (MOD09Q1) and the 1-km MODIS Level 3 8-Day composite active fire products (MOD14A2). The algorithm of MODIS active fire products is a contextual algorithm (Giglio *et al.*, 2003) that exploits the strong emission of mid-infrared radiation from fires (Dozier, 1981), which is based on the thermal characteristics when the fire happens. The meaning of each pixel value in the MODIS products is listed in Table 1.

Table 1 MODIS fire products pixel meaning

Pixel value	Meaning
0	Not processed (missing input data)
2	Not processed (other reason)
3	Water
4	Cloud
5	Non-fire clear land
6	Unknown
7	Low-confidence fire
8	Nominal-confidence fire
9	High-confidence fire

MOD09Q1 and MOD14A2 (H25V03) from 2000 to 2011 were downloaded, covering the period from the end of February to the start of November which is the fire season of the study area. There are total 408 images (34 images per year) for each product, saved originally in Hierarchy Data Format (HDF)and the sinusoidal projection. These images were reprojected to Albers equal-area conic projection and the area to cover the entire study area was clipped out. Since the spatial resolution of MOD14A2 (1000 m) and MOD09Q1 (250 m) are different, we resampled the MOD14A2 to 250 m to make these two products comparable.

2.2.2 *Validation data*

The validation data are the fire statistics from forestry department, including time, location, coordinates, burned area (the data in 2001 are missing), *etc*. The validation data were collected from 2000 to 2005. To keep coincidence between the validation data and the MODIS data, the fire with area smaller than 60 ha (about 3 by 3 pixels in the images) were filtered out. Figure 2 shows the selected fire events as validation data.

2.3 Methods

2.3.1 *Spectral index*

The burned area mapping is based on the spectral difference between pre- and post-fires, and it is necessary to choose the adapted spectral index to represent the difference. The commonly-used indexes include Normalized Difference Vegetation Index (NDVI), Burned Boreal Forest Index (BBFI), Global Environmental Monitoring Index (GEMI) and Burned Area Index (BAI). Among these indices, NDVI has been used extensively since it provides an accurate estimation of vegetation cover (Emilio *et al.*, 2008). However, although it has been widely used for burned area mapping (Fraser *et al.*, 2000; Kucera *et al.*, 2005), there are several problems with it. For example, NDVI would reach the maximum value, particular in the high vegetation cover area (Cai *et al.*, 2011) and lead to the potential errors for burned area mapping (Pereira, 1999; Chuvieco *et al.*, 2002).

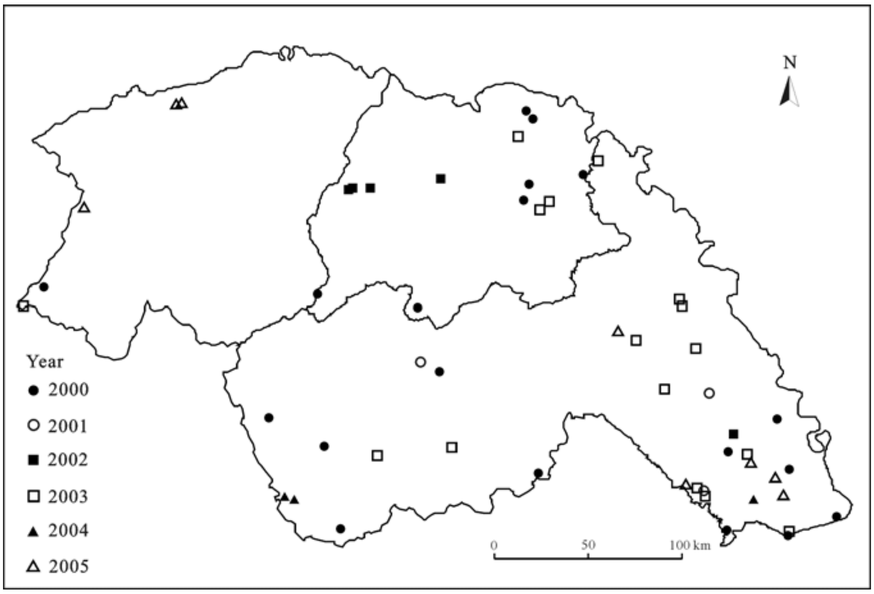

Fig. 2 Location of fire in three counties of study area from 2000 to 2005

In this study, we select an alternative index, GEMI, proposed by Pinty and Verstraete (1992) to estimate vegetation conditions as:

$$GEMI = \eta \times (1 - 0.25\eta) - (\rho_{\text{red}} - 0.125)/(1 - \rho_{\text{red}})$$

$$\eta = (2(\rho_{\text{nir}}{}^2 - \rho_{\text{red}}{}^2) + 1.5\rho_{\text{nir}} + 0.5\rho_{\text{red}})/(\rho_{\text{nir}} + \rho_{\text{red}} + 0.5) \quad (1)$$

where ρ_{red} and ρ_{nir} are red and near infrared band of MODIS images.

