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## Decreasing methane emissions from China's coal mining with rebounded coal production

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## LETTER

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E-mail: [zhangbo@cumt.edu.cn](mailto:zhangbo@cumt.edu.cn) and [keli@nuist.edu.cn](mailto:keli@nuist.edu.cn)**Keywords:** methane emissions, coal mining, emission factors, bottom-up inventories, ChinaSupplementary material for this article is available [online](#)**Abstract**

China is the world's largest anthropogenic methane (CH<sub>4</sub>) emitter, with coal mine methane (CMM) as one of the main contributors. However, previous studies have not reached consensus on the magnitude and trend of China's CMM emissions since 2010. Through distribution fitting and Monte Carlo methods, dynamic emission factors (EFs) of CMM at the province-level were derived with high confidence; along with the updated data on surface mining, abandoned coal mines, and methane utilization, we revealed that China's annual CMM emissions were estimated at 20.11 Tg between 2010 and 2019 with a decline of 0.93 Tg yr<sup>-1</sup>. Although coal production was revived in 2017, we found that the growing trend of China's CMM emissions since 2012 were curbed by the previously-overlooked factors including the growth of CMM utilization and coal production from surface mining, and decrease of EFs driven by the closure of high CH<sub>4</sub>-content coal mines and a regional production shift to lower-emission areas.

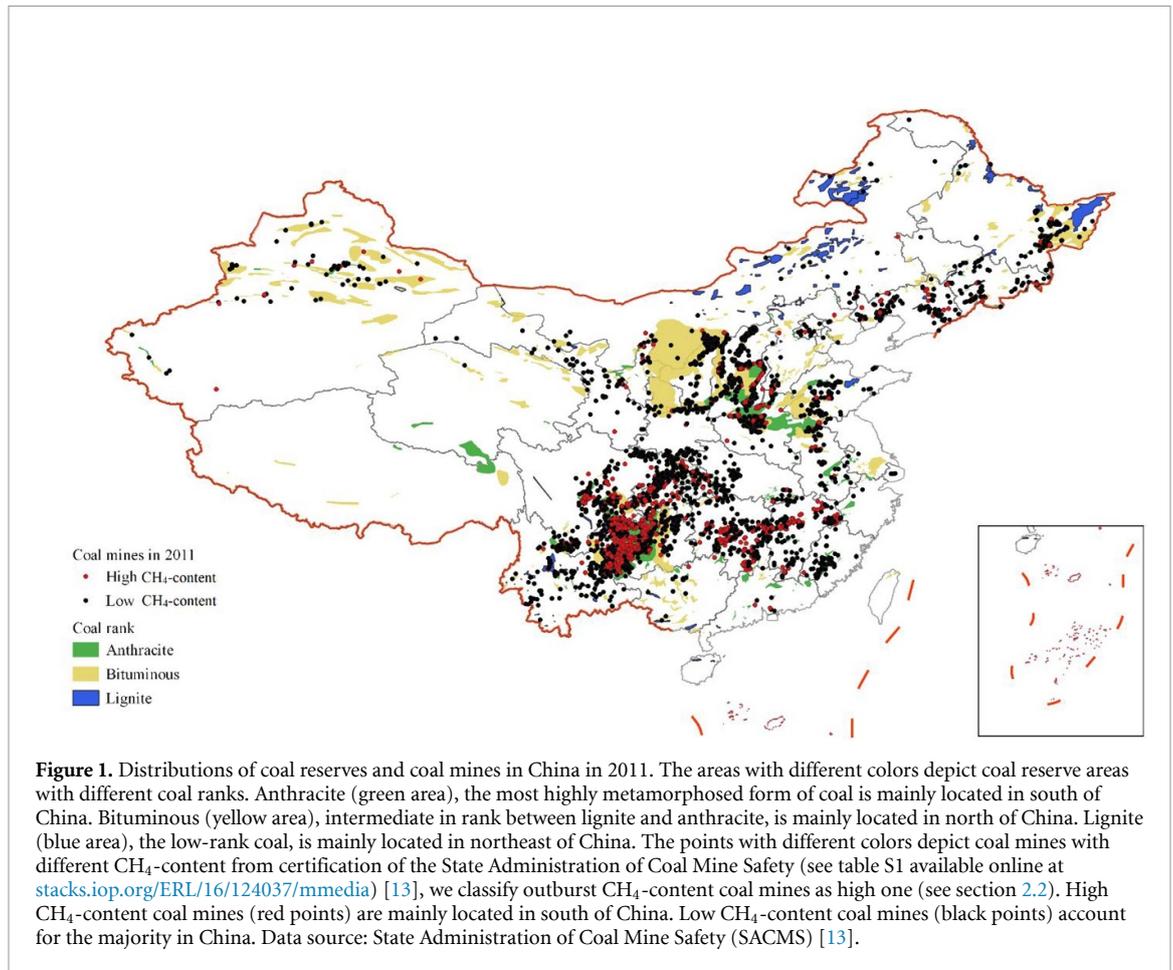
**1. Introduction**

Methane (CH<sub>4</sub>), as a short-lived climate pollutant, has substantial mitigation potential [1, 2]. CH<sub>4</sub> emissions are of increasing concerns, particularly for anthropogenic CH<sub>4</sub> emissions [3–7], of which 12% were attributable to coal mine methane (CMM) emissions globally. As the largest CMM emitter, China was responsible for 44% of global CMM emissions in 2015 [8]. Coal mining in China largely explained the increasing trend in global anthropogenic CH<sub>4</sub> emissions from 2000 to 2012 [9] and the increasing trend in China's CH<sub>4</sub> emissions from 2010 to 2015 [10], and also was recognized as one of the main reasons for the increase of global fossil fuel emissions from 2005 to 2010 [11] and from the period 2000–2006 to 2017 [12].

Coal mines in Mainland China are scattered in 26 provinces and consisted of about 1000 coalfields and

more than 10 000 coal mines in 2011 (figure 1) [13]. The numerous coal mines have various coal ranks, capacities, geological conditions, and mining technologies, which strongly affected the emission factors (EFs) of CMM emissions. The diversity and large number of coal mines necessitate reasonable classification to improve the accuracy of estimating CMM emissions in China.

Moreover, the implementation of CMM utilization policy and coal de-capacity policy have also influenced CMM emissions in China. Methane explosion has caused many fatalities in underground mining in China [14] and removing methane from work area could improve safety during production. As such, the State Council has issued three special regulations on CMM capture and utilization since 2006. In combination with increasing demand of clean energy production and Greenhouse Gas (GHG) emission reduction, the State Council issued concrete targets on



CMM extraction and utilization in the national 12th and 13th five-year plan [15, 16]. To promote the economic benefit of coal industry, the government issued a low efficient coal production capacity phase-out policy in 2010, and a high CH<sub>4</sub>-content with low efficiency coal mines phase-out policy in 2013. In 2016, in order to solve the imbalance between supply and demand, the government issued the opinions of the State Council on reducing overcapacity in the coal industry [17]. These de-capacity policies resulted in a large number of abandoned coal mines in the 2010s. The aforementioned factors have challenged the annual CMM emission estimate in China due to the year-to-year variability. Therefore, the magnitude and trend of China's CMM emissions in the recent decade remains elusive. Previous top-down studies argued that CMM emissions in China were overestimated by China's official government inventory [18, 19] and Community Emissions Data System (CEDs) [20]. Previous bottom-up estimates, including official government inventories, global inventories, and individual studies, fell into a large range from 1980 to 2016 [21]. Moreover, recent studies did not agree on the trend since 2012 [22]. The existing divergencies necessitate a better bottom-up methane emission estimates for China's coal mining.

