Environmental Science & Technology Letters

Letter

Cite This: Environ. Sci. Technol. Lett. 2019, 6, 473−478

pubs.acs.org/journal/estlcu

Bottom-Up Estimates of Coal Mine Methane Emissions in China: A Gridded Inventory, Emission Factors, and Trends

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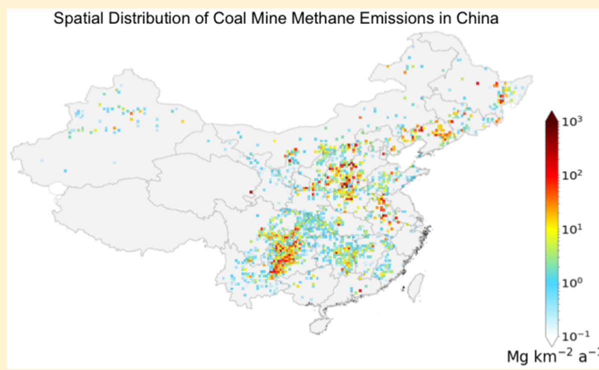
Supporting Information

ABSTRACT: China has large but uncertain coal mine methane (CMM) emissions. Inverse modeling (top-down) analyses of atmospheric methane observations can help improve the emission estimates but require reliable emission patterns as prior information. To serve this urgent need, we developed a high-resolution (0.25° × 0.25°) methane emission inventory for China's coal mining using a recent publicly available database of more than 10000 coal mines in China for 2011. This number of coal mines is 25 and 2.5 times, respectively, more than the number available in the EDGAR v4.2 and EDGAR v4.3.2 gridded global inventories, which have been extensively used in past inverse analyses. Our inventory shows large differences with the EDGAR v4.2 as well as its more recent version, EDGAR v4.3.2. Our results suggest that China's CMM emissions have been decreasing since 2012 on the basis of coal mining activities and assuming time-invariant emission factors but that regional trends differ greatly. Use of our inventory as prior information in future inverse modeling analyses can help better quantify CMM emissions as well as more confidently guide the future mitigation of coal to gas in China.



INTRODUCTION

China is the largest producer of coal in the world. China's coal mine methane (CMM) emissions are a major anthropogenic source in the global methane budget but are poorly quantified.[1,2] The most recent CMM emissions in China reported to the United Nations Framework Convention on Climate Change (UNFCCC) are 23.8 Tg of CH_4 year^{-1} for 2012, accounting for >60% of the reported global CMM emissions, while estimates from independent bottom-up inventories[3−7] vary significantly from 14 to 28 Tg of CH_4 year^{-1}.

Inverse modeling (top-down) analyses of atmospheric methane observations can help improve the estimates but require an accurate spatial distribution of emissions as prior knowledge.[8] National emission inventories reported to the UNFCCC often do not include spatial information. Past inverse modeling analyses[9−13] have relied on the Emission Database for Global Atmospheric Research (EDGAR) gridded global inventories,[3,7] which contains information about 400−4000 coal mines in China, while the Chinese State Administration of Coal Mine Safety (SACMS) reported more than 10000 operating coal mines in 2011.[14] Incomplete prior information about coal mine locations may bias top-down estimates and their interpretations and mislead the assessment of China's CMM mitigation policy.[13]

Gridded emission inventories with an improved spatial distribution of methane emissions have been developed for Australia,[15] Canada,[16] Mexico,[16] the United Kingdom,[17] Switzerland,[18] the United States,[19] and the global oil/gas sector.[20] Results from Maasakkers et al.,[19] Sheng et al.,[16] and Scarpelli et al.[20] show large differences with the EDGAR v4.2 and v4.3.2 inventories for the oil/gas sector. The regional inversion in the Southeast United States from Sheng et al.[21] using the improved prior estimates of Maasakkers et al.[19] supports the Environmental Protection Agency (EPA) bottom-up inventory,[22] while previous inversion studies relying on the EDGAR v4.2 inventory have suggested that the EPA inventory is too low.