To avoid the potential errors of using a single spectral index, the BAI (Martín, 1998) was selected for the further discrimination of burned area, defined by:

$$BAI = 1/((\rho_{\text{nir}} - \rho_{\text{cnir}})^2 + (\rho_{\text{red}} - \rho_{\text{cred}})^2) \quad (2)$$

where ρ_{cred} and ρ_{cnir} are the convergence values for burned vegetation (defined as 0.1 and 0.06, respectively).

Moreover, after comparing the difference of the spectral index between pre- and post-fires, the thermal characteristics at the fire time is considered as another restriction of burned area mapping. The MODIS active fire products are added into the algorithm as an input band which represents the abnormal temperature of the surface caused by fires.

2.3.2 Flowchart of proposed method

The proposed method is a two-step algorithm for burned area mapping based on the algorithm developed by Emilio *et al*. (2008) for AVHRR data. We modified the algorithm to fit MODIS data and added the MODIS active fire products to achieve a better discrimination.

The burned area mapping procedure is divided into two phases (Fig. 3). The first phase aims to identify 'core' pixels which are the most possible burned pixels by defining strict threshold values for the input bands. The first phase was based on the temporal change of GEMI, BAI and MODIS active fire products with an effort to reduce the commission errors as much as possible. There is a big decrease for GEMI between pre- and post-fires, and an obvious increase for BAI. Then the 'core' pixels were used to identify the entire area affected by the fire through applying more flexible criteria to the neighboring pixels of these identified core pixels. The purpose of the second phase is to reduce omission errors of burned area.

The input bands of the first stage include GEMI, BAI and the value of MODIS active fire pixel (ρ), and the extracted pixels must meet the following conditions:

First, the GEMI should be above a certain value before the fire to make sure that the area is covered by vegetation:

$$GEMI_{t-1} > 0.170 \quad (3)$$

where $GEMI_{t-1}$ is $GEMI$ at 8-day period $t-1$ ($0 < t \leq 34$).

There must be a sharp decrease in GEMI after the fire and this decrease do not resumed back to exclude the sudden change produced by clouds. The process is defined as follows:

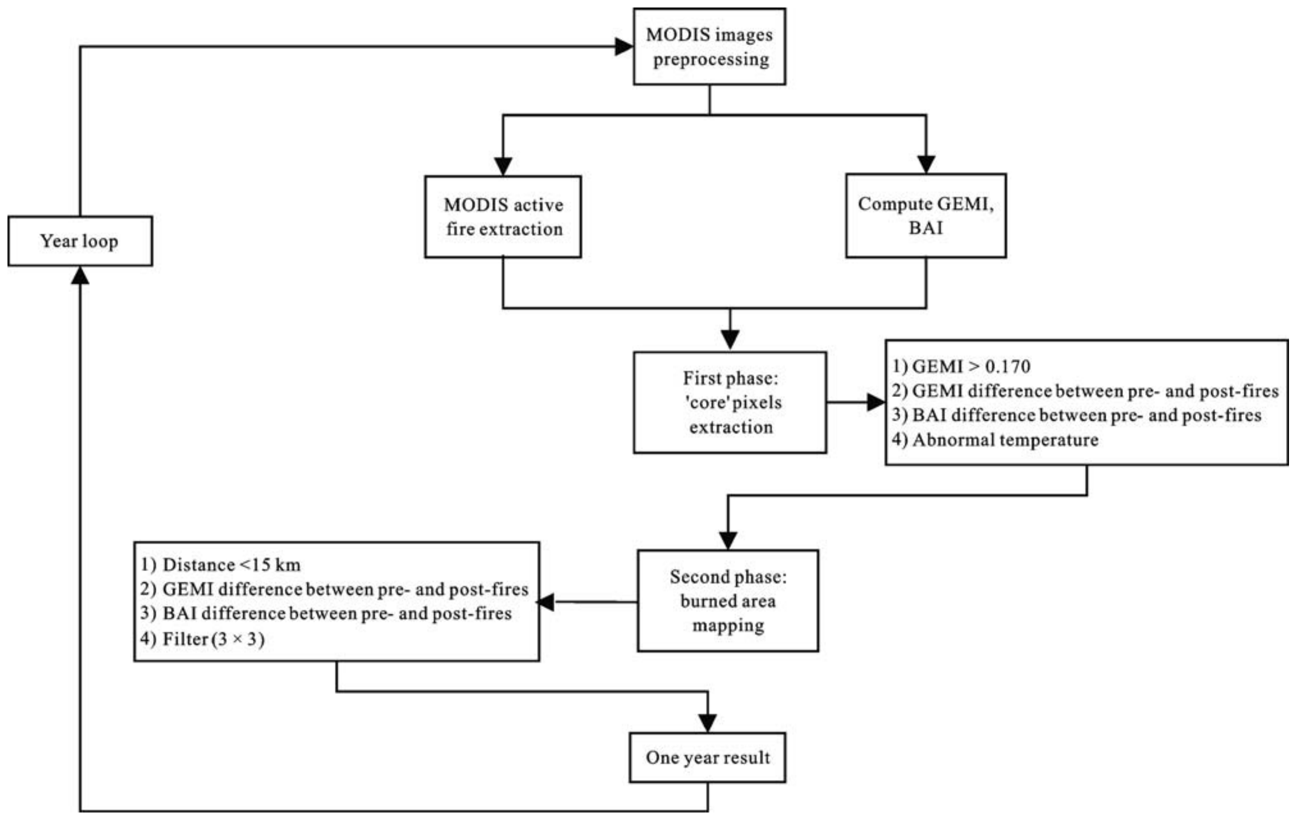

Fig. 3 Flowchart of proposed method. MODIS: Moderate-Resolution Imaging Spectroradiameter; GEMI: Global Environmental Monitoring Index; BAI: Burned Area Index

$$(GEMI_t - GEMI_{t-1}) / GEMI_t < -0.1 \quad (4)$$

$$(GEMI_{t+2} - GEMI_{t-1}) / GEMI_{t+2} < -0.1 \quad (5)$$

where $GEMI_t$ and $GEMI_{t+2}$ are $GEMI$s at 8-day period t and 8-day period $t + 2$, respectively.

Then, the BAI value of identified burned area should increase significantly after the fire, thus we used BAI for the restriction of burned pixels. It is defined as:

$$BAI_t > 250 \text{ and } BAI_{t+1} > 200 \quad (6)$$

where BAI_t and BAI_{t+1} are BAIs at 8-day period t and 8-day period $t + 1$, respectively.

Finally, the MODIS active fire products are used to mask the extracted pixels to make sure that the pixels exhibit an abnormal temperature before the change of the spectral index:

$$\rho_t > 6 \text{ or } \rho_{t-1} > 6 \quad (7)$$

where ρ_t and ρ_{t-1} are the values of MODIS active fire pixel at 8-day period t and 8-day period $t + 1$, respectively.

The second stage of the algorithm is based on the 'core' pixels detected from the first phase, and use more flexible conditions to identify the burned area from the surrounding pixels. After analyzing the fire characteristics of the study area, we set the maximum distance from the 'core' pixels as 15 km and delete the 'identified' burned area outside the 15-km buffer in the second phase. The rules are listed as follows:

$$GEMI_t - GEMI_{t-1} < -0.03 \quad (8)$$

$$GEMI_{t+1} - GEMI_{t-1} < -0.02 \quad (9)$$

$$GEMI_{t+2} - GEMI_{t-1} < 0 \quad (10)$$

$$GEMI_{t+1} - GEMI_t \leq 0 \quad (11)$$

$$BAI_t > 250 \quad (12)$$

Finally, all detected pixels were stitched together into polygons and a 3 by 3 filter windows was applied to the detected result to eliminate small polygons.

3 Validation and Results

3.1 Validation

The statistics data of fire in the study area collected from 2000 to 2005 is used as the validation data to analyze the extracted burned area map including commission error, omission error and the comparison of the area (Table 2). Because the fire statistics only provides the location of the fire, we can not analyze the error at the pixel level. Based on the coordinates of the fire from the statistics, we analyzed the extracted result and the rules are: 1) the correct extraction: the location of the extracted fire is the same as the statistics; 2) omission error: the location of fire statistics exists but no fire extracted; and 3) commission error: the location without fire statistics but extract fire.

