Health effects of banning beehive coke ovens and implementation of the ban in China

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Environmental legislation and proper implementation are critical in environmental protection. In the past, beehive coke ovens (BCOs) were popular in China, resulting in enormous emissions of benzo[*a*]pyrene (BaP), a common indicator of carcinogenic polycyclic aromatic hydrocarbons. BCOs were banned by the Coal Law in 1996. Although BCO numbers have declined since the ban, they were not eliminated until 2011 due to poor implementation. Here, we present the results of a quantitative evaluation of the health effects of historical BCO operation, the health benefits of the ban, and the adverse impacts of the poor implementation of the ban. With only limited official statistics available, historical and geospatial data about BCOs were reconstructed based on satellite images. Emission inventories of BaP from BCOs were compiled and used to model atmospheric transport, nonoccupational population exposure, and induced lung cancer risk. We demonstrated that more than 20% of the BaP in ambient air was from BCOs in the peak year. The cumulative nonoccupational excess lung cancer cases associated with BaP from BCOs was 3,500 (±1,500) from 1982 to 2015. If there was no ban, the cases would be as high as 9,290 (±4,300), indicating the significant health benefits of the Coal Law. On the other hand, if the ban had been fully implemented immediately after the law was enforced in 1996, the cumulative cases would be 1,500 (±620), showing the importance of implementing the law.

beehive coke oven | lung cancer risk | benzo[*a*]pyrene | ban | law implementation

Over the past few decades, China has experienced rapid development and industrialization along with extensive and severe environmental contamination (1). Although there were continuous efforts to solve the issue, the trend of the environmental deterioration did not slow down until recent years. Fortunately, enormous attention and actions are currently being undertaken at the national and local levels to battle against pollution in China (2, 3). As part of the effort, a series of laws and regulations have been enacted, playing a central role in environmental protection (2, 4). Although the current legislation covers almost all aspects, implementation is always a weak link in China (5). Moreover, the performance of the legislation is rarely, if ever, quantitatively evaluated.

Coke production from very simple beehive coke ovens (BCOs) has a long history in China, and the earliest documented coke ovens can be traced back to the fourth century (6). Unfortunately, the technique did not advance much over centuries, and BCOs were still produced in the traditional way in modern times (7). Even 10 y ago, low-cost BCOs were still popular in China (7). As an important industrial process, coke production ranks high in terms of the emission of many air pollutants including polycyclic aromatic hydrocarbons (PAHs), a major group of compounds that can lead to incremental lung cancer (8). Benzo[*a*]pyrene (BaP) is a representative compound often used as marker of carcinogenic PAH exposure (8). BCOs are low-cost brick ovens without any control measures, and the exhaust gasses and smoke can escape directly to the atmosphere (8–10). Moreover, low-grade, cheap coal is often fed to BCOs. As a result, the emission factor (EF) (the quantity of pollutant emitted per unit of coke produced) of BaP from BCOs can be several orders of magnitude higher than that for regular coke ovens (11), contributing a large fraction of the BaP from the coke industry (12).

In 1996, the Coal Law was enacted in China, and BCOs were legally banned by the end of 1996 by law (13). One result of the ban was that the emission of BaP in China began to decrease, resulting in a much earlier tipping point for BaP than those for most other air pollutants (11, 14). On the other hand, the phasing-out of BCOs lasted for more than a decade, and they did not disappear entirely until 2011 due to poor implementation of the law (15–17).

The legislation-driven BCO phasing out can serve a good lesson to show how science can help to evaluate the performance of environmental legislation and implementation. In this study, we develop a procedure to evaluate the health benefits of the BCO ban focusing on major carcinogenic PAHs using BaP as an indicator. To do so, historical emissions of BaP from BCOs were compiled using government statistics and satellite images, which have previously been used to detect BCOs in Shanxi based on fire spots (18). This inventory was used to model population exposure and lung cancer risk under three scenarios: (*i*) the actual situation, that is, the ban was enacted in 1996 but was not fully implemented until 2011; (*ii*) business as usual, that is, no ban at all; and (*iii*) an ideal case, that is, the ban was fully implemented immediately after the law came into force.

