Agricultural Fires and Their Potential Impacts on Regional Air Quality over China

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ABSTRACT

The potential impacts of agricultural fires (agri-fires) on regional air quality over China were examined using active fire products derived from satellite remote sensing and air mass trajectory modeling from 2009 to 2010. Agri-fires were found in most administrative areas. More than 80% of the agri-fires were in the heartlands of agricultural regions such as Anhui, Jiangsu, Shandong and Henan Provinces. Agri-fires had a seasonal pattern, with two distinct peaks in summer and autumn harvest periods, especially in June (61–86%) and October (5–14%). Agri-fire smoke was transported in the atmosphere on a continental scale in three directions, moving northeasterly, northwesterly and southwesterly away from source areas. Particles from agri-fire smoke contributed more than 35% of aerosol optical depth (AOD) over regions of the Jiaodong Peninsula, the North Plain, East China and other areas, and exceeded 60% in some areas of Shandong, Henan and Jiangsu Provinces. In the boundary layer atmosphere, particles from agri-fire smoke contributed more than 29% of PM\textsubscript{10} in parts of Anhui, Jiangsu and Shandong Provinces. Due to agri-fires the amount of PM\textsubscript{10} was highly correlated ($R^2 = 0.6$) with the smoke air masses in the main potential sink regions, and the mean PM\textsubscript{10} during the summer harvest of 2010 reached 0.24 mg/m$^3$, far higher than the adjacent periods without smoke.

Keywords: Agricultural fire; Smoke; Air quality; Transport.

INTRODUCTION

Particles and trace gases emitted from biomass burning influence atmospheric chemistry and aerosol physical, chemical, optical and radiative properties (Crutzen and Andreae, 1990; Andreae and Merlet, 2001; Kim et al., 2011; Reddy et al., 2012; Salako et al., 2012). Biomass burning smoke contains large amounts of partially oxidized organic material and black carbon or soot, which result in significant climatic implications (Christopher et al., 2000), and represent one of the largest sources of uncertainties in climate change assessment (IPCC, 2007). Agricultural waste field combustion is one important type of anthropogenic biomass burning especially in the developing countries, in which simultaneous combustion over extended areas can usually facilitate agricultural fire (agri-fire), and then related emissions cause serious local or regional air pollution during harvesting seasons (Levine, 1999; Koe et al., 2001; Ryu et al., 2007; Niyobuhungiro et al., 2013). In China, the open field combustion is a common approach for eliminating agricultural waste, and this region is considered as one large source of anthropogenic biomass burning in the world.

Agri-fires over China have been of particular concerns for about decades. Streets et al. (2003) and Yan et al. (2006) estimated that 17–25.6% of total agricultural residue production or 110–157.5 Tg of crop wastes were burned in the field in China every year. Cao et al. (2007) and Ohara et al. (2007) calculated the emission amount and inventory of agri-fire or domestic biofuel over China. Based on in situ measurements, many studies traced the transport routes of remote agri-fire smoke in the atmosphere, and estimated the impact of these pollutants on the air quality of observation sites (Han et al., 2008; Yang et al., 2008; Cheng et al., 2010; Zhang et al., 2010). Other studies used the wildfire products derived from satellite remote sensing to analyze the pollution events (e.g., haze) caused by agri-fires, and to study their impacts on urban air quality within downwind regions (Qian
et al., 2006; Li et al., 2009; Li et al., 2010; Zhang et al., 2010). However, to our knowledge, few have focused on the influence of widespread rural biomass burning over Chinese agricultural areas on air quality on a larger size and longer time scale.

This paper presents the spatial distributions of nationwide agri-fires in view of relatively longer periods using satellite remote sensing data of active fire sites over China from 2009 to 2010. In addition, we investigate the diffusion climatology of agri-fire smoke in the tropospheric atmosphere and their potential impacts on regional air quality.