Previous efforts in the bottom-up methods, to a certain extent, improved the accuracy of China's CMM emission estimates. From the perspective of methodology, different from the EF method, Ju *et al* calculated methane emissions by measuring methane in the original coal seams and then remeasuring methane left after coal mining. However, it is not suitable for large number of coal mines due to the heavy measurement work [23]. From the perspective of data resolution, EFs, which were used to estimate China CMM emissions, have been improved from European averaged EFs [20] to China regional EFs [22, 24]. However, limitations still exist on the coverage of emission sources, the application of activity-data, and the calculation of regional EFs within bottom-up methods.

Firstly, as for coverage of emission sources, abandoned mine methane (AMM) emissions have not been considered in individual studies previously [22, 24–28]. Although AMM emissions were considered in official government inventories [29–32] and global inventories (EDGAR, CEDs) [33, 34], the values of their AMM emission estimates are not publicly available. Secondly, in terms of activity-data, individual studies on China's CMM emissions usually set the proportion of surface mining as a default

value (e.g. 5%) [24–26, 35, 36], or even neglected [22]. Actually, the proportion of surface mining was more than 10% in the 2010s and fluctuated every year [21]. China's official government inventories updated this proportion, however, as a Non-Annex I Party, provided estimates for only four years from 2000 to 2020 [29, 31, 32]. According to the Intergovernmental Panel on Climate Change (IPCC) guidelines [37], CH<sub>4</sub> emission intensity of surface mining is ten times lower than underground mining. Thus, the underestimated portion of surface mining can result in overestimation of CMM emissions. Thirdly, as for regional EFs, the methods to derive them still need to be improved from previous individual studies [24, 27, 38], which will be discussed in detail in section 2. Meanwhile, due to the de-capacity policy, many high emission intensity coal mines were closed. Consequently, static regional EFs in certain years were an imperfect analogue for other years, owing to variation of coal mines. These issues were not properly addressed in previous studies, including both global inventories and individual studies [22].

In this study, to address the limitations of previous studies, based on a bottom-up approach, we produced a comprehensive estimate of historical CH<sub>4</sub> emissions from coal mining in the 2010s and quantified the contribution of different drivers to the changes of emissions. The improvement in national inventory of CMM emissions in China will be fourfold: (a) AMM emissions were estimated with new data on the abandoned coal mines; (b) the updated annual proportion of surface mining allowed for more precise attribution of activity data to underground mining and surface mining; (c) regional dynamic EFs of underground mining were derived to reflect changes of coal mines; (d) data on CMM utilization was updated to ensure the accuracy of inventory. Furthermore, we conducted source attribution analysis on China CMM emission changes to different drivers (the amount of coal production, the proportion of surface mining, regional EFs of underground mining, the amount of CMM utilization, and AMM emissions), which will provide additional insights into CMM emissions mitigation in China.

## 2. Materials and methods

In this study, Tier 2 method proposed by the IPCC is adopted to estimate emissions from underground mining and post underground mining. Tier 1 method is adopted to estimate emissions from surface mining, post surface mining, and abandoned coal mines. The choice of estimate method is based on the latest publicly available data in China (see note S1 in supplementary material (SM)).

### 2.1. Activity data

Provincial coal production data in a given year (table S7) was used for deriving annual CMM emissions.

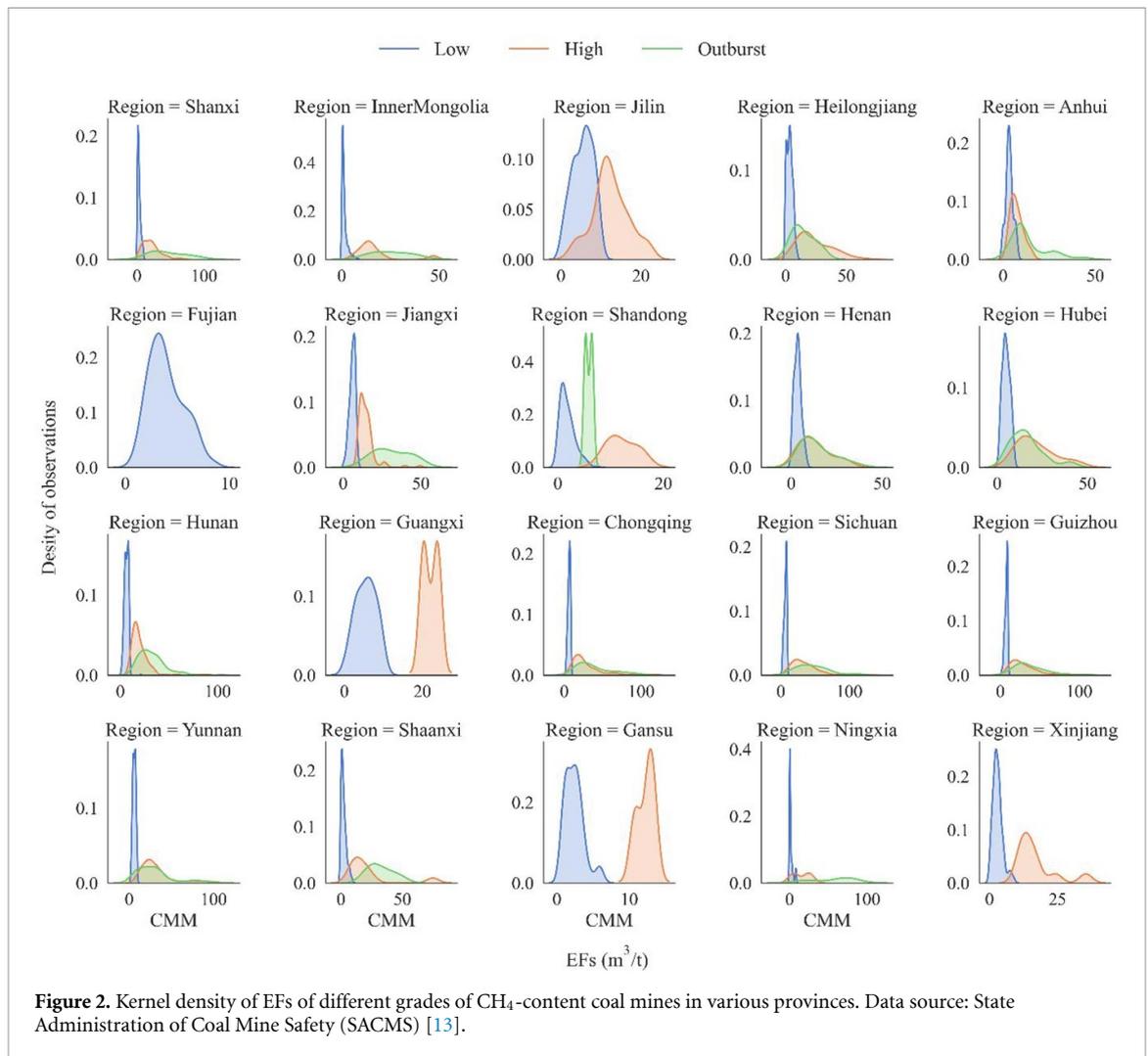
The data on the amount of coal production from surface mining in given years (table S8) were collected from reports and references. To our knowledge, the annual data on surface mining at the provincial level has never been provided by inventories before, including individual studies, official government inventories, and global inventories. The national average percentage of surface mining (5%) was the commonly-used value before [24–26, 35, 36]. The amount of coal production from underground mining was taken to be the residual between total production and production from surface mining.