Results and Discussion

Historical Trends of BCOs. We modified the previously reported method (18) by including digital numbers (DNs) to extract the

Significance

At present, many environmental laws and regulations are enforced in China, but they are often not well evaluated for their performance. In this study, the health effects of beehive coke oven operations, the ban of the ovens, and the slow implementation of the ban were assessed quantitatively, showing the importance of not only the legislation but also the implementation of the law. This study provides a good example that shows how environmental legislation and implementation can be evaluated to scientifically support decision making.

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historical geospatial distributions of BCOs in China for the period from 1987 to 2011 (*Methodology*) because remote sensing data are not available before 1987, and there were no BCOs after 2011.

The result of the remote sensing-based interpretation (as the sum of product of fire grid area and DN) is compared with official statistics on coke production from BCOs in Fig. 1*A*, indicating a linear relationship between them (log-transformed). This good agreement is further demonstrated in Fig. 1*B* by comparing the historical trends of annual BCO production between our results (circles) and official statistics (line) (7).

A sharp peak from 1958 to 1962 was a direct result of the Great Leap Forward (19), corresponding to an extremely high but unsustainable increase in steel production from 2.75 million tons in 1957 to 40.4 million tons in 1960 and a sharp decline to 1.51 million tons in 1963 (7). Starting in the early 1980s, BCO production had increased continuously due to rapid economic growth until 1996 when the Coal Law was in force, by which BCOs were immediately banned. After 1996, the production decreased rather than ceased completely, suggesting that the ban was only partially effective. The poor implementation of environmental laws and regulations is common in China (20). One reason, in this case, was that the ovens were often built and operated by local farmers at locations scattered across rural areas and were difficult to be monitored. In addition, it is technically easy and economically cheap to build a BCO, and the demolished ovens were often rebuilt by the owners shortly after the law enforcement officers left the sites (21). Moreover, the demand gap caused by the ban could not be filled quickly by modern mechanized coke ovens, which usually take years to construct. Therefore, there was even a considerable rebound of illegal BCOs around 2001, when the market demand for coke, and subsequently the coke price, soared (22). Therefore, central and local governments had to endlessly issue a series of executive orders and notifications to reenforce the ban. For example, the National Development and Reform Commission and seven other ministries and agencies coissued a notice on BCO banning in 2004, 8 y after the law was in force (23, 24). Fortunately, BCO production had finally ceased by 2011 after 15 y of cat-and-mouse games between law enforcement and the owners.

In addition to verification of the historical trend from official statistics, geospatial distributions of BCOs over the study years, which are not previously available at all, were able to be reconstructed using the remote sensing data. The detailed spatiotemporal information on production is critical for the emission and transport simulation as well as the exposure and health effect assessment. According to the interpretation results, it was found that there were densely distributed BCOs in Shanxi and Guizhou, the two provinces with the largest coal reserves and production in China (7, 25). This agrees well with those reported in the literature. According to a local study, there were 2,268 BCOs in a single valley in Shanxi in 1986 (26).

Factors Affecting BCO Production. In addition to the effects of the Coal Law, the temporal variation in BCO production was driven by market demand for coke. For example, steel production had jumped from 35.6 million tons in 1981 to over 100 million tons in 1996 (27–29), resulting in a rapid increase of BCO production during that period. Although steel production had continuously increased by a factor of 8 since 1996, reaching 823 million tons in 2014 (27–29), BCO production decreased due to the implementation of the Coal Law. For the purpose of evaluating the effect of the Coal Law, it is necessary to project hypothetical BCO production based on key economic parameters assuming that there was no such law at all. To quantify the factors affecting BCO production, a number of macro- and micro-socioeconomic factors were statistically tested using data before 1996. Among the 12 variables tested, including gross domestic product (GDP), per capita income, productions of steel, coal, and coke and prices of steel and coke, significantly positive correlations were found between BCO production and fine coal production ($P = 0.000$), total coke production ($P = 0.011$), and GDP ($P = 0.091$). The dependence on the producer's price index for coke was also revealed, although this was slightly less significant ($P = 0.056$). Coke production and price directly reflect the market demand, while GDP and coal production are primary driving forces for coke demand. The correlations are no longer significant when the data after 1996 are included, indicating the interference of the Coal Law with the supply–demand relationship. Accordingly, a regression model was developed based on the pre-1996 data. Since the important variables identified by the bivariate correlations are often correlated to one another, a stepwise regression analysis was conducted to develop the following model for predicting BCO production (P_{BCO}, million tons per year):