MATERIAL AND METHODS

Satellite Fire Products

The dataset of fire sites is from space observations of MODIS on board NASA’s Terra and Aqua satellites. Active fire detection for MODIS is based on the improved algorithms in lieu of heritage algorithms developed for the AVHRR and TRMMVIRS (Kauffman et al., 1998), with superior sensitivity to smaller, cooler fires and yielding fewer blatant false alarms. The 1-km active fire record used for the analysis was generated with the improved MODIS version 4 active fire detection algorithm (Giglio et al., 2003). The data of agri-fires used in this study was finally derived from the Ministry of Environmental Protection of China, which was screened out from MODIS daily 1km-resolution level 3 hotspot or fire products using high resolution real-time land use based on Geography Information System.

Potential Sink Contribution Function

Three-dimensional 7-days forward trajectories starting at 500m above ground level were calculated for each agri-fire site using the NOAA hybrid single particle Lagrangian integrated trajectory (HYSPLIT 4) model (Draxler and Hess, 1998). The meteorological data used for modeling was from GDAS archived meteorological data set (http://ready.arl.noaa.gov/archives.php). All forward trajectories were used to trace the movement regimes of air pollution caused by agri-fires, and to identify the potential sink of smoke transported in the atmosphere. It is necessary to remind that the potential sink is different with the real aerosol sink as a result of dry and wet deposition, and theoretically the former overestimates the latter.

Potential sink contribution function (PSCF) is a statistical method to evaluate the possible sink of agri-fire emissions from a initiative site by counting trajectory segment endpoints that terminate within each cell, imitating potential source contribution function (Cheng et al., 2010). The PSCF value for single grid cell (1° × 1°) is a normalized value that can be calculated as follows:

\[
PSCF_{ij} = \frac{m_{ij}}{n_{ij}}\]

where \(m_{ij}\) is the number of air trajectories falling in \(ij\)th grid higher than a given reference. The mean number of air trajectories of all grids is selected as the reference value. \(n_{ij}\) is the number of all trajectories that fall in the same grid.

High PSCFs are always associated with more air parcels with pollutants arriving at one receptor site than the given reference. These cells indicate a potential serious pollution most possibly influenced by agri-fire smoke.

Aerosol Optical Depth

Aerosol optical depth (AOD) is a proper value to reflect aerosols loadings in columnar atmosphere and their spatio-temporary distributions. In this study, the daily mean AOD at 550 nm from the MODIS Collection 5.1 (MOD08_M3.051, MYD08_M3.051) over a period of two years (2009 and 2010) were used to analyze aerosol spatial and temporal distributions (http://disc.sci.gsfc.nasa.gov).

We calculated the contribution ratio (CR) of AODs between aerosols only from agri-fire smoke and all aerosols to evaluate the influence of agri-fire emissions on aerosol loadings and even regional air quality. The calculation equation is described as follow:

\[
CR_{ij} = \frac{A_{ij} - B_{ij}}{A_{ij}}
\]

where \(A_{ij}\) is mean AOD in \(ij\)th grid cell (1° × 1°) over a focused period (e.g., season or year) with some days that agri-fires appeared. \(B_{ij}\) is mean AOD in remaining times without fire occurrence excluding rainy days over the same period, reflecting the background of aerosol loadings. CR is the ratio of \(A-B\) and \(A\), which apparently represents the potential contribution of entire aerosols emitted from agri-fires to total aerosols. High CR coverage indicates a region seriously affected by agri-fire smoke. It is worth to point out that CR is an index to qualitatively characterize the relative contribution of focused aerosol component (e.g., carbonaceous matter) in entire aerosols, which can cause some uncertainties induced by extreme pollution events such as dust storm.

RESULTS AND DISCUSSION

Agricultural Fire Distribution

Fig. 1 illustrates a map of agri-fire sites over primary agricultural areas of China in 2009 and 2010. The number of total agri-fire sites was about 9739, separately 5514 in 2009 and 4225 in 2010. Overall, agri-fires distributed in most administrative areas of China about 33 provinces (97%). And, more than 80% of agri-fires scattered in heartland of agricultural regions such as Anhui (2569), Jiangsu (1599), Shandong (1494), Henan (1364) and Hebei (459) provinces, while only less than 10% appeared in Beijing, Shanghai, Hunan and others.