Here we present a 0.25° × 0.25° resolution inventory of China's CMM emissions for 2011 based on the most recent publicly available SACMS database, including more than

Received: May 14, 2019
Revised: May 29, 2019
Accepted: May 31, 2019
Published: May 31, 2019

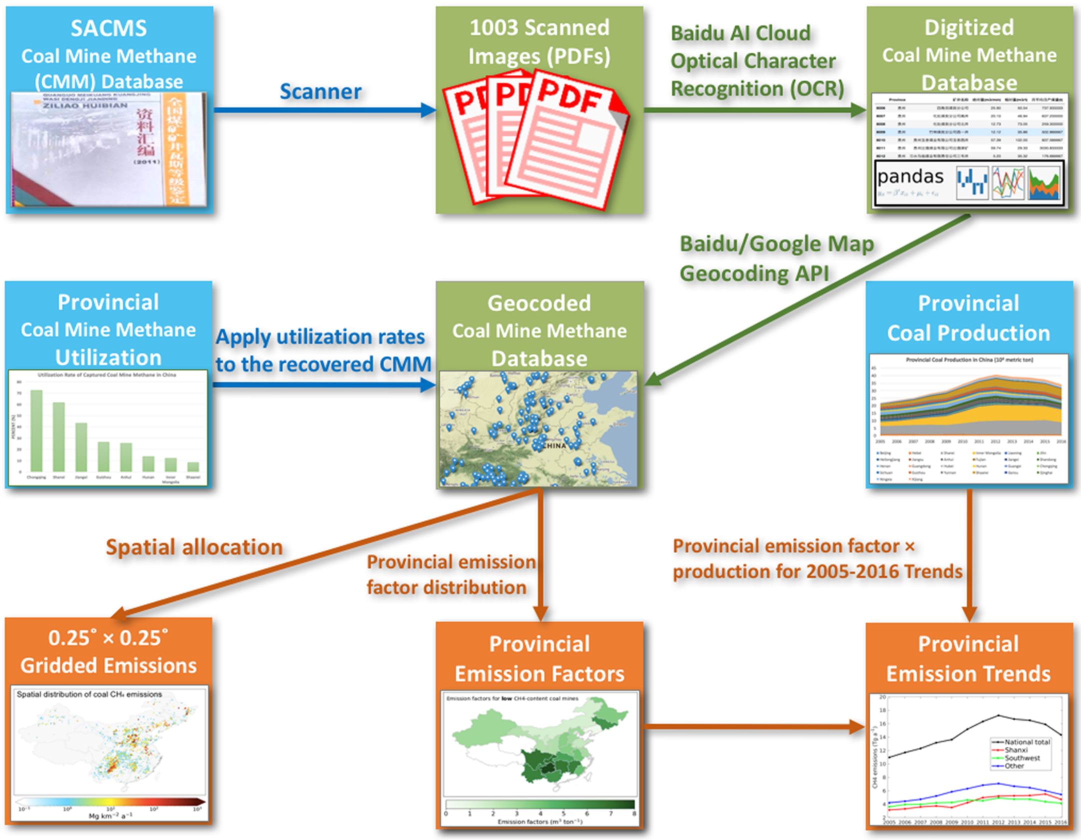


Figure 1. Diagram of steps for estimating coal mine methane emissions in China. The databases, methods, and results of this study are indicated by the colors blue, green, and orange, respectively.

10000 coal mines, to serve the urgent need to better quantify China's methane emissions on a finer scale and to more confidently attribute CMM contributions and guide CMM mitigation policy.

■ MATERIALS AND METHODS

The databases and methods used in this study are depicted in Figure 1. We start from the database of the National Coal Mine Methane Level Identification for 2011 compiled by SACMS.[14] All coal mines in China are required to report their methane emissions to SACMS for safety evaluations, but emission factors and production are not mandatory. The SACMS database covers 10963 coal mines in 26 coal-producing provinces in mainland China, in which 10093 operating mines measured and reported their methane emissions (total of 53000 m^3 min^{-1}) and 1046 mines reported their captured methane (total of 15000 m^3 min^{-1}), which can be used in natural gas applications. According to the SACMS database, each coal mine measured its emissions by continuously monitoring its ventilation and degasification systems during its annual safety evaluation (2−3 months). The number of coal mines in the SACMS database is 25 and 2.5 times more than that available in the EDGAR v4.2 and EDGAR v4.3.2 gridded global inventories,[3,7] respectively. The coal mine database[23] used in EDGAR v4.3.2 covers 4243 coal mines and 36% of China's coal production in 2011 but is strongly biased toward Shanxi province. It excessively includes 3347 coal mines in Shanxi (>3 times the number of Shanxi coal mines in the SACMS database), while it represents only 10% of coal mines and 24% of coal production for the rest of the country (see Figure S1).

The national total for 2011 derived from the SACMS database is 16.7 Tg of CH_4 $year^{-1}$ by applying the IPCC conversion factor of 0.67 kg m^{-3} and the provincial level utilization rate for captured methane (see Figure S2). The SACMS labels coal mines either high CH_4 content (emissions of >40 m^3 min^{-1} or emission factors of >10 m^3 Mg^{-1}) or low CH_4 content. High-CH_4 content mines account for 27% of the total coal mines but contribute 75% of the total emissions. The reported emissions from the SACMS database may have large uncertainties, but the derived total emissions are in the range of 13−30 Tg of CH_4 $year^{-1}$ from the 2000−2012 Global Carbon Project,[2] comparable to the independent bottom-up estimates (16.1−17.7 Tg of CH_4 $year^{-1}$)[5,6] using provincial level emissions factors, but much lower than those (20.5−28.4 Tg of CH_4 $year^{-1}$)[3,7] using generic emission factors.

