Marked rebound of agricultural fire emissions in Asia after the outbreak of COVID-19

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Abstract

East and South Asia are major hotspots of crop straw burning worldwide, with profound impacts on air quality and climate change. The Northeast China Plain (NECP) and Punjab, India, are two of the most fertile areas for crop production, which have large-scale agricultural fires during post-harvest seasons. Leveraging established fire-emission databases and satellite-retrieved agricultural fire spots, we show that, while the years 2018 and 2019 recorded low agricultural fire emissions in both the NECP and Punjab, probably due to the implementation of crop straw sustainable management, fire emissions markedly rebounded in 2020, reaching about 190% and 150% of 2019 levels, respectively. The COVID-19 lockdown measures somewhat disrupted eco-friendly crop straw management through restrictions on labor and transportation availability, such that farmers may have had to burn off crop wastes to clear up the land. We further demonstrate that the increased fire emissions in the NECP resulted in serious particulate matter pollution during the fire season in spring 2020, as opposed to considerable decreases in particles from fossil fuel emissions caused by the COVID-19 lockdown. This study suggests the unintended impacts of the COVID-19 pandemic on the agricultural sector and human health.

1. Introduction

Huge efforts to control the spread of COVID-19 hampered social-economical activities to a large extent, resulting in dramatic reductions of air pollutant emissions including nitrogen oxides and particulate matter (PM) after the outbreak of the virus (Liu et al 2020, Venter et al 2020). The unprecedented decrease of air pollutants from fossil fuel combustion provides a unique natural lab to study the human imprint on the atmosphere (Forster et al 2020, Laughner et al 2021).

Little attention has been paid to agricultural activities and associated emissions affected by the COVID-19 pandemic. One potential issue is the disposal of crop straw after harvest seasons. To limit straw burning and mitigate air pollution, recycling of straw, for example, for use as compost manure, in power/heat generation, and as animal feed, was increasingly advocated and applied in Asian major crop-production regions (e.g. India and China) (Ren et al 2019, Venkatramanan et al 2021). However, since COVID-19 control measures could restrict both transport and labor availability, which help to dispose of crop waste in an eco-friendly way, excess straw was instead left on farmland and burned off rather than being recycled (Ravindra et al 2022). Plumes of toxic smoke from crop residue burning would then result in adverse impacts on atmospheric visibility and public health in local and outflow areas. Such an unintended consequence of the COVID-19 pandemic may have taken place in areas with extensive agricultural production.

The Northeast China Plain (NECP), located at a latitude of 40°–50°N (marked in figures S1 and S2), is one of the three largest black soil belts in the world and the primary crop-production region in Asia. Planting seasons start from late April for maize...
and japonica rice and early May for soybeans, and in October harvest season starts. About 145 million tons of crop straw are produced annually in this region (Fang et al. 2019). Due to the cold climate and high economic cost, the fraction of crop straw burning was less than 70% in the NECP before 2017 (Shi et al. 2019). Recent remote sensing detections suggest that the number of crop straw burning events presents an oscillatory, increasing trend from the 2000s to 2017 in the region (Wang et al. 2020). Another fertile place in Asia, Punjab in northern India, also known as 'India’s Bread Basket', abounds with wheat, rice, and vegetables while leaving tremendous crop stubble. During autumn and winter, Punjab suffers from toxic smog released by active agricultural fires, which can drift towards Delhi and cause severe air pollution there (Cusworth et al. 2018, Kanawade et al. 2020).

Here, we analyze the temporal dynamics of agricultural fire emissions in Asian major crop-production areas prior to (2012–2019) and during the COVID-19 pandemic (from 2020 onwards) to explore the unintended impacts of COVID-19 control measures on agricultural activities and associated environmental consequences. As opposed to the substantial reductions in fossil fuel emissions in transport and industrial sectors brought about by COVID-19 controls, we find that fire emissions markedly increased in Asian croplands in 2020 compared to the previous few years.