With the rapid economic development and population growth of China for recent several decades, in rural regions fossil fuel consumption has been increasing, but domestic biofuel usage has been decreasing. As a result, more agricultural residues were directly burned in the field by farmers and replaced by fossil fuel in household use. Compared with 2009, less agri-fires occurred in 2010 for two reasons. One is to improve urban air quality for holding the 2010 World Expo, the government took some actions to prohibit agricultural residue burning in the surrounding regions of...
Shanghai (Lu et al., 2011). Another is frequent floods in the South China result in a reduction of agricultural residue yield in 2010, particularly in areas south of the Yangtze River (Zhao et al., 2011; http://www.weather.com.cn/zt/).

Agri-fires varied in an obvious seasonal pattern with two distinct peaks corresponding to summer and autumn harvest periods. In general, the summer harvest is defined as from late May to early July, and the autumn harvest is late September to early November. There were 3394 (61.6%) and 775 (14.1%) agri-fires in the June and October of 2009, and 3612 (85.5%) and 245 (5.8%) agri-fires in the June and October of 2010. Note that more than 80% of agri-fires occurred in the summer harvest in either 2009 or 2010. The possible explanation is that most of agricultural areas implement two quarter farming system, which is associated with primary summertime planting and secondary fall sowing in China.

**Atmospheric Transport of Agri-Fire Smoke**

Based on HYSPLIT modeling and PSCF calculations, the atmospheric transport of agri-fire smoke originating from agricultural fires in China was investigated. The HYSPLIT model is a Lagrangian particle dispersion model that can be used to simulate the transport and dispersion of pollutants in the atmosphere. The model is widely used for air quality and meteorological research. In this study, the model was applied to track the movement of agri-fire smoke plumes and estimate the potential impact on air quality in various regions.

The Preliminary Results

The results of the HYSPLIT model simulations showed that agri-fire smoke plumes from different regions in China were transported to various parts of the country. For example, smoke from agricultural fires in the northern region of China was found to be transported to the southern region, indicating the potential for long-range dispersion of agri-fire smoke. Additionally, the model estimated that the concentration of particulate matter in the air increased in areas where agri-fires were occurring, indicating the potential for air quality deterioration in these areas.

**Conclusion**

The study highlights the importance of understanding the transport of agri-fire smoke and its potential impact on air quality in China. Further research is needed to more accurately quantify the dispersion patterns and to develop effective strategies to mitigate the adverse effects of agri-fires on air quality.

**Fig. 1.** Map of agricultural fire sites in 2009 and 2010. Abbreviations of Chinese provinces: XJ (Xinjiang), XZ (Xizang), GS (Gansu), QH (Qinghai), SC (Sichuan), YN (Yunnan), LMG (Inner Mongolia), SNX (Shaanxi), HUB (Hubei), SH (Shanghai), AH (Anhui), HUN (Hunan), JX (Jiangxi), ZJ (Zhejiang), FJ (Fujian), GD (Guangdong), GX (Guangxi), GZ (Guizhou), SD (Shandong), HEN (Henan), JS (Jiangsu), BJ (Beijing), HLJ (Heilongjiang), JL (Jilin), LN (Liaoning), HEB (Hebei), SX (Shanxi), TW (Taiwan) and CQ (Chongqing).
from Chinese agricultural areas on a large spatial scale was analyzed. In the autumn harvest, agri-fire smoke didn’t present a special transport pathway because agri-fires occurred scarcely and dispersely in either 2009 or 2010. However, in the summer harvest, agri-fires occurred very intensively so that agri-fire smoke transported in special routes in the atmosphere. Figs. 2 and 3 show the PSCF spatial distributions of agri-fire smoke at 0- to 5-day intervals in the summer harvests of 2009 and 2010, in which the interval refers to a time of smoke transported in the atmosphere away from sources. As shown in Fig. 2, in 2009 the most serious potential sink of agri-fire smoke (PSCF ≥ 0.8) at 0-day interval mainly scattered in the north of Anhui province, Henan and Jiangsu provinces, the south of Hebei province and Shandong province, almost corresponding with agri-fire source areas. Companying with atmosphere movement,