The original SACMS database is a paperback book. We scan it into 1003 image files and apply the Optical Character Recognition (OCR) algorithm (with an accuracy of >99%) provided by Baidu AI Open Platform[24] to generate a digitized database. We manually verify the OCR results with the top 100 methane-emitting coal mines (accounting for 32% of total emissions) and find no differences. The SACMS database provides no geological coordinates of coal mines. To spatially allocate emissions to mine facilities, we use coal mine names in the database and apply the geocoding algorithms from Baidu Map Platform[25] to retrieve coal mine locations. We find that the accuracy is typically within 0.25° (i.e., town or village level) by comparing the Baidu results with those from Google Maps

DOI: 10.1021/acs.estlett.9b00294
Environ. Sci. Technol. Lett. 2019, 6, 473−478

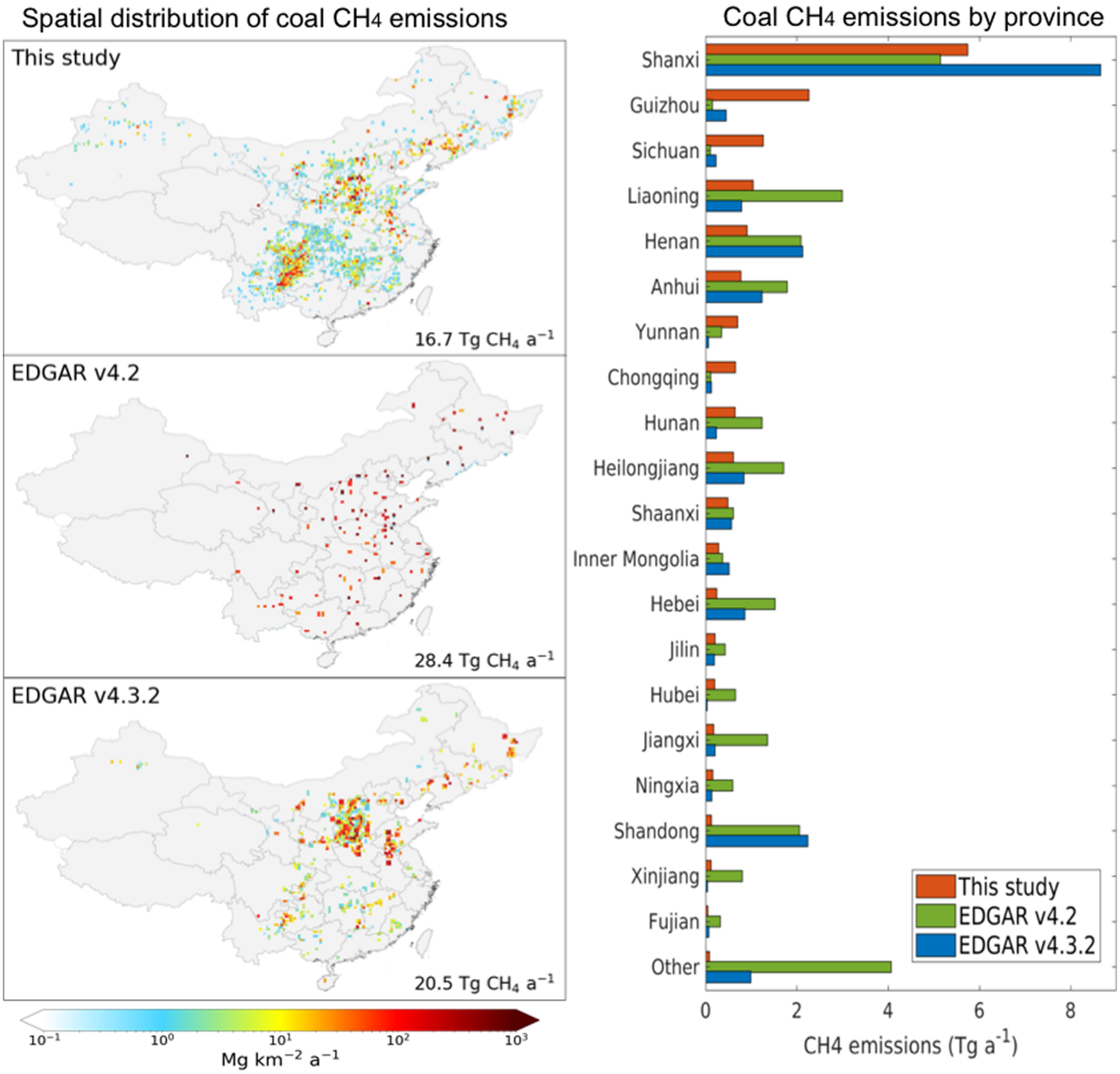


Figure 2. China's coal mine methane emissions for 2011. The left panel shows the spatial distributions of China's coal mine methane emissions at 0.25° × 0.25° resolution from this study, EDGAR v4.2, and EDGAR v4.3.2. The right panel shows coal methane emissions from the top 20 CMM-emitting provinces and the rest of China ("Other").

Platform,[26] which are offset by 50−500 m because of restrictions on geographic data in China.