The number of abandoned coal mines were collected from provincial government announcements. If the numbers were missing in a given year, the National Energy Administration announcements on the national annual coal mine production capacity with details were used to check the disappeared coal mines in the corresponding year [39]. By checking the aforementioned information, the number of closed and abandoned mines reached ~12 000 from 2010 to 2019 (table S9). Similar to the data on surface mining, the time series data on abandoned coal mines at the provincial level were also missing in previous individual studies.

Following the IPCC guidelines, methane utilization should be subtracted from the total CMM emissions. The specific targets on CMM extraction and utilization were issued in the 12th and 13th five-year plans [40] (table S10). Although the CMM extraction and utilization did not reach the targets, they have been largely improved in the last decade (table S10). For example, CMM extraction per ton of coal increased from 1.14 m<sup>3</sup> in 2004 to 4.80 m<sup>3</sup> in 2017 [41]. CMM extraction from underground and surface increased from 0.32 billion m<sup>3</sup> in 2010 to 22.46 billion m<sup>3</sup> in 2019 [40].

### 2.2. EFs of underground mining

In order to be consistent with the activity data, the EFs of underground mining at provincial level were calculated based on the data from the State Administration of Coal Mine Safety (SACMS) (Database details see note S2 in SM). After removing the coal mines with missing data on EFs or production, 7840 coal mines were taken as the sample data. Different from SACMS, we split coal mines in each province into two categories: low and high CH<sub>4</sub>-content coal mines. This is because the outburst CH<sub>4</sub>-content coal mines defined by SACMS are characterized by the phenomenon that the broken coal, rock, and gas are suddenly thrown into the excavation space triggered by in site stress and CH<sub>4</sub> rather than emission volumes. Figure 2 shows that there are no significant differences in EFs between the high and the outburst CH<sub>4</sub>-content coal mines. Therefore, we classify outburst CH<sub>4</sub>-content coal mines into the high CH<sub>4</sub>-content ones. The mean of EFs probability distribution of



low and high CH<sub>4</sub>-content coal mines at the provincial level (figure 3) were taken as the EFs of those two categories of coal mines (Distribution fitting method see note S3 in SM). The production-weighted EFs in a given province were taken as the provincial EFs of underground mining. To generate production-weighted EFs at the provincial level, the EFs of the two categories of coal mines were multiplied by corresponding production proportion in a given province derived from the sample data. Based on Monte Carlo Method, uncertainties of provincial EFs of underground mining were estimated (see note S4 in SM). The advantages of our method to derive provincial EFs of underground mining are described in note S5 in SM.

The EFs of the post underground mining from high and low coal mines in China were reported to be  $3 \text{ m}^3 \text{ t}^{-1}$  and  $0.9 \text{ m}^3 \text{ t}^{-1}$  [32], respectively. Based on the share of the production from low and high CH<sub>4</sub> content mines in each province, we calculated the production-weighted provincial EFs of post underground mining over 2010–2019 (table S11).