2. Materials and methods

We explore the temporal variations of agricultural open fire emissions using the Fire INventory from NCAR (FINN) version 2.5 (Wiedinmyer et al. 2011). The latest version of the FINN database combines active fire data from the Moderate Resolution Imaging Spectroradiometer (MODIS) and Visible Infrared Imaging Radiometer Suite (VIIRS) satellite instruments, the latter of which provides a higher spatial resolution (375 m) of fire detection from 2012 to the present. This inventory would be best suitable for the estimation of agricultural fires in Asia that commonly feature small sizes in space (Zhang et al. 2018, 2020). The inventory framework produces daily emission estimates at a horizontal resolution of 1 km². For individual fire emission estimates, the FINN inventory also provides land-type information, whereby we identified agricultural fire emissions and merged them into a 0.25° grid. This study analyzed crop straw fire emissions using the FINN inventory for the calendar years 2012–2020.

As a comparison, we included another two widely used global emission databases, the Global Fire Emission Database (GFED) (van der Werf et al. 2017) and the Global Fire Assimilation System (GFAS) (Kaiser et al. 2012). Both databases make use of MODIS observations only. Gridded daily emission rates are provided for past decades on a global scale with spatially horizontal resolutions of 0.25° × 0.25° and 0.1° × 0.1°, respectively. The GFED version 4 with modifications for small fires provides the agricultural contribution of open fire emissions (Randerson et al. 2012) and we derived crop straw emissions using total biomass burned at each grid, agricultural percentage contribution at the corresponding grid, and generic emission factors.

The GFAS employs a fire radiative power-based approach to constrain vegetation combustion rates for different land cover types and exhibits advantages of small fire detections (Kaiser et al. 2012). It also corrects the observation gaps due to partial cloud cover. The MODIS land cover product (MCD12Q1) at a spatial resolution of 500 m was used to identify agricultural fire emissions in the GFAS. Within each GFAS grid (0.1° × 0.1°), if agricultural land is the dominant type based on the MODIS data, the fire emission at that grid was marked as crop straw burning emission in our analysis. Otherwise, crop straw fire emission was calculated as the product of the total biomass burning emission and fraction of cropland area at each grid. It should be noted that none of these three emission products are designed to accurately map agricultural emissions, and they could use generic values for emission factors and/or combustion conditions across regions and seasonal periods.

To further understand the evolution of agricultural fire intensity, we obtained data from the VIIRS product (VNP14IMGTDL), which provides daily fire spots at a 375 m resolution (Schroeder et al. 2014). The MODIS active fire product was also used for long-term analysis from 2003 to 2021 (Giglio et al. 2016). The annual International Geosphere-Biosphere Programme (IGBP) classification from the MODIS land cover product in a 500 m resolution was utilized to define the cropland pixels and to then pinpoint the occurrence of agricultural fires based on their latitude and longitude information (Liu et al. 2015). The IGBP classification from the MODIS land cover product provides 17 land cover classes and we used class 12 and class 14 for cropland pixels. We calculated the number of agricultural fire spots over the regions during typical fire seasons to reveal the inter-annual tendency of fire activities.

As aerosol optical depths (AODs) retrieved by the remote sensing may be used as an indicator of intensive field-burning events during fire seasons (Torres et al. 2010), we explore the linkage of AOD variations to agricultural fire emissions in target areas. Herein, the Level-3 MODIS Atmosphere Eight-Day Global Product, named MOD08_E3, was used to reveal spatial heterogeneity and inter-annual changes of AOD. We used the dark target and deep blue combined mean AOD at 550 nm extracted from the MOD08_E3 product (Platnick et al. 2015). Absorption AOD (AAOD) and aerosol index
at 388 nm from an ozone monitoring instrument (OMI) were obtained to detect the absorbing aerosols from biomass burning (Torres et al 2007). Besides, to indicate fine particle pollutions related to agricultural fires, a ground-level PM$_{2.5}$ (PM with diameters less than 2.5 μm) product at a 1 km spatial resolution derived from satellite and surface observations was used in our analysis (Wei et al 2021) in conjunction with measured PM$_{2.5}$ concentrations from the China Ministry of Ecology and Environment.