Fig. 2. PSCFs for agricultural fire smoke at 0- to 5-day intervals in the summer harvest of 2009.
agri-fire smoke was transported northward over and cross the north part of Jiangsu province and the Bohai Bay at 2-day interval. As time went on, agri-fire smoke spread out and diluted in the atmosphere, and their outflows reached to the Northeast China with a larger coverage. While the most serious potential sink at 5-day interval mainly scattered in the north of Heilongjiang province. Therefore, in the summer harvest of 2009, agri-fire smoke was transported over Chinese continental lands in northeastern direction. But, in the summer harvest of 2010, because the western Pacific subtropical high pressure is very abnormal in varying degrees within each member of Asian summer monsoon system (Zhao et al., 2011), agri-fire smoke was transported in three directions of northeastern, northwestern and southwestern. As shown in Fig. 3, the most serious potential sink of agri-fire smoke at 0-day interval mainly scattered in

![Fig. 3. Same as Figure 2 only for 2010.](image-url)
the north of Anhui and Jiangsu provinces, the south of Hebei and Shandong provinces and the east of Henan provinces. While the most serious potential sink at 5-day interval decreased to only small parts of Inner Mongolia, Liaoning, Shanxi, Sichuan, Heilongjiang and Guizhou provinces. The evolution of smoke potential sink with time stretching in 2009 was roughly different from that in 2010. This trend indicated that meteorological conditions (e.g., atmospheric cycle and wind) often play an important role in the transport, diffusion and deposition of agri-fire smoke.

Fig. 4 shows the seasonal PSCF spatial distributions of agri-fire smoke outflows. As agri-fires mainly occurred in the summer harvest, the regions of PSCF greater than 0.8 were much extensive in the summer harvest than in the autumn harvest. The most serious potential sink of the summer harvest covered more lands in 2010 than that in 2009. However, it was opposite for the autumn harvest that their coverage was far larger in 2009 than in 2010. Overall, the most serious potential sink of agri-fire smoke covered vast domain including Bohai Bay, the North Plain, the north of Anhui and Jiangsu provinces, etc. Compared with 2009, the intensity of smoke potential sink in the Yangtze River Delta (YRD) diminished in 2010, while it strengthened in the Bohai Bay and Shanxi province due to agri-fires mainly occurred in the north of the Yangtze River, and the summer monsoon pushed air towards northern China.

Impacts of Agri-Fire Smoke on Regional Air Quality

AOD is useful to characterize particulate pollutants and air pollution events over a larger region. Many studies on comparisons of MODIS AODs with surface measurements of aerosols have demonstrated AOD suitability for monitoring air pollution on local to global scales (Hutchison, 2003; Wang and Christopher, 2003; Engel-Cox et al., 2004; Al-Saadi et al., 2005; Mathur, 2008). Furthermore, MODIS AOD retrievals performed well over ‘dark-object’ surfaces such as farmland and forest sites (Wang et al., 2007). MODIS AOD was so feasible to use in analyzing agri-fires smoke impacts on air quality in the tropospheric and boundary layer atmospheres in eastern China.

Fig. 5 provides CR ratios of agri-fire smoke in the summer harvests of 2009 and 2010. Carbonaceous aerosols (BC + OC) have been estimated to contribute about 18–21% of AOD over East Asia (Streets et al., 2008), thus CR 0.35 is selected as one available threshold to identify the region significantly influenced by smoke. Relatively higher CR values (> 0.35) mainly scattered in the Jiaodong Peninsular, the North Plain, and Hunan and Hubei provinces, indicating important impacts of agri-fire smoke on tropospheric atmospheric environment over these regions.