[27] We manually verify the locations of the top 100 emitters and find that most spatial errors are within 0.15° and the maximum error is 0.21° (see the Supporting Information for details). To minimize errors due to imprecise locations, we thus limit our gridded inventory at 0.25° × 0.25° resolution, which is sufficient for regional studies. At such a resolution, we also find that emission patterns can likely be applied to more recent years (see Figure S4).

We derive region-specific emission factors based on 8027 reported emission factors (EFs) in the SACMS database. We assume that emission factors for a given province follow the same distribution because of the similarities in local practices and coal mine basins, which are well separated by province.[28] We first adjust individual emission factors accordingly if capture and utilization of methane are reported. Then we calculate the density distribution of the adjusted emission factors for low- and high-CH_4 content mines at the provincial level. This density distribution is facility-normalized regardless of its emissions or production because emission factors depend on only local practices (i.e., utilization of CMM), the underground structure of the coal mine layers, and the type of coal.[2,7] The mean of the density distribution of emission factors for each province is applied to production data from 2005 to 2016 (see Table S1) to calculate provincial CMM emission trends. The resulting error standard deviations are applied to all mines in the corresponding province to derive

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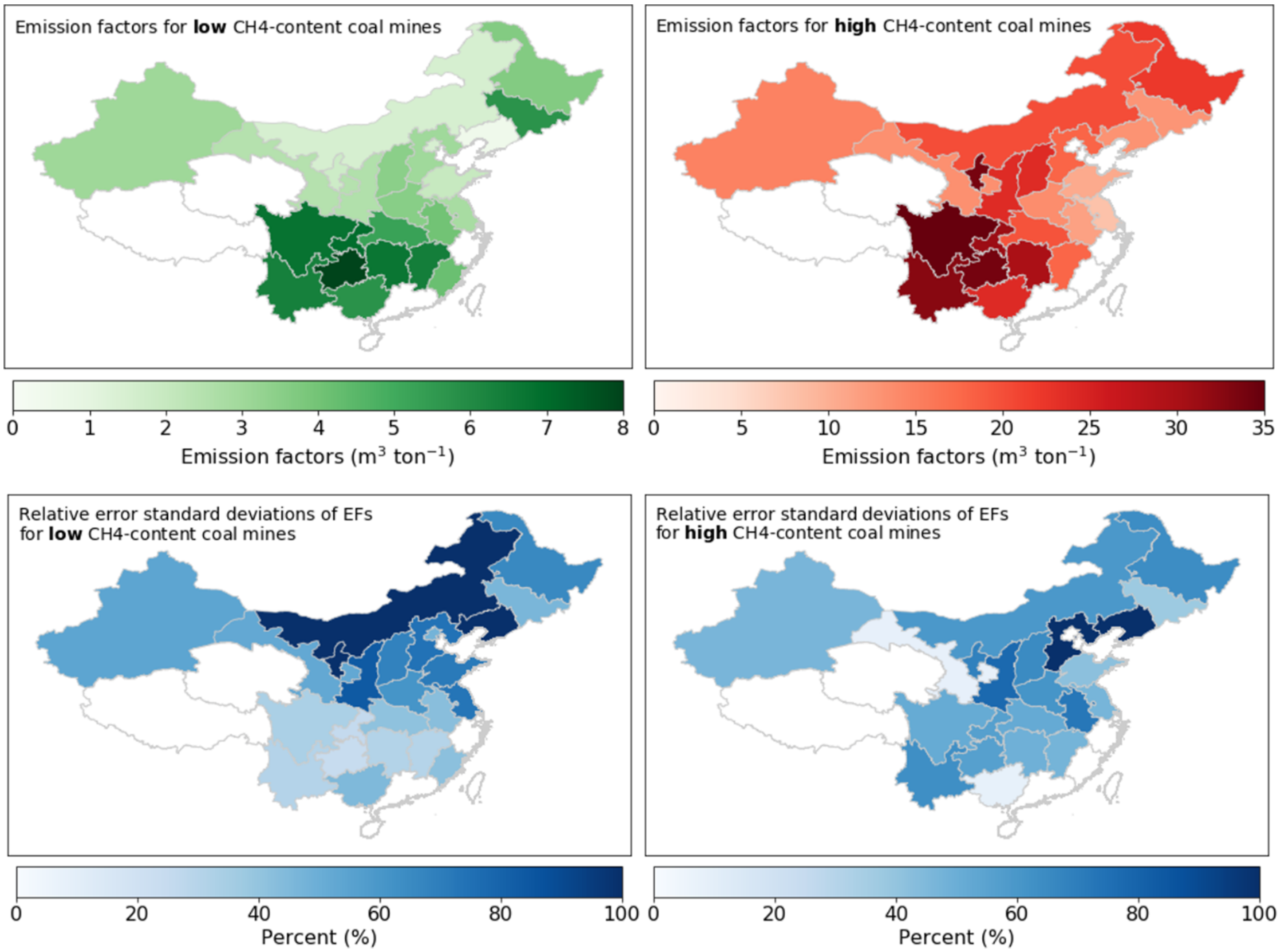