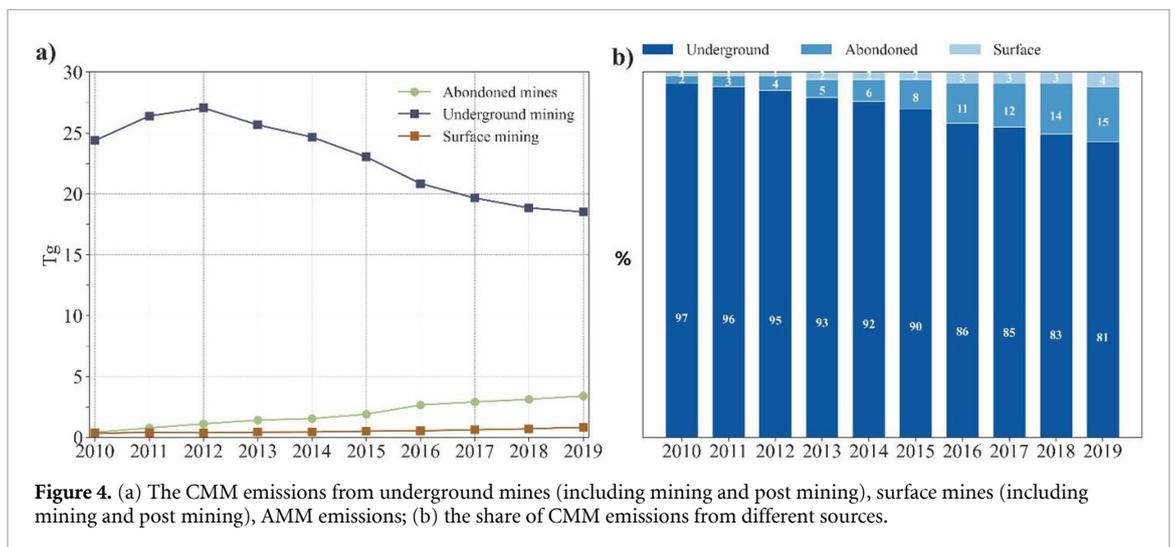
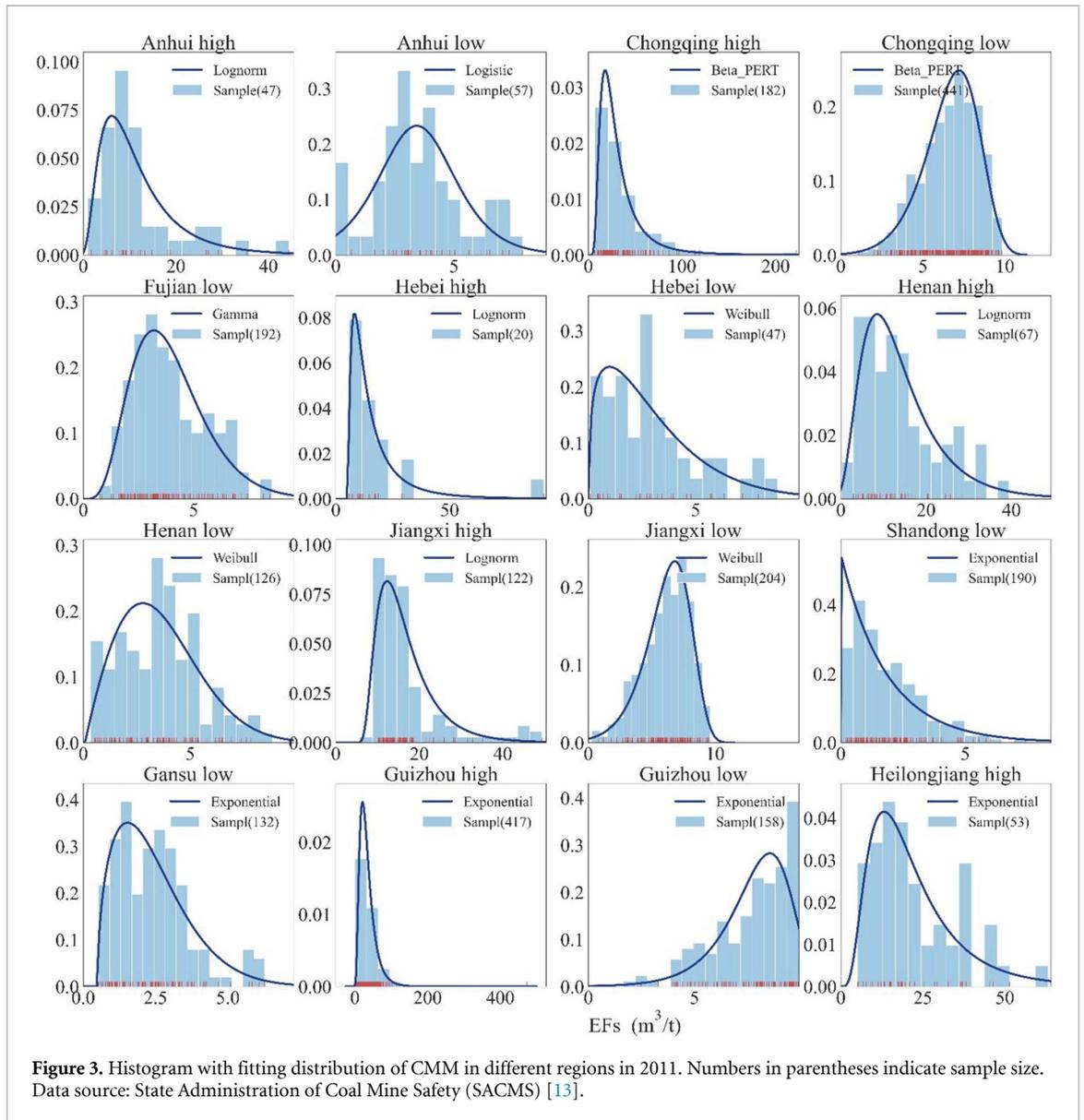
### 3. Results

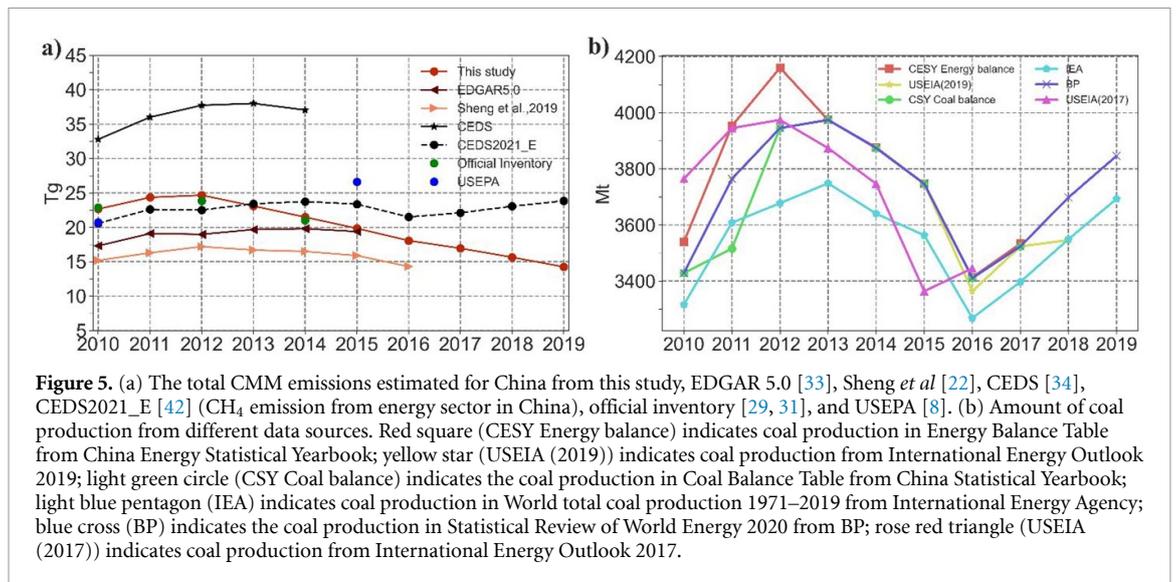
#### 3.1. Trend of CMM emissions from different emission sources

The trend of CMM emissions from different emission sources (figure 4(a)) shows that emissions from underground mining dominated the trend of total CMM emissions, whereas contributions from abandoned mines and surface mining experienced a sustained increase in the 2010s. Specifically, the share of emissions from underground mining decreased from 97% in 2010 to 81% in 2019 (figure 4(b)), while the emissions from abandoned mines experienced the opposite trend (increased from 2% in 2010 to 15% in 2019), suggesting the impact of coal mine de-capacity.

#### 3.2. Total CMM emissions and comparison with other studies

The total annual CMM emissions from 2010 to 2019 were estimated by aggregating the emissions from underground, surface, abandoned mines, and





**Figure 5.** (a) The total CMM emissions estimated for China from this study, EDGAR 5.0 [33], Sheng *et al* [22], CEDS [34], CEDS2021\_E [42] ( $\text{CH}_4$  emission from energy sector in China), official inventory [29, 31], and USEPA [8]. (b) Amount of coal production from different data sources. Red square (CESY Energy balance) indicates coal production in Energy Balance Table from China Energy Statistical Yearbook; yellow star (USEIA (2019)) indicates coal production from International Energy Outlook 2019; light green circle (CSY Coal balance) indicates the coal production in Coal Balance Table from China Statistical Yearbook; light blue pentagon (IEA) indicates coal production in World total coal production 1971–2019 from International Energy Agency; blue cross (BP) indicates the coal production in Statistical Review of World Energy 2020 from BP; rose red triangle (USEIA (2017)) indicates coal production from International Energy Outlook 2017.

utilization in each province. Our result shows that from 2010 (22.66 Tg) to 2019 (14.25 Tg), CMM emissions in China have decreased by 8.41 Tg (37%) (table S6), which is comparable to the total anthropogenic  $\text{CH}_4$  emissions from countries like Australia and Nigeria in 2015 [33]. The annual CMM emissions over 2010–2019 averaged 20.11 Tg, which equaled the total anthropogenic  $\text{CH}_4$  emissions from Brazil in 2015 (the fourth largest anthropogenic  $\text{CH}_4$  emissions emitter) [33].