Fig. 4. PSCFs for agricultural fire smoke in the summer and autumn harvests.
The highest CR values (> 0.6) centered in some areas of Shandong, Henan and Jiangsu provinces, of which regions were marked by blue circle in Fig. 5, and roughly kept consistent with the most serious potential sinks of agri-fire smoke (Fig. 4). Since Asian Russian forest wildfire occurred in 2010 but in 2009, relatively higher CRs also appeared in some areas of the Northeast China in the summer of 2010. Cheng et al. (2010) argued that the forest wildfires located in the boundary regions between Asian Russia and East China is a near source of smoke and imposed somewhat impacts on air quality in the Northeast China.

To elucidate agri-fire smoke impacts on air quality in the boundary layer atmosphere, airborne particulate matter in aerodynamic diameter smaller than 10 µm (PM10) was used to calculate PM CR, a ratio of PM10 influenced only by agri-fire smoke to total PM10 like AOD (section 2.3). Daily PM10 is derived from the Air pollution index (API) released online by the State Environmental Protection Monitoring Station (http://www.zhb.gov.cn/), and on the basis of API derivation equation, we computed daily PM10 concentration in major cities. As shown in Fig. 6, the most serious regions (PM CR > 0.3) centralized in Jiangsu, Anhui and Shandong provinces, which was very consistent with the most serious potential sinks of agri-fire smoke (Fig. 4). Previous studies have measured that carbonaceous aerosols contribute 20–50% of aerosol (CR: 20–50%) in Chinese urban atmosphere from small-scale urban or regional atmosphere (Cao et al., 2007).

Shanting (35°04’N, 117°27’E) was chosen as a representative for examining agri-fire smoke impacts on particulate matter in the surface atmosphere over downwind regions. This site is beside a small town without major pollution sources except sparse anthropogenic emissions, and particulate matter (e.g., PM10) is its principal pollutant as an indicator of local air quality. It is expected to reflect local atmospheric background avoiding near source disturbance, as well as to easily suffer from air pollutants transported from upwind sources. Note that Shanting is located in the most serious potential sink regions of agri-fire smoke (Fig. 3), in which air quality would be easily influenced by remote agri-fire smoke.
The summer harvest of Shanting lasted 14 days from 14 to 27 June in 2010, and at the same time about 3144 agri-fires occurred nationally accounting for more than 87% of annual agri-fires. Fig. 7 shows a time series of daily PM$_{10}$ in Shanting from 14 to 27 June. The mean PM$_{10}$ over the summer harvest was 0.24 mg/m$^3$, which was far higher than the average (0.12 mg/m$^3$) of adjacent days without smoke disturbance, and very close to 0.25 mg/m$^3$ namely the third standard level of Chinese ambient air quality. As shown in Fig. 7, PM$_{10}$ increased sharply accompanying with agri-fire occurrence, implying the air quality of Shanting deteriorated in this period. The correlation coefficient (R$^2$) between air trajectories of agri-fire smoke arriving at Shanting and PM$_{10}$ concentrations reached up to 0.6, indicated a significant effect of agri-fire smoke on air quality in downwind regions.

CONCLUSIONS

Agri-fires mainly occurred in the summer and autumn harvests of China. The agri-fire smoke was transported in the atmosphere in three major routes of northwestern, northeastern and southwestern directions. The agri-fire smoke had a significant potential impact on the atmospheres in tropospheric and boundary layers over Chinese continental lands. The near potential sink of agri-fire smoke mainly scattered in regions close to sources such as the North of Anhui and Jiangsu provinces, the south of Hebei province, and Shandong and Henan provinces. Whereas the remote potential sink scattered in some areas of Inner Mongolia, Liaoning, Shanxi, Sichuan, Heilongjiang and Guizhou provinces. Future works are needed to estimate agri-fire emissions and their impacts on regional climate, as well as agri-fire response to climate changes using modeling and satellite remote sensing products.

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