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Using spatiotemporal remote sensing data to assess the status and effectiveness of the underground coal fire suppression efforts during 2000–2015 in Wuda, China

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ABSTRACT

China, the largest coal consumer in the world, is one of the countries that experience the most coal fires. Hence, it is critical for China to monitor coal fires and carry out coal fire monitoring, assessment, and appropriate suppression work. The Wuda coalfield, located in China's Inner Mongolia Autonomous Region, was selected as the study area. This paper was aiming to analyze spatiotemporal changes of coal fires located in Wuda of China from 2000 to 2015 and focused on the assessment of fire protection project during 2006–2008. Landsat Thematic Mapper and Enhanced Thematic Mapper Plus images were used to detect changes in coal fires over the last 16 years by utilizing a generalized single-channel method to retrieve land surface temperature data and natural breaks extracting coal fire zones. The results showed that: 1) the changes of coal fires area represented obvious three stages: Stage I (2000–2006) was before the fire suppression project with fire spread and expansion; Stage II (2006–2008) was the implementation of this project with rapid reduction of fire area; Stage III (2008–2015) was after this project with stable fire area at a low level; 2) the fire suppression work was highly successful; the area of coal fires basically remained at 192.98 ha, a reduction by 45.74% from 2000 and 62.40% from 2006 (before fire suppression projects); 3) fire suppression work in the south (zone F) and in the northwest (zone A) was the most successful, while some new patches sporadically appeared in other regions (zone B, C and D); 4) coal fire suppression methods have led to significant destruction of local geomorphology; 5) it was difficult to completely extinct coal fires underground with current suppression method. Compared with previous studies, this research paid more attention to the estimation of fire suppression projections which provided an available way for environment decision makers and coal energy producers to qualitatively assess the status and effectiveness of coal fire suppression projects.

1. Introduction

Coal fire is a natural phenomenon in which carbon in the coal seams is oxidized to burn, generally combusting in underground coal seams, open-cast coal mines, coal heaps and coal waste piles (Kuenzer and Dech., 2013). Coal fires occur around the world, especially in China (Kuenzer et al., 2007; Wessling et al., 2008; Jiang et al., 2011a) and India (Gautam et al., 2008; Guha and Kumar, 2012; Roy et al., 2015). Other locations such as the United States (Hower et al., 2011; Engle et al., 2012, 2013), South Africa (Pone et al., 2007) and Russia (Sokol et al., 2014) have also had coal fires. Coal seam burning causes tremendous waste of resources and economic loss. It has been estimated that 10 to 13.6 million tons per year of high quality coal burned in northern China (Gangopadhyay et al., 2005). Coal accounts for 29.6% of global energy consumption (Liang et al., 2013), and global demanded coal has been increasing because of its low cost and stable supply (Restrepo et al., 2015). China is the largest consumer of coal in the world (Bloch et al., 2012), combusting 48.2% of global coal consumption every year (Liang et al., 2013). Coal was the major energy resource of China (Song et al., 2015), accounting for 70% of national energy

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consumption (Li and Leung, 2012; Song et al., 2015). Therefore, it is critical for China to control coal fires and carry out appropriate suppression practices.

Coal seam burning impacts the surrounding temperature, magnetic field and chemical composition. Recent literature indicated that coal fires could be detected by remote sensing, physical, chemical, thermal and drilling exploration. Physical, chemical, thermal and drilling methods had high precision as a direct guidance of coal fire management in the coalfield. However, they were only used for coal fire detection in small area. With the advent of the "Big Data" era, remote sensing has provided a new technology to obtain a massive amount of information about land surfaces (Guo et al., 2014; Tang and Liu, 2015). Remote sensing "Big Data" allows for huge capacity, great diversity and complexity (Ma et al., 2015). It can be applied for monitoring at a range of hundreds of square kilometers, even for global detection. Remote sensing "Big Data" was the ideal data source for coal fire monitoring. Remote sensing images provide large-scale and rich information about land surfaces at low cost, and are especially useful for time series analysis. Furthermore, since coal fires often occur in dangerous and remote areas, they can be more effectively monitored by remote sensing. Remote sensing recognizes fire zones through thermal anomalies on land surfaces that are caused by coal fires. Underground heat conduction over a long period of time causes the bedrock heated to 60 °C and releases hot gases from vents, and the temperature even reaches over 1000 °C (Kuenzer and Dech, 2013). Therefore, a thermal band of remote sensing can be used to detect temperature changes on the land surface and extract coal fire zones.