Table 2 shows the comparison between the extracted area and the validation data for each year. The result shows that only in 2000 the extracted fire area is larger than the validation data (except 2004 for a particular reason explained as follows), which contains four commission errors, and other years are all smaller than the validation data. Among all these years, the result of 2002 has the best estimation of forest fire area with the highest accuracy as 96.61%, which has only one omission error and no commission error. The largest difference between the extracted area and validation data is found in 2004. The possible reason is that there is a large fire happened at the borderline between Huma County and Nenjiang County but we do not have the validation data in Nenjiang County in 2004. The fire exceeded 70 000 ha between these two counties but the main fire field was located in the Nenjiang County as the coordinate of the fire is within the Nenjiang County. The way to record the forest fire as coordinate points might lead to inconsistency between the real forest fire and statistic records. Without considering this particular fire, the extracted area was 812.5 ha in 2004 and the area accuracy will improve to 80.45%. The same situation also happened in 2003 which cause a relatively bigger error of the fire area.

3.2 Results

Using the algorithm mentioned above, we extracted the burned area of the study area from 2000 to 2011 (Fig. 4). The results show that the study area was significantly influenced by the forest fire, and the level and extent of fire happened in each year were different. Among the three counties, Mohe County had the least influence from fire, which has the smallest number and area of fire. During the studied period, there was only one catastrophic forest fire with the fire area more than 1000 ha in Mohe County. Tahe County has been significantly influenced by the fire, with more numbers of fire and larger fire area than Mohe County. Compared to the two counties mentioned above, Huma County has been influenced by the forest fire most seriously with more catastrophic forest fires and the largest fire affected areas. There were two large fires detected in February 2003 and October 2005, one was found along the border area between Huma County and Tahe County and another one was in the southeast of Huma. The area of these two large forest fires is larger than 100 000 ha.

Table 3 shows the total burned area extracted from the proposed algorithm in this study. The results show that the burned areas in 2000, 2003, 2004, 2005, and 2006 were obviously larger than those in other years with the total area exceeding 10 000 ha for each year. The highest burned area was found in 2003 (284 843.75 ha). The years 2001, 2002, 2008 and 2010 are the second group which have the total burned area between 1000 ha and 10 000 ha for each year. The least fire area was found in the other years, especially in the year 2009 and 2011 with the total fire area of only 325.00 ha and 362.50 ha, respectively. Generally, most catastrophic forest fires concentrated before 2006, mainly in 2003 and 2005. After 2006, the influence of the fire began to decrease and there was almost no catastrophic forest fire happened except in 2010.

Table 2 Validation results for burned area mapping

	2000	2001	2002	2003	2004	2005
Number of fire happened	18	3	5	16	3	8
Number of fire extracted	22	4	4	14	2	8
Omission error	0	1	1	2	1	2
Commission error	4	2	0	0	0	2
Extracted area (ha)	25368.75	4231.25	1194.35	284843.80	21075.00（812.50）	73243.75
Validation area (ha)	20492.00	–	1236.28	446151.40	1010.00	110076.20

Notes: 1) ′–′ means that fire area data of 2001 are missed; 2) extracted area value ′812.50′ means fire areas without considering big fire happened between Huma and Nenjiang counties in 2004