Figure 3. China's coal methane emission factors and their uncertainties. Top panels show the spatial distribution of emission factors at the provincial level for low- and high-CH_4 content coal mines. Bottom panels show the uncertainties (relative error standard deviations) of the emission factors for low- and high-CH_4 content coal mines. White areas indicate that no data are available.

uncertainties in each grid cells, which can serve as prior errors in inversions, though they may not fully account for uncertainties in the SACMS database.

RESULTS AND DISCUSSION

Figure 2 (left panel) shows the calculated spatial distribution of China's CMM emissions for 2011 at 0.25° × 0.25° resolution derived from 10093 coal mines reporting to SACMS. Also shown are the results from the EDGAR v4.2 inventory,[3] which has been widely used as prior information in past inverse analyses,[9−13] and its recently updated version, EDGAR v4.3.2.[7] There are significant differences in spatial patterns between our work and the two EDGAR inventories. There are only ~400 Chinese coal mines available in EDGAR v4.2[7] (<4% of the SACMS database). Allocation of national total emissions to its limited mine locations leads to incorrect spatial patterns and artifactual emission hot spots. EDGAR v4.3.2 significantly improves on v4.2 by using a database of 4243 coal mines from Liu et al.[23] However, EDGAR v4.3.2 still tends to underestimate emissions in the north, overestimate them in the east, and miss most of them in the southwest when compared to our newly derived inventory. In addition to incomplete information about coal mine locations, this difference may also be due to a lack of sub-country-specific emission factors for China in EDGAR v4.3.2.[7] These spatial errors will cause an incorrect relative fraction of CMM emissions within the grid box that would bias the analysis of trends and source attribution in inversions.

Figure 2 (right panel) shows the top 20 CMM-emitting provinces in China for 2011 in our inventory and the results from the EDGAR v4.2 and v4.3.2 inventories. In our inventory, Shanxi province is the largest source of CMM emissions in China and contributes 35% of the national total. The southwest (Sichuan, Chongqing, Guizhou, and Yunnan) is also a major source region, accounting for 28% of the national total. Anhui and Liaoning are the provinces that emit the most in the east and north, respectively. The spatial errors in the EDGAR v4.2 and v4.3.2 inventories remain on the provincial level (coarser resolution) as their relative contributions of provinces to CMM emissions differ significantly from ours.

Figure 3 shows the derived spatial distribution of emission factors at the provincial level for low- and high-CH_4 content mines in the SACMS database, along with their uncertainties (relative error standard deviations) that can be used as prior error estimates in the inversion. Emission factors for low- and high-CH_4 content mines in the southwest are the highest, explaining their large emissions despite their relatively small production. The spatial variation in emission factors across the country could be related to different local practices (e.g.,