3. Results

The NECP and Punjab are the two major hotspots of agricultural fire emissions in Asia (figure S1; the locations of the NECP and Punjab are marked) due to quantities of crop straw produced every year. From 2012 to 2019, fire emissions reached a peak in the years 2016–2017 in the NECP and Punjab, and then moderately declined until 2019 (figures 1(a) and (c)). Unexpectedly, the fire emissions in these regions are found to markedly rise in 2020 relative to 2019. In the NECP, the regional annual CO$_2$ emission from crop straw burning is estimated to increase by 17 Tg, corresponding to 90% of the 2019 level. In particular, the rise of emissions within the NECP took place predominantly in central Jilin province and west Heilongjiang province (figure S2). In Punjab, in northern India, there was an increase of 15 Tg (50%) for the annual emissions from 2019 to 2020.

The monthly dynamics of FINN fire emissions during 2012–2020 further point to the unusual fire emissions in 2020 (figures 1(b) and (d)). The NECP marks an approximately bimodal distribution of monthly agricultural fires in a year, with the fire emissions concentrated in early spring and autumn. After the outbreak of COVID-19 in 2020, fire emission was extraordinarily high in April compared to the same period in 2012–2019. In Punjab, fire emission in autumn (October and November) of 2020 was the second highest over the periods based on the FINN database (figure 1(d)), in line with the observed increase of fire activities in the region (Ravindra et al 2022). A similar rebound is captured by the GFED data for Punjab (figure S3). Note that Montes et al (2022) showed much higher emission rates of rice residue burning in Punjab during the autumn of 2020 than those in 2012–2019, though they did not explain it. Considering that the disposal of crop straw is driven by farmers’ agricultural practices, which may have been disrupted by COVID-19 control measures, we infer that such an abrupt rise in fire emissions is linked to the outbreak of COVID-19.

The evolution of fire emissions is determined directly by the inter-annual variability of agricultural fire counts in the NECP during the fire seasons in spring (March–April) and autumn (October–November) (figure 2(a)). As fire activities commonly occur by accident and primarily depend on farmers’ agricultural practices, the number of fire spots reached a peak in spring 2017 and autumn 2014 in the past ten years. In line with a prior study (Wang et al 2020), our analysis shows an upward trend in fire occurrences from 2012 to 2017, while in particular we reveal that fire numbers decreased in 2018 by 58% and 98% for spring and autumn months relative to those in 2017 and remained low in 2019. The Ministry of Agriculture of China launched a special crop straw-management policy for Northeast China in 2017 to prompt straw recycling (MOA 2017). This straw regulation policy presumably came into play from 2018, consequently leading to a dramatic decline in crop fire counts during 2018 and 2019.

However, the COVID-19 pandemic tends to reverse the inter-annual tendency of fire numbers in the spring months. Though fire counts in the autumn of 2020–2021 remained as low as those in 2019 owing to the crop straw-management policy, fire activity in the spring season markedly rebounded with the number increasing by a factor of 4.7 (figure 2(a)). After the outbreak of COVID-19, China imposed a lockdown in the city of Wuhan and the restriction of commercial activities at a national scale during early spring of 2020 (from late January to early April) to prevent the spread of the new virus. Because agricultural activities were also disrupted, a large portion of crop straw produced in the 2019 harvest season were probably not disposed of. To manage croplands for the sowing of corn and soybean before May 2020, and to ensure crop productivity, farmers would have had to burn crop straw as it is the convenient and time-saving way. Consequently, such a striking increase in the number of fire spots in the springtime of 2020 translated into the rise of yearly fire emissions from 2019 to 2020, as revealed in figure 1(a). Besides, the MODIS product combining both daytime and nighttime detections from 2003 to 2021 supports the rebound of fire activities in 2020 relative to preceding years (figure S4). This long-term analysis also shows fire numbers in 2021 were similar to those in 2020 and markedly higher than 2018–2019 (figure S4), as the COVID-19 disruption still existed.