$$P_{BCO} = 0.959\,P_{coke} - 0.152\,P_{coal} - 0.393\,P_{steel} - 0.775\,P_i + 170.4,\quad R^2_{adj} = 0.98,$$

where P_{coke} (10^4 ton), P_{coal} (10^4 ton), and P_{steel} (10^4 ton) are the production of coke, coal, and steel, respectively, and P_i is the producer's price index for coke. The four independent variables and the intercept are significant at P values of 0.00, 0.012, 0.005, 0.004, and 0.003, and 98% of the variation is accounted for in the model. The model-predicted annual BCO productions are plotted against the officially reported data for the period from 1982 to 1996 in Fig. 2*A*, showing good agreement.

The model was then applied to project the hypothetical BCO production after 1996 assuming that the Coal Law was never in place. The results are compared with actual annual production data in Fig. 2*B*, and the effects of the Coal Law on annual coke production can be quantified by the differences between the predicted and real coke productions. As shown in the figure, the two lines overlapped before 2003 and moved in totally different

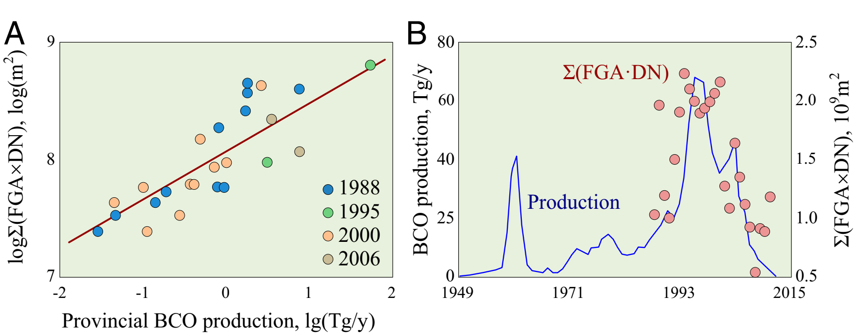

Fig. 1. (*A*) The linear relationship between the BCO production based on government statistics and the sum of products of fire grid areas (FGAs) (in square kilometers) and DNs from Landsat-5 (FGA-DN). (*B*) Time trend of the BCO production based on government statistics (line) and the FGA-DN (dots).

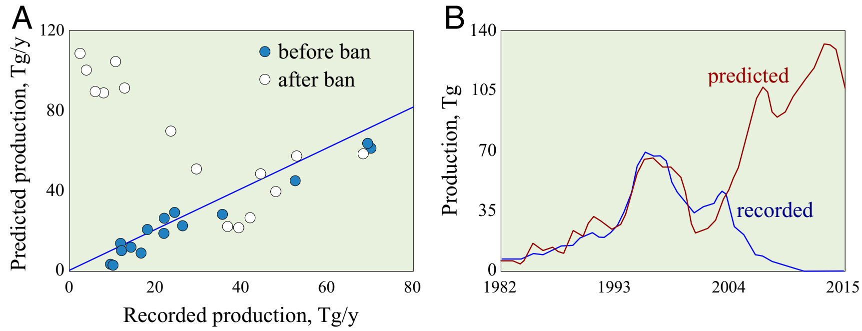

Fig. 2. (*A*) Comparison between the predicted and recorded coke productions. The prediction was based on the data before the ban (blue symbol), while most data after the ban (white symbol) deviate from the 1:1 line. (*B*) Time trend of beehive coke production from 1980 to 2015 including the true production (black line) and model-predicted production assuming there was no ban (red line).