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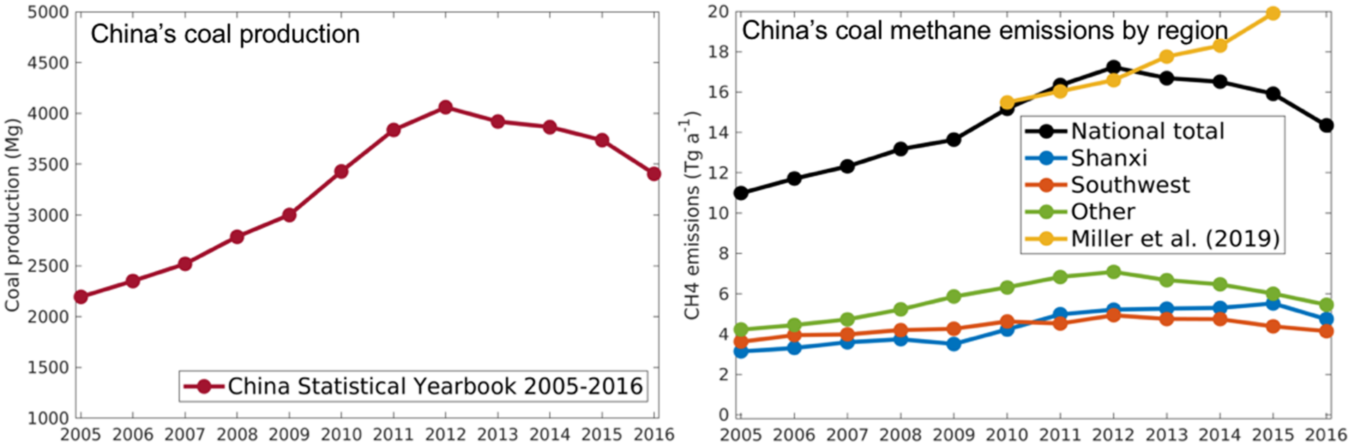

Figure 4. Trends in China's coal activities and emissions from 2005 to 2016. The left panel shows historical coal production from the China Statistical Yearbook (provincial level). The right panel shows emission trends inferred from the provincial level production data and emission factors derived in this study (see the text) for Shanxi province, the southwest region (Chongqing, Guizhou, Sichuan, and Yunnan), and the rest of China ("Other").

utilization of CMM), the underground structure of the coal mine layers, and the type of coal.[2,7] Uncertainties (relative error standard deviations) are relatively small (40−60%) in the south, while uncertainties are the highest in the northern provinces such as Liaoning and Inner Mongolia.

Figure 4 shows China's coal production activities and their methane emissions trends for 2005−2016, along with emission contributions from Shanxi, the southwest region (Sichuan, Chongqing, Guizhou, and Yunnan), and the rest of the country. Here methane emissions are derived from multiplying the coal production data by our 2011 time-invariant emission factors. China's national coal methane emissions have declined since 2012, which is consistent with its coal production activities but deviates from the inversion results of Miller et al.[13] using EDGAR v4.2 as prior information. The emission trend in Shanxi has been continuously increasing from 2006 to 2015. However, the emission trends in the southwest region and the rest of the country slowed in 2010−2011 and have declined since 2012. This seems to conform to China's CMM mitigation policy that closes small township and village coal mines (∼50% of which are in the southwest) and expands production at the largest operators (mainly in Shanxi). Inverse modeling (top-down) analyses without prior information in the regions with concentrated small coal mines (e.g., EDGAR v4.2 in Figure 2) are unlikely to be able to detect the declining emissions from these regions.

CMM emission trends, often not accounted for in previous relevant studies, could play a significant role in understanding net climate benefits of coal-to-gas mitigation policy, which has been debated since the late 1980s.[29−32] The decline of China's CMM emissions inferred in this study would further support a coal-to-gas shift in China, though our results may be limited by the assumption of time-invariant emission factors because some studies suggest that China's CMM EFs could evolve over time, but their trends are being debated.[6,13]

In conclusion, we have developed a gridded inventory of methane emissions from the coal mining sector in China at 0.25° × 0.25° resolution that can serve as prior information in inverse modeling using atmospheric methane observations. Our inventory uses the best available information to derive the spatial distribution of China's CMM emissions, which should constitute an improvement upon existing emission inventories. Our bottom-up analyses also suggest that China's CMM policy has successfully reduced national CMM emissions. This is in contrast with the results from a recent Bayesian inversion,[13] which however is limited by its erroneous prior assumptions of emission patterns (EDGAR v4.2). Future inversions combining satellite and surface network data with our work should improve the estimation of China's CMM emissions and provide a more robust assessment of China's coal-to-gas policy.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.estlett.9b00294.

Chinese coal mine databases, coal mine methane utilization in China, geocoding of the SACMS database, emission patterns in 2011 and 2014, coal production in China, coal mine methane emissions and emission factors in China, and references (PDF)

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Notes

The authors declare no competing financial interest.
The gridded inventory in this study is available at https://forms.gle/NGMXUTfMumMFkMZPA.

■ ACKNOWLEDGMENTS

This work was supported by NASA Grant NNX16AC98G to the Massachusetts Institute of Technology. S.S. was supported by the Harvard Global Institute. Y.Z. was partially supported by the Kravis Scientific Research Fund of the Environmental Defense Fund.