In a similar manner, Punjab, India (figure 2(b)) experienced a 50% decrease of fire spots during the autumn fire seasons from 2016 to 2019 and a subsequent 60% increase in autumn 2020, while spring fire numbers remained at a relatively low level in these few years. The significant contrast in fire counts between spring and autumn in Punjab is associated with the rice–wheat rotation as the primary cropping system. Because of the short time frame window between rice harvest and wheat sowing in the autumn, farmers often burn off crop straw to clear land. During the year 2020, many laborers migrated from the crop-production region like Punjab to their hometown in southern India due to the government’s
lockdown measures (O’Leary 2021). The resultant lack of laborers in Punjab resulted in delayed rice transplanting, a shorter time frame window for wheat sowing, and then increased fire emissions in the autumn (figure 1(d)).

The daily dynamics of region-aggregated fire CO$_2$ emission rates in the NECP (figure S5) also show that the 2020 spring fire emissions were generally much stronger compared to the same period in 2019, especially in April with the daily emission rates orders of magnitude higher than the 2019 levels. The lockdown measures to tackle COVID-19 were lifted in the NECP at the beginning and in middle of March 2020. After that, a series of crop fire episodes were recorded for about 30 days. The longer fire season and higher daily emission rates in spring 2020 compared to 2019 imply that the management of crop straw was disrupted by the COVID-19 lockdown with delayed disposal of crop straw as well as labor shortages. In the early spring of 2022, because control measures were implemented to curb the rapid spread of the Omicron variant in the NECP, occurrences of active fires lagged about one month behind preceding years.

Figure 3 compares the fire emission of black carbon (BC), satellite-derived AOD at 550 nm, and estimated PM$_{2.5}$ concentrations in the NECP area between the spring fire seasons of 2020 and 2019. We note that the rise of agricultural fire emissions is concentrated in the central-west of the NECP, which recorded a dramatic increase in BC emissions, having orders of magnitude higher emission fluxes in the northern part during spring 2020 compared to 2019. In the meantime, the temporal-averaged AOD increased by up to 200% within the NECP. The Jilin province featured high AOD levels of about 0.8 during the fire season, suggesting a strong link between extraordinary AOD values and fire episodes. The observation-based PM$_{2.5}$ estimates in the NECP during the target period increased on average from 31 $\mu$g m$^{-3}$ in 2019 to 56 $\mu$g m$^{-3}$ in 2020. Results of daily dynamics of FINN fire emissions and PM$_{2.5}$ concentrations show that the PM pollution
Figure 2. Number of fire spots during fire seasons in (a) the NECP and (b) Punjab for the years 2012–2020. Fire detections are derived from the VIIRS 375 m (VNP14IMGTDL) product. The geographical scopes of the NECP and Punjab are marked in figure S2. Note that P1 marks the initiation of crop straw-management action for the NECP region; P2 marks the lockdown period in China from late January to early April.

coincides with increased fire activities during spring 2020 (figure S6). The satellite-derived estimate captured the severe haze episodes with the maximum daily PM$_{2.5}$ concentrations at 130 µg m$^{-3}$, which was boosted by agricultural fire emissions. As a comparison, in spring 2019 there were much fewer fire outbreaks, and daily PM$_{2.5}$ concentrations lay mostly below 50 µg m$^{-3}$. Increases in AOD were also found in Punjab and surrounding areas during the autumn fire season of 2020 relative to 2019, though less pronounced than that of the NECP (figure S7).