directions afterward, indicating that the decrease from 1997 to 2003 was driven by economic factors, rather than the legislation. Significant influence was shown since 2003. The BCO production would increase dramatically after 2003 if there was no ban at all, driven by rapid increases of coke, coal, and steel production, as well as by the soaring coke price. For example, the coke price jumped from 450 RMB/ton in 2002 to 1,200 RMB/ton in 2003 and even reached 3,300 RMB/ton in 2008 (30–32). In reality, the BCO production decreased compared with the hypothetical trend due to the ban. The differences between the real production and the hypothetical production without the influence of the Coal Law increased continuously after 1996 and reached 131 million tons in 2014, which is almost twice the peak production in 1996 (66.9 million tons). Over the entire period from 1997 to 2015, the cumulative reduction in BCO production due to the ban was as high as 1,140 million tons.

BaP Emissions from BCOs With and Without the Ban. Without any improvement literally in terms of emission control, the EFs of BCO did not change over decades. In contrast, the EFs of modern mechanized coke ovens have decreased over years when the technology was continuously improved and better emission control facilities were installed under increasingly strict regulations. As a result, a general decreasing trend of the EFs of BaP for non-BCO sources was reported in the literature (11). For example, the median EF of BaP measured before 1997 was 468 ng/ton(coke) with a maximum value of 3,208 ng/ton(coke) recorded. After 1997, however, the reported EFs were all less than 160 ng/ton(coke) with a median value of 26 ng/ton(coke) (11).

During the study period, annual BaP emissions from BCOs followed the same trend as BCO production, increasing an order of magnitude from 0.11 Gg in 1982 to 1.03 Gg in 1995, declining after the peak year of 1996, and finally disappearing by 2011. On the other hand, BaP emissions from mechanized coke ovens depend on both the total production and EFs. Since the decreasing trend in EFs was overcompensated by the rapid increase in production, especially after BCOs began to be phased out, the emissions increase accelerated after 2002. The relative contributions of BCOs to the annual BaP emissions from the coke industry varied from 75.5 to 94.7% before 2002 and fell steeply afterward. Such a rapid decline was obviously driven by the implementation of the Coal Law, although with more than a decade lag time. An overall result was that the total BaP emission from the coke industry decreased from 1.09 Gg in 1995 to 0.22 Gg in 2011. As discussed above, if the ban had not occurred, instead of decreasing, the coke production from BCOs would have increased to 107 million tons in 2015 driven by economic development and market demand for coke, given that there was never a Coal Law. If this was the case, the annual BaP emissions from BCOs would have reached as high as 1.63 Gg in 2015, 58% higher than the peak value of 1.03 Gg in 1995. Consequently, the cumulative reduction of BaP emissions from BCOs during the period from 1997 to 2015 was 17.4 Gg, equivalent to 16 times the total annual emissions from coke production during the peak year around 1995–1996.

By using the satellite images, the geospatial distributions of annual coke production and consequently BaP emissions in mainland China were calculated for individual years from 1982 to 2010. As one of the provinces with the richest coal reserves, Shanxi had the largest number of BCOs and the highest BaP emission densities for all years. For example, the coke production from BCOs in Shanxi accounted for 43% of the national total in 1988, and the ratio increased to 85% in 1995, indicating the fastest growth of BCOs in that province (7). The emissions in eastern provinces including Hebei and Shandong actually decreased even before the Coal Law came into force. Although Guizhou ranked immediately after Shanxi in the number of BCOs as well as BaP emissions from BCOs, it was a distant second, contributing only 5.6% of the BCO production in 1995 (16). The BaP emissions from BCOs followed a similar spatial pattern as locations of BCOs, with slight differences among years. After the Coal Law was enforced in 1996, the relative contribution of BaP emission from BCOs in Shanxi compared with the total BaP emissions from all BCOs in the country actually decreased, and a spreading of BCOs to neighboring provinces can be seen. One explanation for this phenomenon was that the measures taken in Shanxi were stricter than those in other provinces after the Coal Law was enacted in 1996 (19).