■ REFERENCES

(1) Kirschke, S.; Bousquet, P.; Ciais, P.; Saunois, M.; Canadell, J. G.; Dlugokencky, E. J.; Bergamaschi, P.; Bergmann, D.; Blake, D. R.;

Bruhwiler, L.; et al. Three decades of global methane sources and sinks. *Nat. Geosci.* **2013**, *6*, 813−823.
(2) Saunois, M.; Bousquet, P.; Poulter, B.; Peregon, A.; Ciais, P.; Canadell, J. G.; Dlugokencky, E. J.; Etiope, G.; Bastviken, D.; Houweling, S.; et al. The global methane budget 20002012. *Earth System Science Data* **2016**, *8*, 697−751.
(3) Joint Research Centre (JRC)/Netherlands Environmental Assessment Agency (PBL), European Commission. *Emission Database for Global Atmospheric Research (EDGAR), release version 4.2*; 2011.
(4) Smith, S. J.; Zhou, Y.; Kyle, P.; Wang, H.; Yu, H. *A Community Emissions Data System (CEDS): Emissions For CMIP6 and Beyond*; 2015.
(5) Peng, S.; Piao, S.; Bousquet, P.; Ciais, P.; Li, B.; Lin, X.; Tao, S.; Wang, Z.; Zhang, Y.; Zhou, F. Inventory of anthropogenic methane emissions in mainland China from 1980 to 2010. *Atmos. Chem. Phys.* **2016**, *16*, 14545−14562.
(6) Zhu, T.; Bian, W.; Zhang, S.; Di, P.; Nie, B. An Improved Approach to Estimate Methane Emissions from Coal Mining in China. *Environ. Sci. Technol.* **2017**, *51*, 12072−12080.
(7) Janssens-Maenhout, G.; Crippa, M.; Guizzardi, D.; Muntean, M.; Schaaf, E.; Dentener, F.; Bergamaschi, P.; Pagliari, V.; Olivier, J.; Peters, J.; et al. EDGAR v4.3.2 Global Atlas of the three major Greenhouse Gas Emissions for the period 1970−2012. *Earth System Science Data Discussions* **2019**, 1−52.
(8) Jacob, D. J.; Turner, A. J.; Maasakkers, J. D.; Sheng, J.; Sun, K.; Liu, X.; Chance, K.; Aben, I.; McKeever, J.; Frankenberg, C. Satellite observations of atmospheric methane and their value for quantifying methane emissions. *Atmos. Chem. Phys.* **2016**, *16*, 14371−14396.
(9) Alexe, M.; Bergamaschi, P.; Segers, A.; Detmers, R.; Butz, A.; Hasekamp, O.; Guerlet, S.; Parker, R.; Boesch, H.; Frankenberg, C.; et al. Inverse modelling of CH4 emissions for 20102011 using different satellite retrieval products from GOSAT and SCIAMACHY. *Atmos. Chem. Phys.* **2015**, *15*, 113−133.
(10) Turner, A. J.; Jacob, D. J.; Wecht, K. J.; Maasakkers, J. D.; Lundgren, E.; Andrews, A. E.; Biraud, S. C.; Boesch, H.; Bowman, K. W.; Deutscher, N. M.; et al. Estimating global and North American methane emissions with high spatial resolution using GOSAT satellite data. *Atmos. Chem. Phys.* **2015**, *15*, 7049−7069.
(11) Pandey, S.; Houweling, S.; Krol, M.; Aben, I.; Chevallier, F.; Dlugokencky, E. J.; Gatti, L. V.; Gloor, E.; Miller, J. B.; Detmers, R.; et al. Inverse modeling of GOSAT-retrieved ratios of total column CH_4 and CO_2 for 2009 and 2010. *Atmos. Chem. Phys.* **2016**, *16*, 5043−5062.
(12) Maasakkers, J. D.; Jacob, D. J.; Sulprizio, M. P.; Scarpelli, T. R.; Nesser, H.; Sheng, J.-X.; Zhang, Y.; Hersher, M.; Bloom, A. A.; Bowman, K. W.; et al. Global distribution of methane emissions, emission trends, and OH concentrations and trends inferred from an inversion of GOSAT satellite data for 2010−2015. *Atmos. Chem. Phys. Discuss.* **2019**, 1−36.
(13) Miller, S. M.; Michalak, A. M.; Detmers, R. G.; Hasekamp, O. P.; Bruhwiler, L. M. P.; Schwietzke, S. Chinas coal mine methane regulations have not curbed growing emissions. *Nat. Commun.* **2019**, *10*, 303.
(14) State Administration of Coal Mine Safety. *Compilation of National Coal Mine Gas Level Identification for 2011*; 2012.
(15) Wang, Y.-P.; Bentley, S. T. Development of a spatially explicit inventory of methane emissions from Australia and its verification using atmospheric concentration data. *Atmos. Environ.* **2002**, *36*, 4965−4975.