We also detect markedly higher AAOD in the spring fire season of the NECP and the autumn fire season of Punjab using satellite observations from the OMI (figure 4). The rise of agricultural fire emissions in 2020 relative to the same periods in 2019 produced more absorbing aerosols like BC and brown carbon that contributed primarily to AAOD. In addition, the OMI-derived aerosol indexes associated with absorbing aerosols from biomass burning were increased in both areas (figure S8). These results show spatially consistent variations among fire emissions, AAOD, and aerosol index, providing strong evidence of the increases in fire emissions in the study regions.

4. Discussion

The trends in agricultural fire emissions in China in the past decade have been regionally divergent, and are associated with government policies and solutions for crop straw recycling. China has taken the toughest action to tackle air pollution, especially from 2013 to the present, and thereby has seen a marked improvement in air quality. Owing to regulatory effort, crop straw burning events have declined by more than 50% in central and eastern China, which used to be the most active fire spot in China before 2013 (Zhuang et al 2018, Wang et al 2020). However, the NECP region shows an overall increase in crop burning activities until a special policy of crop straw management for the NECP was issued in 2017 by the central government. Then, the NECP saw a significant drop in 2018 and 2019 (figure 1). Reductions of agricultural fire activities were achieved by increased
fractions of recycling in the disposal of crop straw (Shi et al 2019). Some effort has been also taken in India to ban crop burning, by means of which fire activities in Punjab had declined during 2017–2019 (Ravindra et al 2022). Under these targeted policies, fire activities would be further reduced in these major crop agricultural regions. This work, however, reveals an unexpected rebound of agricultural fire emissions during the COVID-19 pandemic, presumably because the

Figure 3. (a), (b) Agricultural fire emissions, (c), (d) MODIS AOD, and (e), (f) \( \text{PM}_{2.5} \) concentrations during spring fire seasons between 2019 and 2020 in the NECP. \( \text{PM}_{2.5} \) maps are derived from satellite-based estimates, overlaid by colored dots showing observations from environmental-monitoring stations. The first row of panels presents the black carbon emissions from the FINN database. All variables are the temporal mean in the period from March 20 to April 25 of 2019 or 2020. Grey areas denote no available data.
effective crop straw sustainable management was somewhat disrupted by COVID-19 controls. We find that the increased fire particle emissions caused severe air pollution episodes in the NECP during spring 2020, which may appreciably increase the risk of people’s premature death associated with cardiorespiratory diseases. As COVID-19 infection remains a threat to human health, communities have paid attention to its complex association with short-term exposure to air pollution (Xu et al. 2022, Yu et al. 2022). In a similar manner, agricultural fire emissions in Punjab, India, during the COVID-19 pandemic were increased, which could contribute not only to air pollution in the local and outflow areas, like the haze in Delhi (Montes et al. 2022), but also to the melting of Himalayan glaciers (Li et al. 2016). Interestingly, our findings are in contrast with Poulter et al. (2021) who found that the COVID-19 lockdown led to a 21% reduction in active fire during 2020 through the reduction in ignitions controlled by human activities. These consequences mirror the comprehensive impacts of COVID-19 on society and the environment.

Improving air quality and reducing carbon emissions are both critical for the 2030 Agenda for Sustainable Development set up by the United Nations. Policy-makers should develop strategies and take positive action to ensure crop yields while promoting alternatives to field burning. For example, China has provided subsidies for farmers and companies to encourage the recycling of crop straw since 2016, such as the ‘straw-returning to soil’ approach, which is conducive to crop productivity and carbon emission cuts (Han et al. 2018). It was reported that China’s straw-management policy launched in 2016 had led to much larger economic benefits than the costs and avoided almost 20 000 premature deaths annually (He et al. 2020). In spite of the current COVID-19

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Figure 4. (a) and (b) Observed AAOD at 388 nm in the NECP for 2019 spring and 2020 spring. (c) and (d) AAOD388 in northern India for autumn 2019 and autumn 2020. The AAOD observations were obtained from the OMI instrument.
disruptions, agricultural fire emissions in China are anticipated to continue declining in the future following the 2019 levels.