Effect of the Ban on Population Exposure to BaP. The majority of BCOs were located in a few provinces, and those in Shanxi and Guizhou contributed 79.9% and 5.6% to the total BaP emission from BCOs in 1995 (16). After being emitted to the air, however, BaP can be transported long distance and spread to vast surrounding areas, which was quantified by an atmospheric chemical transport model in this study. The model calculated the annual mean BaP concentrations originating from the emissions of BCOs in ambient air at ground level for all study years. In addition to Shanxi and Guizhou, where the majority of BCOs were located, the neighboring provinces of Inner Mongolia, Hebai, Shandong, Henan, and Sichuan were severely affected, especially in the mid-1990s. Since eastern China is under a strong influence of the East Asian monsoon, the regions to the northwest and southeast of Shanxi were strongly affected in winter and summer, respectively. The regions heavily affected by the emissions of BaP from BCOs were mainly in eastern China, especially in northern and southwestern China, where most people live. The influence was intensified by the overlap of ambient air BaP concentrations and population.

In 1996, the peak BCO production year, the mean incremental exposure concentration of BaP from BCOs was 1,150 ng/g

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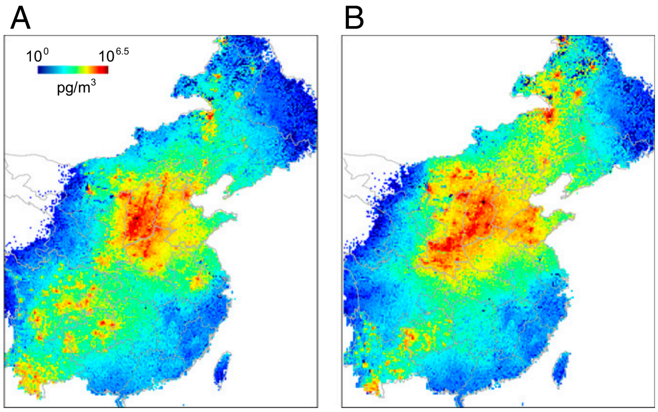

Fig. 3. Spatial distributions of the population-weighted exposure concentrations of BaP originally from BCOs in eastern China in real case of 1996 (*A*) and the assumed no-ban scenario in 2015 (*B*).

nationwide. The incremental exposure had decreased after the ban in 1996 and totally terminated by 2011. If, however, the ban had never been implemented, BCO production would be only affected by the market and the mean incremental exposure concentrations of ambient air BaP originating from BCO production would be 1,970 ng/g in China in 2015, significantly higher than that in 1996. The largest increases would occur in the southeast provinces of Sichuan, Guizhou, and Yunnan, in addition to Shanxi. For example, mean BaP exposure concentration attributable to BCO would increase from 1.15 μg/g in 1996 to 1.97 μg/g in 2015 in Shanxi. Fig. 3 shows spatial distributions of the BaP exposure concentrations in eastern China in the peak emission year of 1996 and the assumed no-ban scenario in 2015. If there was no ban, the region severely affected by BCO would expand, especially Shaanxi where more coal mines have been in operation in recent years.