CMM emissions in China peaked in 2012 and were on a downward trend in the past years (figure 5(a)). Compared to other bottom-up studies which presented estimates for 2010–2016, this decreasing trend is in consistent with Sheng *et al* [22] and CEDS [34]. The overall trend from 2010 to 2015 in EDGARv5.0 was increasing but not statistically significant ( $p = 0.13$ , M-K two-sided test). Downward trend was clear from China's official government inventory [29, 31] although it only provided estimates in three years. The U.S. Environmental Protection Agency (USEPA) [8] only presented estimates in 5 year intervals, which is not enough to draw conclusions about overall trends.

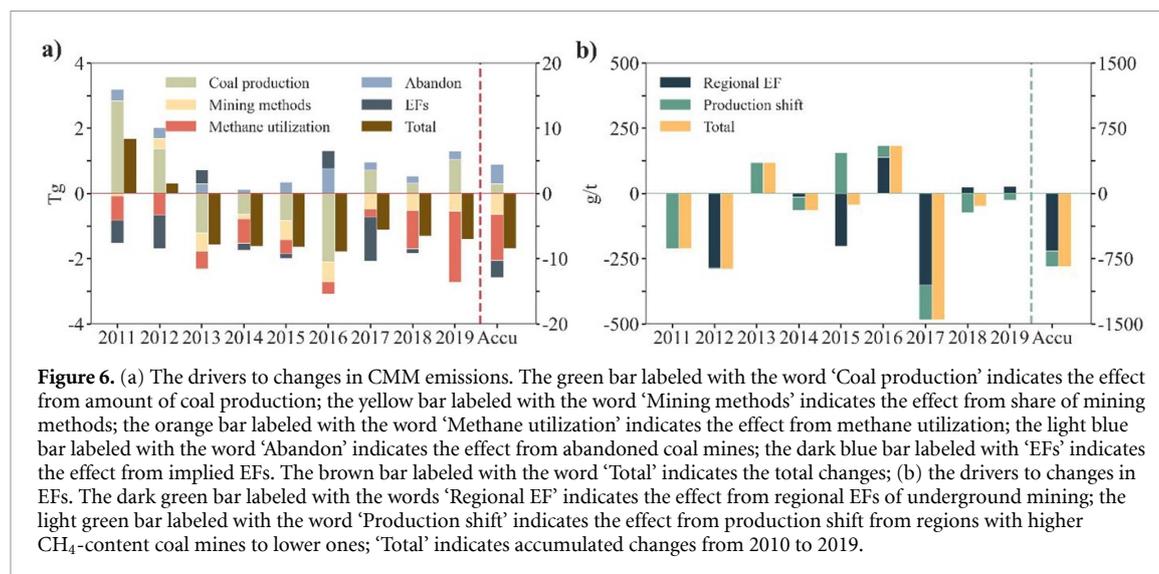
Few bottom-up studies shed light on estimates of CMM emissions in China over 2016–2019 due to data availability. Increasing trends in this period were reported by Lin *et al* [42] which extended inventory with activity data from China Statistics Yearbook and EFs from official inventories. CEDSv2021-02-05 also provided an upward trend over 2016–2019 of  $\text{CH}_4$  emissions from energy sector [42], which indicated an upward trend of CMM emissions, given coal mining contributed to 85% of  $\text{CH}_4$  emissions from energy sector in 2014 [29]. The upward trend from their studies could be largely attributable to increasing coal production and neglecting of impact from the shift of mining methods and changes in EFs.

From the perspective of top-down studies, Lu *et al* [19] presented a decreasing trend over 2010–2017

using *in situ* and satellite observation. However, Miller *et al* [10] reported an upward trend from 2010 to 2015, which could be largely attributed to the prior assumption from EDGARv4.2 inventory with few coal mining locations [22]. Saunio *et al* [20] has highlighted that EDGARv4.2 inventory overestimated China CMM emissions by a factor of approximately 2. Meanwhile, biased distribution of coal mines in the year of 2008 in EDGARv4.2 inventory resulted in an uncorrected fraction of CMM emissions within each grid box [22, 43]. Liu *et al* [43] argued that the fixed fraction adopted by Miller *et al* might cause the wrong trend of CMM emissions.

By comparing the magnitude of this study with other independent inventories, figure 5(a) shows that the results of this study are in the range of estimates from existing bottom-up inventories. During the same time period, the estimate of cumulative emissions from this study is two-thirds of the highest estimate from CEDS [34] and 38% higher than the lowest estimate from Sheng *et al* [22]. The highest estimate from CEDS can be attributed to the EFs from EDGARv4.2, which largely overestimated China's CMM emissions [20]. Thereby, the estimates from the latest CEDSv2021-02-05 were much lower than the previous version (figure 5(a)). The lowest emission estimates from Sheng *et al* [22] are likely caused by neglecting of emissions from abandoned mines and overestimation of utilization (table S12). Compared to our study, EDGAR5.0 presents a relatively small estimate. The EFs information was not documented in detail in EDGAR5.0; however what we know is that EDGAR5.0 adopted the activity data from the International Energy Agency (IEA) (table S5, figure 5(b)). The lower coal production from IEA compared with China Energy Statistical Yearbook could partly explain the smaller estimate from EDGAR5.0.

From the perspective of top-down studies, recent studies yielded lower estimates than official



government inventories. Zhang *et al* [18] reported that mean anthropogenic emissions over 2010–2018 in China was 47 Tg a<sup>-1</sup>, whereas anthropogenic emission estimate from the latest China's official government inventory for 2014 is 55 Tg a<sup>-1</sup>. They attributed 60% (4.8 Tg a<sup>-1</sup>) of this overestimate to coal mining according to prior inventory (EDGAR4.3.2, Scarpelli *et al* [44]), in which coal mining contributed ~34% of China's anthropogenic emissions. In this case, China's mean CMM emissions over 2010–2018 from their methods are 16.21 Tg a<sup>-1</sup>. Similarly, Lu *et al* [19] reported that posterior China's anthropogenic emission over 2010–2017 was 43 Tg a<sup>-1</sup> based on the same prior inventory (67 Tg a<sup>-1</sup>) with Zhang *et al* [18]. The downward correction in this study was conducted by decreasing China's mean CMM emissions over 2010–2017 to 11 Tg a<sup>-1</sup>. How to attribute overestimation to different sectors may call the results into questions. Miller *et al* [10] showed that China's total anthropogenic and natural methane emissions in 2015 were 61.5 Tg a<sup>-1</sup> and mean CMM emissions over 2010–2015 were around 18 Tg a<sup>-1</sup> which is closest to our results.