**Data availability statement**

The data that support the findings of this study are openly available at: https://zenodo.org/record/6984023.

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**Conflict of interest**

The authors have no conflict of interests.

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**References**

Caswell D H, Mickley J I, Sulprizio M P, Liu T, Marlier M E, DelFries R S, Guttiuknda S K and Gupta P 2018 Quantifying the influence of agricultural fires in northwest India on urban air pollution in Delhi, India Environ. Res. Lett. 13 044018

Fang Y R, Wu Y and Xie G H 2019 Crop residue utilizations and potential for biofuel production in China Renew. Sustain. Energy Rev. 113 109288

Forster P M et al 2020 Current and future global climate impacts resulting from COVID-19 Nat. Clim. Change 10 913–9

Giglio L, Schroeder W and Justice C O 2016 The collection 6 MODIS active fire detection algorithm and fire products Remote Sens. Environ. 178 31–41

Han X, Xu C, Dungat A J, Bol R, Wang X, Wu W and Meng F 2018 Straw incorporation increases crop yield and soil organic carbon sequestration but varies under different natural conditions and farming practices in China: a system analysis Biogeosciences 15 1933–46

He G, Liu T and Zhou M 2020 Straw burning, PM2.5, and death: evidence from China J. Dev. Econ 145 102468

Kaiser J W et al 2012 Biomass burning emissions estimated with a global fire assimilation system based on observed fire radiative power Biogeosciences 9 527–54

Kanawade V P, Srivastava A K, Ram K, Asmi E, Vakkarai V, Soni V K, Varaprasad V and Sarangi C 2020 What caused severe air pollution episode of November 2016 in New Delhi Atmos. Environ. 222 117125

Laughner J L et al 2021 Societal shifts due to COVID-19 reveal large-scale complexities and feedbacks between atmospheric chemistry and climate change Proc. Natl Acad. Sci. USA 118 e2109481118

Li C, Bosch C, Kang S, Andersson A, Chen P, Zhang Q, Cong Z, Chen B, Qin D and Gustafsson O 2016 Sources of black carbon to the Himalayan–Tibetan Plateau glaciers Nat. Commun. 7 12574

Liu F et al 2020 Abrupt decline in tropospheric nitrogen dioxide over China after the outbreak of COVID-19 Sci. Adv. 6 eabc2992

Liu M, Song Y, Yao H, Kang Y, Li M, Huang X and Hu M 2015 Estimating emissions from agricultural fires in the North China Plain based on MODIS fire radiative power Atmos. Environ. 112 326–34

MOA 2017 Action plan for straw disposal in Northeast China Ministry of Agriculture and Rural Affairs of the People’s Republic of China (available at: www.moa.gov.cn/mynbgb/2017/dqk/01712/20171231_6133078.htm)

Montes C, Sapkota T and Singh B 2022 Seasonal patterns in rice and wheat residue burning and surface PM2.5 concentration in northern India Atmos. Environ. X 13 100154

O’Leary M 2021 Could coronavirus drive farmers to adopt sustainable practices in India’s breadbasket? CIMMYT (available at: www.cimmyt.org/news/could-coronavirus-drive-farmers-to-adopt-sustainable-practices-in-indias-breadbasket/)

Plattnick S et al 2015 MODIS atmosphere L3 eight-day product NASA MODIS Adaptive Processing System (Greenbelt, MD: Goddard Space Flight Center) (https://doi.org/10.5067/MODIS/MOD08_E3.061)

Pouliot B, Freeborn P H, Jolly W M and Varner J M 2021 COVID-19 lockdowns drive decline in active fires in southeastern United States Proc. Natl Acad. Sci. USA 118 e2105666118