Health Benefit of the BCO Banning. To evaluate the health impacts of BCO production in the past, the benefits of the Coal Law, and the trade-off resulting from poor implementation, the incremental lifetime cancer risk (ILCR) of the Chinese population induced by the exposure to ambient air BaP originating from BCO emissions was quantified. We used BaP as an indicator of risk due to exposure to all PAH mixtures, following the method described in a previous study (33). The ILCR in the peak risk year (1997) was calculated to be 1.81×10^{-5}, contributing 20.8% of the total lung cancer risk caused by ambient air PAHs from all sources in mainland China (33). According to the temporal trend shown in Fig. 4*A*, the relative contributions of BCOs to the total PAH-induced ILCR was only 4.8% in the early 1980s. Starting from 1992, coke production and PAH emissions from BCO soared, driven by the growing demands in both domestic and international markets (19). The existing mechanized coke production facilities could not support such a sudden change in the market, and BCOs, which can be put into production practically in no time (34), filled the demand gap. As a result, the relative contributions of BCOs to the ILCR increased from 9.4% in 1992 to 20.8% in 1995. After the Coal Law came into force in 1996, the relative contribution decreased significantly and finally vanished in 2011. This reduction was one of the major reasons for the fast decrease in the PAH-associated ILCR in China (33). Still, the implementation of the Coal Law was poor and the BCO ban was not completely realized until 2011, 15 y after the Coal Law was enforced. Over the entire study period from 1982 to 2015, the cumulative excess lung cancer cases induced by BCO production was ∼3,500 (±1,500 as SD). If the ban has never been implemented, BCO production would certainly have soared after 1996. The ILCR would have increased continuously and reached 3.67×10^{-5} in 2013 (Fig. 4*B*). Accordingly, the cumulative excess lung cancer cases from 1982 to 2015 would be 9,290 (±4,300), 165% higher than 3,500. On the other hand, if the ban had been immediately implemented in 1997, the cumulative total cases would have been reduced to 1,500 (±620), a 57% reduction compared with what actually occurred. Therefore, the role of environmental legislation and implementation are well demonstrated.

To quantify health benefits from the ban, the frequency distributions of ILCR caused by ambient air PAHs from all sources in 2015 is shown in Fig. 5 for a real situation and a hypothetical scenario with no ban. The log-normally distributed ILCR are log-transformed. The distributions of the log-transformed ILCR are bimodally distributed, and the air populations to the right of the graph represent the eastern population under the impacts of severe pollution. It appears that the ban caused a significant shift of this population toward the left. Because of the ban, the populations facing the excess lung cancer case frequencies exceeding 10^{-5} and 10^{-4} in 2015 were reduced by 24% and 76% from 15% and 0.72% to 11% and 0.17%, respectively, showing great health benefits particularly to the high-risk population.

Based on the rebuilt spatiotemporal distribution of BCOs, health impact associated with the activity was able to be quantified in this study in the context of the BCO ban by the Coal Law and the implementation of the ban. The similar approach can be applied to assess the consequences of many other activities. Such quantitative evaluation combined with cost–benefit analysis are urgently needed in China as well as other transition economies, where many pollution control actions are either accomplished, ongoing, or planned, without thorough evaluation. One limitation of the study is that only the exposure to BaP in the ambient environment was taken into consideration, which led to certain uncertainty. Unfortunately, it is difficult to model BaP concentrations in indoor air on a regional scale at this stage due to data gaps, and the issue needs to be addressed in the future.

Methodology

BCO Statistics. Annual coke production from BCOs in China was collected from relevant yearbooks (7, 16, 25, 27–29). Limited data at the provincial level

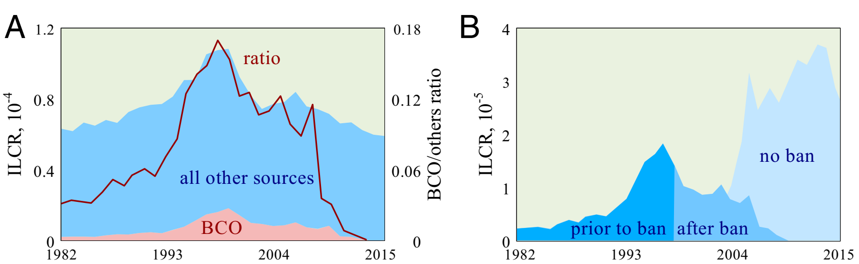

Fig. 4. (*A*) Temporal trends of the ILCR induced by exposure to BaP from BCOs and BaP from all other sources (areas) and the ratio between the two (line). (*B*) The trend of ILCR induced by exposure to BaP from the BCO sources for real case (before and after the ban) and the no-ban scenario.