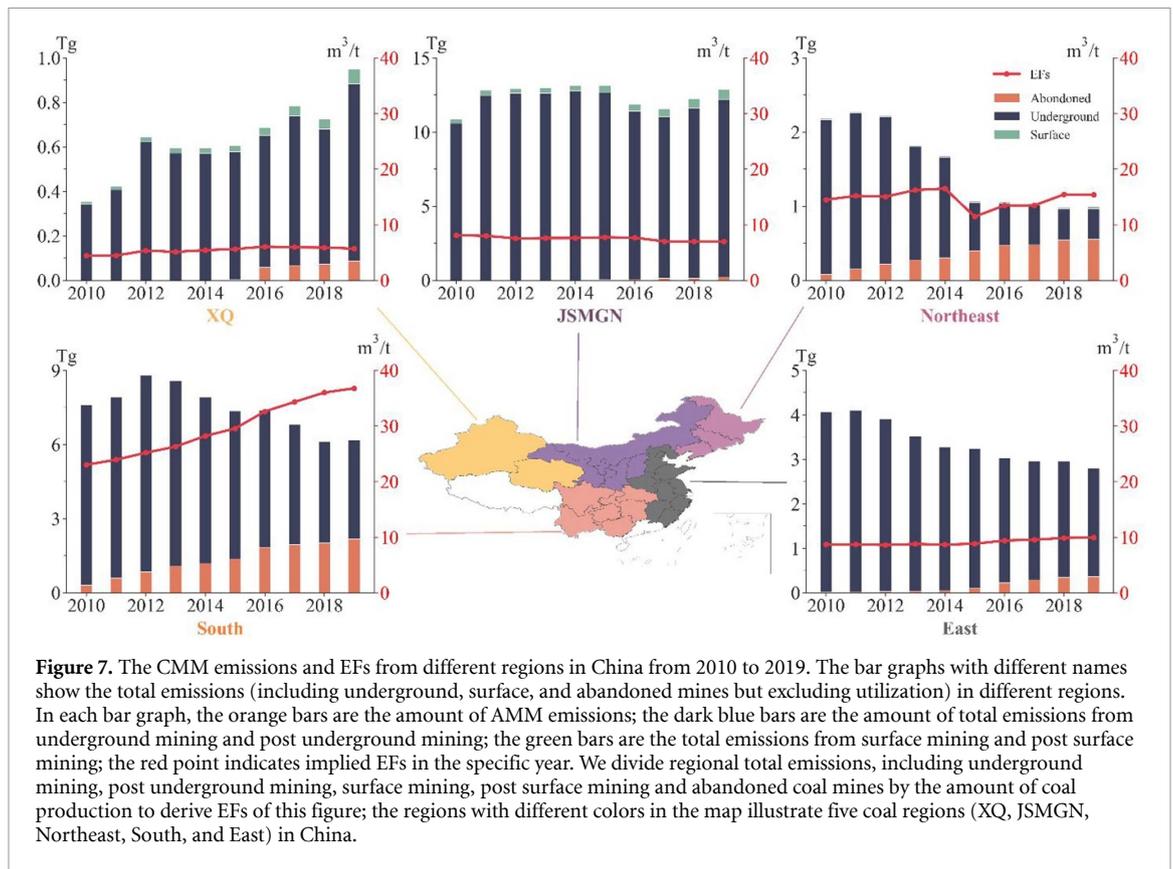
### 3.3. Drivers to changes in CMM emissions

Based on the decomposition analysis (see note S6 in SM), figure 6(a) shows that the changes in CMM emissions before 2017 could be mainly attributed to the decrease in coal production. Although coal production in China started to decline after 2012, it rebounded in 2017 and was larger in 2019 than in 2010. Therefore, the amount of coal production remains a factor having a negative accumulated impact on the decrease of CMM emissions. The accumulated changes (−8.41 Tg) from 2010 to 2019 can be attributed primarily to the growth of utilization, increase in surface mining (figure S7), and drop in the EFs. As discussed above, the upward trend since 2012 reported by previous studies was mainly because they overlooked the impact from mining methods and the

dynamic EFs. Given the default EFs of surface mining we adopted, the decrease in the EFs was attributed to the decrease in regional EFs of underground mining (79%) and production shift from regions with higher CH<sub>4</sub>-content coal mines to lower ones (21%) (figure 6(b)).

### 3.4. Changes in regional CMM emissions

Based on mining geological conditions, mining technology, disaster situation, production capacity, and administrative division, the coal production areas in China are divided into five regions. According to the Chinese Academy of Engineering [45] (figure S8), the regions are East (Anhui, Beijing, Fujian, Hebei, Henan, Jiangsu, Jiangxi, Shandong), JSMGN (Shanxi, Shaanxi, Inner Mongolia, Gansu and Mingxia), Northeast (Heilongjiang, Jilin, Liaoning), South (Chongqing, Guangxi, Guizhou, Hubei, Hunan, Sichuan and Yunnan) and XQ (Xinjiang and Qinghai). Along with the decrease of coal production in the Northeast, East, and South regions, the coal production increased in XQ and JSMGN (figure S9). The center of gravity of coal production over 2010–2019 (figure S10) shifted from the southeast (South and East) to the northwest (XQ and JSMGN) where the average EFs were relatively low (figure 7). With abundant coal reserves, the XQ region was taken as a strategic coal reserves region in the last decade due to long distance to the consumption areas and contributed the smallest emissions over 2010–2019 owing to relatively low EFs. The JSMGN region was the largest contributor to national CMM emissions since that share of coal production in this area has increased from 57% to 73% over 2010–2019. Owing to the exhaustion of coal resources, CH<sub>4</sub> emissions from abandoned coal mines in the Northeast area have increased largely and even exceeded underground mining in this area. The South region was characterized by high CH<sub>4</sub>-content coal mines, and contributed twice as much CMM emissions as East area, even



with less coal production than the East region. Meanwhile, more than 6000 coal mines were closed over 2010–2019 due to the de-capacity policy in the South region, which led to the largest AMM emissions in this region.

## 4. Discussion and policy implication

### 4.1. Uncertainty estimates

The overall level uncertainty estimates for China's CMM emissions and the range of likely change from base year 2010 to a given year is conducted using Monte Carlo method (see note S7 in SM). The results indicate that the largest degree of uncertainty is in the range of  $-26\%$  to  $36\%$  with respect to the total CMM emission estimate in a given year (table S6). Compared with China's official government inventory which only provided uncertainty estimates for CMM emissions in 2005 ( $-62\%$ ,  $46\%$ ) [46], the main reason for the relatively narrow range from our results is that the probability distribution of EFs for low and high  $\text{CH}_4$ -content coal mines at the provincial level is available in the simulation. Compared with U.S. CMM emissions, of which, the uncertainty in 2018 is in the range of  $-17\%$  to  $12\%$  [47], our estimates still contain a relatively large uncertain range. The trend uncertainty estimates present likely change from 2010 to 2019 is in the range of  $-56\%$  to  $-10\%$  (table S6).