Remote sensing was first applied to coal fire monitoring in the 1960s. The earliest reported research used an infrared camera on an airplane to detect fire waste piles (Slavecki, 1964; Du et al., 2015). However, aerial remote sensing had a high cost and aerial images were difficult to analyze with complex geometry due to the airplane's pitch and roll. With the successful launch of Landsat satellites in the 1970s and 1980s, the thermal infrared band was began to be used to monitor coal fires, such as the Jharia coalfield in India (Saraf et al., 1995; Gangopadhyay et al., 2006; Chatterjee, 2006) and coal fire in the Xinjiang Uygur Autonomous Region (Prakash et al., 1999) and the Inner Mongolia Autonomous Region (Jiang et al., 2011a) of China. Advances in other satellites also provided rich data sources for remote sensing monitoring. In China, ASTER data were used by Gangopadhyay et al. (2005) to research Wuda coal fire detection with the Temperature/Emissivity Separation (TES) algorithm. ASTER data with the TES algorithm were also used by Du et al. (2014) to compute adjustment parameters of Wuda coal fires for every season. In addition, the Self-adaptive Gradient-based Threshold (SAGBT) algorithm (Du et al., 2015) was proposed in 2015 to analyze changes in the Wuda coal fires from 2001 to 2011. Landsat ETM+, combined with ASTER and MODIS with the moving window method, was used to study the influence of coal fires on the environment. In India, AVHRR images with the SVM classification algorithm were used by Gautam et al. (2008) to recognize hot spots in the Jharia coalfield. ASTER and Landsat 8 images were used by Roy et al. (2015) to apply statistical analysis to the extraction of Jharia coal fires. ASTER nighttime data were utilized by Guha and Kumar (2012) to retrieve land surface temperature (LST) with ERDAS and compute the extracted threshold determined by prior knowledge, studying the space distribution of Raniga coal fires. It was worth noting that there were some literatures involving long-term coal fire monitoring of Wuda. For example, Du et al. (2014) depicted the changes from 2000 to 2011 and Jiang et al. (2011a) analyzed them from 1989 to 2008. However, these studies (including all literatures listed above) mainly focused on land surface temperature retrieval and extracting coal fire zones to analyze the processing of coal fire burning, yet paid little attention on the assessment of suppression practices.

The Inner Mongolia Autonomous Region in China had the most coal fires. This area had 230 coal fires that covered an area of 63 km^2 (Song and Kuenzer, 2014a). The Wuda coalfield, located in Inner Mongolia, is the site of one of the biggest coal fires in the world. It is also one of the most widely researched areas (Kuenzer et al., 2012). For example, Du et al. (2014) studied changes in this area over four seasons, and Kuenzer et al. (2005) and Jiang et al. (2011a) discussed its fluctuation over a longer time series in 1987–2003 and 1989–2008, respectively. To manage and control the Wuda coal fires, the Coal Fire Suppression Project (CFSP) was proposed in 2001 and approved by China's National Development and Reform Commission in January 2006. The Chinese government and Shenhua Group together spent 163 million yuan over a four-year period on this program. Utilizing Landsat TM/ETM data, the generated single-channel method was used to retrieve land surface temperature and the natural breaks method was adopted to extract coal fire zones. This paper evaluated the changes in coal fires during 2000–2015. This period was divided into 3 stages. Stage I was from 2000 to 2006, when the spread and expansions of coal fire zones were analyzed. The CFSP from 2006 to 2008 was in Stage II with the reduction of coal fire zones. Stage III from 2008 to 2015 was the subsequent process after the CFSP. Our focus was to assess the differences before and after the CFSP from 2006 to 2008. Currently, there was little research on the monitoring and assessment of the CFSP.

2. Study area

The Wuda coalfield is located in northwestern Wuhai city in the Inner Mongolia Autonomous Region and bounded by the Ulan Buh desert on the north, the Helan Mountains on the south, and about 11 km to the Yellow River on the east (Fig. 1). The coalfield extends from longitudes 106°34′E to 106°38′E and latitudes 39°27′N to 39°34′N (Jiang et al., 2011a). The Wuda coalfield belongs to the Shenhua Group and is divided into three mining coals: Suhaitu, Huangbaici and Wuhushan (Du et al., 2015). Its area is 35×10^4 km^2. The Wuda coalfield has proven initial reserves of 2.8×10^8 tons of coal, providing a significant coking coal base in the Inner Mongolia Autonomous Region.

Coal seam burning was first discovered in Suhaitu in 1961. Due to the massive exploitation of small collieries, coal seams caught fire. By 2002, 16 fire patches had been formed, totaling 307.6×10^4 m^2. Coal seams in Wuda have been burning continuously for years. This has not only caused huge economic losses, but has also released toxic gases and threatened local inhabitants' lives and production such as carbon monoxide.

To completely extinguish the underground fires, the CFSP supported by China's National Development and Reform Commission was widely practiced by Shenhua Group since 2006. The total project cost was 163 million RMB over a four-year period. The period from 2006 to 2008 aimed to intensively extinguish shallow coal fires. Because the shallow fires in Wuda field were the most, the top soil above the fires was peeled layer after layer until the fire source was found and extinguished by water injection or other technologies. This method provided a possibility of complete extinguishment. However, complex measures, poor flexibility and high cost were its limitations. So it was only used in shallow fires with small area and slow expansion.

The Wuda Coalfield is dominated by low mountains and hills. The terrain tilts from southwest to northeast; the lowest elevation is 1076 m, the highest elevation is 1380 m, while the mean is about 1200 m. Vegetation cover is relatively low and most areas are bare ground. The coalfield is located in a temperate continental climate

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