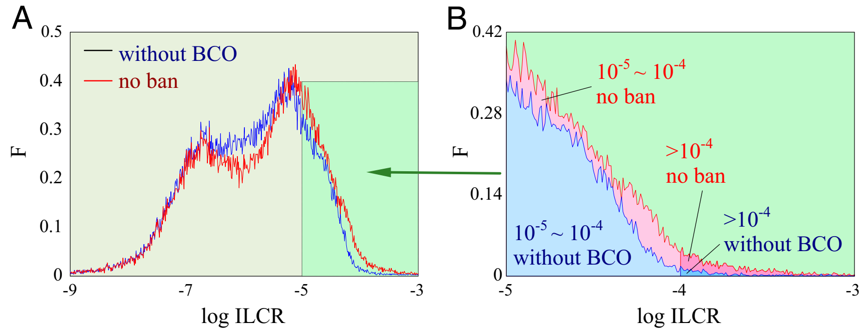

Fig. 5. Comparison between frequency distributions of log-transformed ILCR associated with BaP from all sources in 2015 for the real situation and a hypothetical scenario with no BCO ban. (*A*) Over a range of logILCR from −9 to −3; and (*B*) zoomed in over a range of logILCR from −5 to −3.

were also collected from local yearbooks and papers published previously (15, 16, 31, 32, 34). Although the spatial information about BCOs is not available in the statistics, the statistics were used to validate and calibrate the annual production based on satellite image interpretation.

Remote Sensing Images and Interpretation. Landsat images from 1987 to 2011 were used. It was reported that the TM7 channel was the most sensitive band to the temperature of BCOs (950–1,200 °C) followed by the TM5 channel (18). The grids with BCOs in operation were extracted using TM751 and TM721 band composition technology developed by Kong against the background of the Landsat-5 data (18). As a typical example, BCOs can be seen as the red and yellow grids in Fig. 6*A*. Because more than one BCOs often existed in a single pixel, the procedure was further improved by using the DN values of the grids as identified by manual interpretation. The reclassification of grids with or without BCOs was based on the ENVI decision tree. With all BCOs demolished by the end of 2010, ground truthing was no longer feasible for this study. Fortunately, a similar approach had been applied to monitor BCOs in southeastern Shanxi in a previous study, and the result of thorough ground truthing confirmed that more than 90% of the identified BCOs could be verified (18). Moreover, the BCO location data were further supported by the good agreement between the identified BCO grids and the officially recorded BCO coke production. Without remote sensing data available before 1987, during which the production was relatively low, it is assumed that the spatial distribution patterns of BCOs had not changed before 1987. As an example, Fig. 6*B* shows the distribution of BCOs in 1995, revealing densely distributed BCOs in Shanxi and Guizhou.

Emission Estimation. Gridded emissions of BaP from all activities and total coke production in mainland China were from the data reported by Shen et al. (11). A global BaP emission inventory with 0.1° × 0.1° spatial resolution and monthly temporal resolution can be downloaded free of charge at inventory.pku.edu.cn. In this study, emissions from BCO production were calculated as the products of BCO coke production and EFs of BaP for BCOs from our database (11). It was assumed that there is no significant seasonality in the production of coke, and the annual BaP emissions from BCOs were evenly allocated to individual days.