Without field measurements, the default EFs of surface mining and abandoned coal mines in this study contain relatively large uncertainty. However,

the uncertainties associated with the EFs of underground mining are the top contributors. It influences the overall uncertainty because of the emissions from underground mining account for large part of total CMM emissions (figure S6).

### 4.2. Implications for CMM emissions mitigation in China

For effective strategies to mitigate CMM emissions, it is critical to assume baseline CMM emissions and prioritize CMM emission mitigation options, which is based on accurate total CMM emissions estimates and relative contribution of specific sources. Consistency between different approaches will improve confidence in the accuracy of emission estimates. However, our comparison shows there is two-fold difference between our estimates and the ones from top-down studies, which highlights more comprehensive datasets are required to reconcile between top-down and bottom-up estimates of China's CMM emissions. Relatively large degree of uncertainty comparing with other countries suggests that measurements of CMM emissions in China still have gaps with global best practice [48]. Nowadays, the measured data in China were serviced for safety, and targeted measurements for greenhouse gas emission compilation are still missing. The Chinese government should set a complementary program to improve the quality of the facility-level data on not only active coal mines but also abandoned coal mines since a large number of coal mines will be closed or abandoned in the

next decades owing to the carbon neutral ambition [49, 50].

In addition to the reduction of coal production, the priority of mitigation options implied by our results is to improve CMM utilization. The utilization rate of underground CMM extraction in 2019 is 40%, lower than the target of 13th Five-Year Plan (FYP) (50%) [16, 40, 51, 52]. The low-permeability coal seams, inadequate technology, and inefficient policies may hinder the utilization of CMM [10, 40]. The government might increase investment in both technology innovation and the commercial process. Especially, technologies to promote the utilization of low-concentration CMM should be focused on. Meanwhile, more incentive policies are suggested to be developed, such as subsidies for CMM power generation, accessibility of power grid and natural gas infrastructures. Moreover, China may consider CMM emissions in the policy of coal phase down to reduce CMM emissions from shifting coal production to lower EFs regions.

## 5. Conclusions

Based on more than 10 000 coal mine-specific data in 2011, we derived regional EFs of different types of coal mines. Through aggregating the provincial level data, we estimated emissions from all emission sources, including underground, surface and abandoned coal mines from 2000 to 2019. The main conclusions are as follows:

- (a) Our study suggests that there is a downward trend toward China's CMM emissions over 2010–2019. After a slight increase before 2012, CMM emissions in China had a gradual decline although the coal production has rebounded since 2016 and exceeded the production in 2010. China's annual CMM emissions decreased by 37% between 2010 and 2019 and the average value over 2010–2019 is 20.11 Tg with a decline trend at 0.93 Tg yr<sup>-1</sup>.
- (b) China's regulations on the coal industry have curbed the growing CMM emissions in the 2010s. Firstly, the increasing methane utilization contributes largely to the reduction of China's CMM emissions, although it failed to meet the target of China's methane extraction and utilization policy. Secondly, de-capacity policy has closed many small, less efficient and high CH<sub>4</sub>-content coal mines, which have decreased regional EFs, suggesting the overestimation from static regional EFs in previous studies. Thirdly, the share of coal production from surface mining has continued to grow over 2010–2019, which has also caused the decrease of regional EFs and has been overlooked by previous studies. Fourthly, the coal production has shifted from

South, Northeast and East areas to XQ and JSMGN areas where the regional EFs were lower.

In summary, although the amount of coal production in 2019 was still larger than in 2010, China's CMM emissions saw a sustained decline from 2010 to 2019 with a peak in 2012. Based on our bottom-up estimate, this decreasing trend of CMM emissions is robust and will correct the early argument of an increasing CMM emissions in China.

## Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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## References

- [1] Fesenfeld L P, Schmidt T S and Schrode A 2018 Climate policy for short- and long-lived pollutants *Nat. Clim. Change* **8** 924–36
- [2] Shindell D *et al* 2012 Simultaneously mitigating near-term climate change and improving human health and food security *Science* **335** 183–9
- [3] Schwietzke S *et al* 2016 Upward revision of global fossil fuel methane emissions based on isotope database *Nature* **538** 88–91
- [4] Zhang Z, Zimmermann N E, Stenke A, Li X, Hodson E L, Zhu G, Huang C and Poulter B 2017 Emerging role of wetland methane emissions in driving 21st century climate change *Proc. Natl Acad. Sci. USA* **114** 9647–52
- [5] Alvarez R A *et al* 2018 Assessment of methane emissions from the U.S. oil and gas supply chain *Science* **361** 186–8
- [6] Zhang Y *et al* 2020 Quantifying methane emissions from the largest oil-producing basin in the United States from space *Sci. Adv.* **6** z5120
- [7] Hmiel B *et al* 2020 Preindustrial <sup>14</sup>CH<sub>4</sub> indicates greater anthropogenic fossil CH<sub>4</sub> emissions *Nature* **578** 409–12
- [8] USEPA 2019 *Global Non-CO<sub>2</sub> Greenhouse Gas Emission Projections & Mitigation Potential 2015–2050* (Washington, DC: U.S. Environmental Protection Agency)
- [9] Saunio M *et al* 2016 The global methane budget 2000–2012 *Earth Syst. Sci. Data.* **8** 697–751