Randerson J T, Chen Y, van der Werf G R, Rogers B M and Morton D C 2012 Global burned area and biomass burning emissions from small fires J. Geophys. Res. 117 G04012

Ravindra K, Singh T and Mor S 2022 COVID-19 pandemic and sudden rise in crop residue burning in India: issues and prospects for sustainable crop residue management Environ. Sci. Pollut. Res. Int. 29 3155–61

Ren J, Yu P and Xu X 2019 Strawberry utilization in China—status and recommendations Sustainability 11 1762

Schroeder W, Oliva P, Giglio L and Caisar I A 2014 The New VIIRS 375m active fire detection data product: algorithm description and initial assessment Remote Sens. Environ. 143 85–96

Shi Z, Wang F, Wang J, Li X, Sun R and Song C 2019 Utilization characteristics, technical model and development suggestion on crop straw in China (in Chinese) J. Agric. Sci. Technol. 21 8–16

Torres O, Chen Z, Jethva H, Ahn C, Freitas S R and Bhartia P K 2010 OMI and MODIS observations of the anomalous 2008–2009 Southern Hemisphere biomass burning seasons Atmos. Chem. Phys. 10 3505–13

Torres O, Tankanen A, Veihelmann B, Ahn C, Braak R, Bhartia P K, Veefkind P and Levelt P 2007 Aerosols and surface UV products from ozone monitoring instrument observations: an overview J. Geophys. Res. 112

van der Werf G R et al 2017 Global fire emissions estimates during 1997–2016 Earth Syst. Sci. Data 9 697–720

Venkatramanan V, Shah S, Rai A K and Prasad R 2021 Nexus between crop residue burning, bioeconomy and sustainable development goals over north-western India Front. Energy Res. 8 614212

Venter Z S, Aunan K, Chowdhury S and Lelieveld J 2020 COVID-19 lockdowns cause global air pollution declines Proc. Natl Acad. Sci. USA 117 18984–90

8
Wang L, Jin X, Wang Q, Mao H, Liu Q, Weng G and Wang Y 2020 Spatial and temporal variability of open biomass burning in Northeast China from 2003 to 2017 Atmos. Ocean. Sci. Lett. 13 240–7
Wei J, Li Z, Lyapustin A, Sun L, Peng Y, Xue W, Su T and Cribb M 2021 Reconstructing 1-km-resolution high-quality PM$_{2.5}$ data records from 2000 to 2018 in China: spatiotemporal variations and policy implications Remote Sens. Environ. 252 112136
Wiedinmyer C, Akagi S K, Yokelson R J, Emmons L K, Al-Saadi J A, Orlando J J and Soja A J 2011 The Fire INventory from NCAR (FINN): a high resolution global model to estimate the emissions from open burning Geosci. Model Dev. 4 625–41
Xu L, Taylor J E and Kaiser J 2022 Short-term air pollution exposure and COVID-19 infection in the United States Environ. Pollut. 292 118369
Yu Z et al 2022 Association of short-term air pollution exposure with SARS-CoV-2 infection among young adults in Sweden JAMA Netw. Open 5 e228109
Zhang T, de Jong M C, Wooster M J, Xu W and Wang L 2020 Trends in eastern China agricultural fire emissions derived from a combination of geostationary (Himawari) and polar (VIIRS) orbiter fire radiative power products Atmos. Chem. Phys. 20 10687–705
Zhang T, Wooster M J, de Jong M C and Xu W 2018 How well does the ‘small fire boost’ methodology used within the GFED4.1s fire emissions database represent the timing, location and magnitude of agricultural burning? Remote Sens. 10 823
Zhuang Y, Li R, Yang H, Chen D, Chen Z, Gao B and He B 2018 Understanding temporal and spatial distribution of crop residue burning in China from 2003 to 2017 using MODIS data Remote Sens. 10 390