(16) Sheng, J.-X.; Jacob, D. J.; Maasakkers, J. D.; Sulprizio, M. P.; Zavala-Araiza, D.; Hamburg, S. P. A high-resolution (0.1 × 0.1) inventory of methane emissions from Canadian and Mexican oil and gas systems. *Atmos. Environ.* **2017**, *158*, 211−215.
(17) *National Atmospheric Emissions Inventory*. 2014; http://naei.defra.gov.uk/ (accessed December 12, 2018).
(18) Hiller, R. V.; Bretscher, D.; DelSontro, T.; Diem, T.; Eugster, W.; Henneberger, R.; Hobi, S.; Hodson, E.; Imer, D.; Kreuzer, M.; et al. Anthropogenic and natural methane fluxes in Switzerland synthesized within a spatially explicit inventory. *Biogeosciences* **2014**, *11*, 1941−1959.
(19) Maasakkers, J. D.; Jacob, D. J.; Sulprizio, M. P.; Turner, A. J.; Weitz, M.; Wirth, T.; Hight, C.; DeFigueiredo, M.; Desai, M.; Schmeltz, R.; et al. Gridded National Inventory of U.S. Methane Emissions. *Environ. Sci. Technol.* **2016**, *50*, 13123−13133.
(20) Scarpelli, T.; Jacob, D.; Maasakkers, J.; Sheng, J. X.; Rose, K.; Payer Sulprizio, M.; Worden, J. A Global Gridded Inventory of Methane Emissions from Fuel Exploitation including Oil, Gas, and Coal. *AGU Fall Meeting Abstracts*; American Geophysical Union: Washington, DC, 2018; Vol. *33*.
(21) Sheng, J.-X.; Jacob, D. J.; Turner, A. J.; Maasakkers, J. D.; Sulprizio, M. P.; Bloom, A. A.; Andrews, A. E.; Wunch, D. High-resolution inversion of methane emissions in the Southeast US using SEAC4RS aircraft observations of atmospheric methane: anthropogenic and wetland sources. *Atmos. Chem. Phys.* **2018**, *18*, 6483−6491.
(22) Environmental Protection Agency. *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990−2014*; 2014.
(23) Liu, Z.; Guan, D.; Wei, W.; Davis, S. J.; Ciais, P.; Bai, J.; Peng, S.; Zhang, Q.; Hubacek, K.; Marland, G.; et al. Reduced carbon emission estimates from fossil fuel combustion and cement production in China. *Nature* **2015**, *524*, 335−338.
(24) Baidu AI Open Platform. *Optical Character Recognition (OCR)*; 2018; https://ai.baidu.com/tech/ocr (accessed December 12, 2018).
(25) Baidu Map Platform. *Baidu Map API*; 2018; https://lbsyun.baidu.com/products/products/map (accessed December 12, 2018).
(26) Google Maps Platform. *Google Maps API*; 2018; https://cloud.google.com/maps-platform/maps/ (accessed December 12, 2018).
(27) Wikipedia. *Restrictions on geographic data in China*; 2019; https://en.wikipedia.org/w/index.php?title=Restrictions_on_geographic_data_in_Chinaoldid=894502273 (accessed May 1, 2019).
(28) Dai, S.; Ren, D.; Chou, C.-L.; Finkelman, R. B.; Seredin, V. V.; Zhou, Y. Geochemistry of trace elements in Chinese coals: A review of abundances, genetic types, impacts on human health, and industrial utilization. *Int. J. Coal Geol.* **2012**, *94*, 3−21.
(29) Lelieveld, J.; Crutzen, P. J. Indirect chemical effects of methane on climate warming. *Nature* **1992**, *355*, 339.
(30) Qin, Y.; Edwards, R.; Tong, F.; Mauzerall, D. L. Can Switching from Coal to Shale Gas Bring Net Carbon Reductions to China? *Environ. Sci. Technol.* **2017**, *51*, 2554−2562.
(31) Qin, Y.; Tong, F.; Yang, G.; Mauzerall, D. L. Challenges of using natural gas as a carbon mitigation option in China. *Energy Policy* **2018**, *117*, 457−462.
(32) Tanaka, K.; Cavalett, O.; Collins, W. J.; Cherubini, F. Asserting the climate benefits of the coal-to-gas shift across temporal and spatial scales. *Nat. Clim. Change* **2019**, *9*, 389.

DOI: 10.1021/acs.estlett.9b00294
Environ. Sci. Technol. Lett. 2019, 6, 473−478