Atmospheric Transport Modeling. The atmospheric transport of BaP was modeled using CanMETOP (Canadian Model for Environmental Transport of Organochlorine Pesticides) (35). The following four emission scenarios were developed to simulate BaP concentrations in ambient air so the contributions of BCOs and the effects of the Coal Law and its implementation could be evaluated: (*i*) emissions from all sources, including BCOs, for the period from 1982 to 2015; (*ii*) emissions from all sources, except those from BCOs, for a period from 1982 to 2010 (there were not emissions from BCOs after 2010); (*iii*) all emissions, including those from BCOs, which were predicted using a regression model assuming that there was no ban of BCOs, from 1997 to 2015; and (*iv*) emissions from all sources, assuming the ban was completely implemented immediately after the Coal Law was enacted and that the emissions from BCOs completely disappeared by the end of 1996. Based on the differences between the scenarios, the environmental and health impacts of BCOs, the BCO ban, and the implementation of the Coal Law were quantified. The model grid was 24 × 24 km^2, and the calculated ambient air BaP concentrations were downscaled to 0.1° × 0.1°. The exact same model and the downscaling procedure were satisfactorily validated previously, and a detailed model description can be found in the literature (11, 12).

Lung Cancer Risk Assessment. The health risks due to population exposure to ambient BaP were assessed using the same approach adopted by Shen et al. (33). In brief, the ILCR was derived as the product of the lifetime average daily doses (LADD) and cancer slope factor (CSF). An overall susceptibility (SUS) term was also incorporated into the calculation to quantify susceptibility in the ILCR for lung cancer (36). The parameters, including LADD, CSF, SUS, inhalation rate, body weight, and life expediency, were either from the chemical transport model or follow those reported by Shen et al. (11) for the Chinese population.

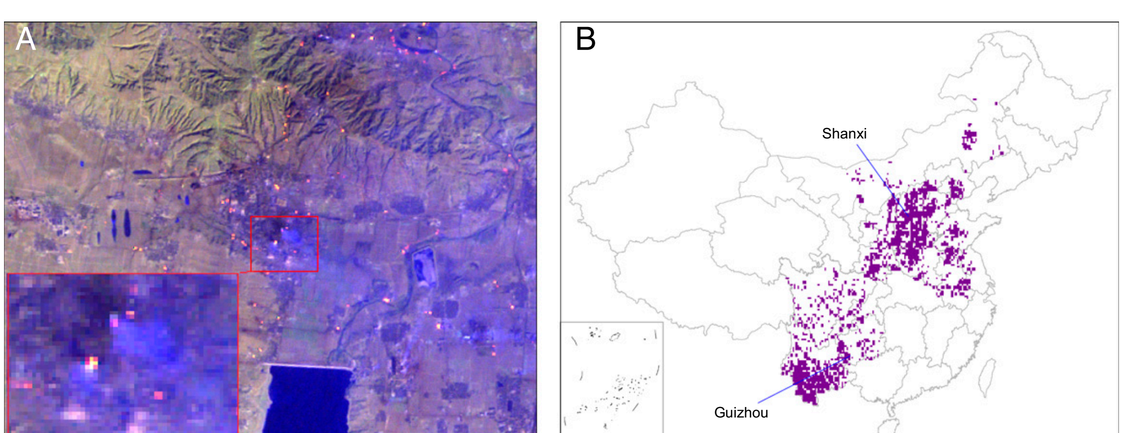

Fig. 6. TM751 and TM721 band composition based on Landsat-5 remote sensing images showing the BCOs in the area as yellow-red grids (*A*) and geospatial distribution of BCOs as fire spots from remote sensing images in mainland China in 1995 (*B*).

The overall uncertainty of the calculation was quantified using a Monte Carlo simulation. The output distribution was created after 1,000 calculations with inputs randomly generated from a priori uncertainty distributions with given coefficients of variation (CVs). The CVs of CSF (0.38) and the distributions of inhalation rate, body weight, age, life expectancy, and GeneSus were derived from Shen et al. (33). The age-sensitivity factor was valued at 10, 2, and 1 for the age groups of <2, 2–16, and >16 y, respectively (37). SPSS 23.0 (38) was used for statistical tests, including stepwise multivariate regress and correlation analysis with a significance level of 0.05. The classification, strength information extraction, and spatial presentation of the remote sensing images were conducted using ENVI5.0 (39) and ArcGIS10.0 (40). Excel 2010 (41) and Matlab R2016b (42) were applied for data processing and Monte Carlo simulations.

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