- [10] Miller S M, Michalak A M, Detmers R G, Hasekamp O P, Bruhwiler L M P and Schwietzke S 2019 China's coal mine methane regulations have not curbed growing emissions *Nat. Commun.* **10** 303
- [11] Kirschke S et al 2013 Three decades of global methane sources and sinks *Nat. Geosci.* **6** 813–23
- [12] Jackson R B, Saunois M, Bousquet P, Canadell J G, Poulter B, Stavert A R, Bergamaschi P, Niwa Y, Segers A and Tsuruta A 2020 Increasing anthropogenic methane emissions arise equally from agricultural and fossil fuel sources *Environ. Res. Lett.* **15** 71002
- [13] SACMS 2012 *Compilation of National Coal Mine Methane Level Identification for 2011* (Beijing: China University of Mining and Technology Press)
- [14] Shi L, Wang J, Zhang G, Cheng X and Zhao X 2017 A risk assessment method to quantitatively investigate the methane explosion in underground coal mine *Process. Saf. Environ.* **107** 317–33
- [15] NEA 2011 *The 12th Five-Year Plan for the Development and Utilization of Coal Bed Methane* (available at: [www.nea.gov.cn/2011-12/31/c\\_131337364.htm](http://www.nea.gov.cn/2011-12/31/c_131337364.htm))
- [16] NEA 2016 *The 13th Five-Year Plan for the Development and Utilization of Coal Bed Methane* (available at: [http://zfxgk.nea.gov.cn/auto85/201612/t20161202\\_2326.htm?keywords=](http://zfxgk.nea.gov.cn/auto85/201612/t20161202_2326.htm?keywords=))
- [17] Wang X, Liu C, Chen S, Chen L, Li K and Liu N 2020 Impact of coal sector's de-capacity policy on coal price *Appl. Energy.* **265** 114802
- [18] Zhang Y et al 2021 Attribution of the accelerating increase in atmospheric methane during 2010–2018 by inverse analysis of GOSAT observations *Atmos. Chem. Phys.* **21** 3643–66
- [19] Lu X et al 2021 Global methane budget and trend, 2010–2017: complementarity of inverse analyses using *in situ* (GLOBALVIEWplus CH<sub>4</sub> ObsPack) and satellite (GOSAT) observations *Atmos. Chem. Phys.* **21** 4637–57
- [20] Saunois M et al 2020 The global methane budget 2000–2017 *Earth Syst. Sci. Data.* **12** 1561–623
- [21] Gao J, Guan C and Zhang B 2020 China's CH<sub>4</sub> emissions from coal mining: a review of current bottom-up inventories *Sci. Total Environ.* **725** 138295
- [22] Sheng J, Song S, Zhang Y, Prinn R G and Janssens-Maenhout A G 2019 Bottom-Up estimates of coal mine methane emissions in China: a gridded inventory, emission factors, and trends *Environ. Sci. Tech. Lett.* **6** 473–8
- [23] Ju Y, Sun Y, Sa Z, Pan J, Wang J, Hou Q, Li Q, Yan Z and Liu J 2016 A new approach to estimate fugitive methane emissions from coal mining in China *Sci. Total Environ.* **543** 514–23
- [24] Zhu T, Bian W, Zhang S, Di P and Nie B 2017 An improved approach to estimate methane emissions from coal mining in China *Environ. Sci. Technol.* **51** 12072–80
- [25] Peng S, Piao S, Bousquet P, Ciais P, Li B, Lin X, Tao S, Wang Z, Zhang Y and Zhou F 2016 Inventory of anthropogenic methane emissions in mainland China from 1980 to 2010 *Atmos. Chem. Phys.* **16** 14545–62
- [26] Zhang B, Chen G Q, Li J S and Tao L 2014 Methane emissions of energy activities in China 1980–2007 *Renew. Sustain. Energy Rev.* **29** 11–21
- [27] Wang K, Zhang J, Cai B and Yu S 2019 Emission factors of fugitive methane from underground coal mines in China: estimation and uncertainty *Appl. Energy* **250** 273–82
- [28] Wang D, Wan K, Song X and Liu Y 2019 Provincial allocation of coal de-capacity targets in China in terms of cost, efficiency, and fairness *Energy Econ.* **78** 109–28
- [29] MEE 2019 *The People's Republic of China Third National Communication on Climate Change* (Ministry of Ecology and Environment of People's Republic of China)
- [30] MEE 2019 *The People's Republic of China Second Biennial Update Report on Climate Change* Ministry of Ecology and Environment of People's Republic of China
- [31] NDRC 2017 *The People's Republic of China First Biennial Update Report on Climate Change* (National Development and Reform Commission)
- [32] NDRC 2012 *The People's Republic of China Second National Communication on Climate Change* (National Development and Reform Commission)
- [33] Crippa M et al 2019 *Fossil CO<sub>2</sub> and GHG Emissions of All World Countries—2019 Report* (Luxembourg: Publications Office of the European Union)
- [34] Hoesly R M et al 2018 Historical (1750–2014) anthropogenic emissions of reactive gases and aerosols from the Community Emissions Data System (CEDS) *Geosci. Model Dev.* **11** 369–408
- [35] Schwietzke S, Griffin W M, Matthews H S and Bruhwiler L M P 2014 Global bottom-up fossil fuel fugitive methane and ethane emissions inventory for atmospheric modeling *ACS Sustain. Chem. Eng.* **2** 1992–2001
- [36] Gong S and Shi Y 2021 Evaluation of comprehensive monthly-gridded methane emissions from natural and anthropogenic sources in China *Sci. Total Environ.* **784** 147116
- [37] IPCC 2019 *Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories*
- [38] Wang N, Wen Z and Zhu T 2015 An estimation of regional emission intensity of coal mine methane based on coefficient-intensity factor methodology using China as a case study *Greenh. Gases.* **5** 437–48
- [39] NEA 2021 Announcements on national coal mine production capacity (available at: [www.nea.gov.cn/ztlz/mtscnlgg/scnlgg.htm](http://www.nea.gov.cn/ztlz/mtscnlgg/scnlgg.htm))
- [40] Lu Y Y, Zhang H D, Zhou Z, Ge Z L, Chen C J, Hou Y D and Ye M L 2021 Current status and effective suggestions for efficient exploitation of coalbed methane in China: a review *Energy. Fuel.* **35** 9102–23
- [41] Tan J 2018 Development status and suggestion of comprehensive utilization of coal mine gas in China *Coal Process. Comprehen. Utiliz.* **2018** 59–61
- [42] Lin X, Zhang W, Crippa M, Peng S, Han P, Zeng N, Yu L and Wang G 2021 A comparative study of anthropogenic CH<sub>4</sub> emissions over China based on the ensembles of bottom-up inventories *Earth Syst. Sci. Data.* **13** 1073–88
- [43] Liu G et al 2021 Recent slowdown of anthropogenic methane emissions in China driven by stabilized coal production *Environ. Sci. Tech. Lett.* **8** 739–46
- [44] Scarpelli T R, Jacob D J, Maasackers J D, Sulprizio M P, Sheng J-X, Rose K, Romeo L, Worden J R and Janssens-Maenhout G 2020 A global gridded (0.1°\*0.1) inventory of methane emissions from oil, gas, and coal exploitation based on national reports to the United Nations Framework Convention on Climate Change *Earth Syst. Sci. Data.* **12** 563–75
- [45] Yuan L 2017 *Strategic Studies of High-efficient and Energy-effective Coal Extractions in China* 1st edn (Beijing: Science Press)
- [46] NDRC 2014 *The People's Republic of China National Greenhouse Gases Emissions Inventory 2005* (Beijing: China Environment Press)
- [47] USEPA 2020 *U.S. Greenhouse Gas Emissions and Sinks:1990–2018*
- [48] Patyńska R 2014 Methodology of estimation of methane emissions from coal mines in Poland *Stud. Geotech. Mech.* **36** 89–101
- [49] Mallapaty S 2020 How China could be carbon neutral by mid-century *Nature* **586** 482–3
- [50] Duan H et al 2021 Assessing China's efforts to pursue the 1.5 °C warming limit *Science* **372** 378–85
- [51] Si R and Li R 2020 Dynamic characteristics of low-concentration oxygen-containing gas explosion and prevention and control key technology *Coal Sci. Technol.* **48** 17–36
- [52] Association of Coal Industry 2021 *Annual Report on coal Industry Development 2020*