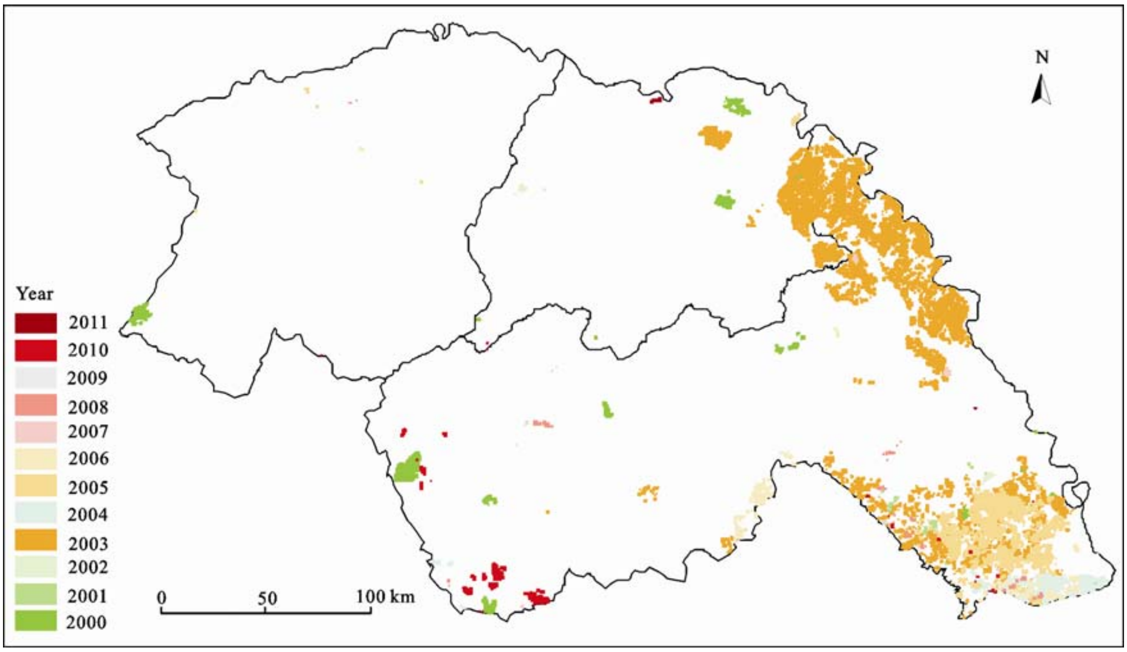

Fig. 4 Burned area from proposed algorithm

Table 3 Burned area of forest fire in study area from 2000 to 2011

Year	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
Burned area (ha)	25368.75	4231.25	1194.35	284843.75	21075.00	73243.75	10775.00	925.00	1787.50	325.00	7900.00	362.50

4 Discussion

The study proposed an algorithm to map the forest burned area using time series MODIS images. The algorithm uses the thermal band to identify the fire spots and the spectral difference between pre- and post-fires to map the burned area. As a result, the consideration of both the two conditions decreased the commission and omission errors and produced a more accurate estimation with a higher accuracy.

There is an important step of the algorithm to extract burned area: the suitable threshold value of the spectral index (GEMI and BAI) between pre- and post-fires. Different threshold values will cause different accuracy. In this study, we firstly selected several fires happened in different times and spaces to analyze the spectral index differences between pre- and post-fires. A threshold value range was produced based on the analysis. Then we chose different values from the range to extract burned area repeatedly until the best result. The process is tedious and time-consuming. In the next step we will try to develop a more simple and rapid method to fix the threshold vale.

This proposed algorithm performed not well for the fire area exceeding 100 000 ha. There are some error existing in the estimation of two large fires with the area over 100 000 ha in 2003 and 2005, respectively. In these two years, although the commission and omission errors were low, the extracted area accuracy was lower than the other years, which indicates that the algorithm should be modified to the fire with large area.

Compared to the previous study that chose fires over 200 ha as the validation data (Emilio *et al*., 2008), we chose the fires over 60 ha to validate our estimation in consideration of the spatial resolution of MODIS images. From the result, we can conclude that the main omission errors come from the fires nearly 100 ha which represent the small burned area. This indicates that MODIS is still coarse to detect the forest fire in the small area due to the limitation of spatial resolution. However, for the remote sensing data with higher spatial resolution (such as TM), the temporal resolution is usually too low to record the change between pre- and post-fires. Our next research is to do the data fusion of different remote sensing data to acquire both high spatial and high temporal resolution data.

5 Conclusions

The annual burned area maps were produced from MODIS time series data for the study area including three counties (Mohe, Tahe and Huma) of Heilongjiang Province from 2000 to 2011. The proposed algorithm considered both the thermal abnormal character when fires take place (represent by MODIS fire product) and the spectral difference between pre- and post-fires. The algorithm was divided into two steps. The first phase was to identify ′core′ pixels using more strict threshold values, which aimed to reduce commission errors. The second stage used more flexible conditions to extract whole burned areas from the ′core′ pixel surrounding pixels, which aimed to reduce omission errors.

The results show that the study area was affected by forest fires seriously, especially in 2000, 2003, 2004, 2005 and 2006 with the burned area more than 10 000 ha for each year. The most affected county is Huma which included more large fires of the study area. Applying the algorithm to produce long time series burned area maps will improve understanding of fire regimes and the spatial-temporal feature of the forest fires in the study area. And it also provide a way to understand the relationships between fires and forest dynamic changes.

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