LETTER

China should be wary of the methane emissions from mine closure

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Dear Editor,

Methane is the leading greenhouse gas after carbon dioxide (CO_2).[1] The research shows that methane emissions have led to global warming, increasing the risk of food insecurity, disease transmission, and natural disasters both in China and around the world. Moreover, Chinese methane emissions amounted to 55,676 thousand tons in 2022, accounting for about 15.6% of global total methane emissions, making it the largest anthropogenic methane emitter in the world.[2] Chinese Ministry of Ecology and Environment and ten other departments recently jointly issued the first methane emission control action plan, taking a significant step. However, more forceful actions are still needed to address methane emissions effectively, particularly in the energy sector.[3] The energy sector is China's largest source of methane emissions, accounting for about 46% of national methane emissions, with more than half arising from coal.[4] Therefore, formulating effective coal methane mitigation strategies and assessing their synergetic benefits are crucial to achieving climate goals. Unfortunately, the accounting framework of methane emissions from the coal industry has huge uncertainties, which might hinder the formulation of effective mitigation strategies.

Methane management in China's coal industry has always focused on gas prevention for safety reasons during the mining and production process. Early studies concluded that methane emissions from abandoned coal mines in China accounted for less than 1% of coal methane emissions and were negligible.[5] However, recent top-down inversion studies have shown that implementing mitigation strategies for closed/abandoned coal mines played an important role in methane emission reductions in China.[6] With the depletion of resources and the policy implementation of addressing overcapacity, China has left many closed/abandoned coal mines, about 12,000 in 2020, most of which are high gas and gas outburst mines. Due to the restriction of mining technology and the complexity of geological structure, a large amount of coal containing gas is left in the mine. Under the influence of temperature difference, pressure difference, and groundwater, it is easy for the free methane in the goaf to escape to the surface atmosphere through channels such as wellheads and overburdened fissures. Moreover, this continued unorganized escape has long-term and potential climate implications. China has committed to reducing the share of fossil fuels in its energy consumption to 75% by 2030. As coal's phasing out becomes a major trend, the continuous closure of coal mines is inevitable. This will significantly increase the difficulty and cost of methane emissions reduction in China's coal industry, hindering the achievement of the 1.5 °C warming target.[7]

However, amount of methane emissions from abandoned coal mines are unclear in China. Most bottom-up coal methane inventories do not take into account China's abandoned mine methane (AMM) emissions. Although some studies have considered AMM emissions, they have not adequately discussed the emission reduction potential and regional differences of existing production mines as they are phased out.

This study provided a high-resolution production mine dataset in China, extracted from the National Energy Administration of China (NEAC) (Source: https://www.nea.gov.cn/ztzl/mtscnlgg/scnlgg.htm), containing production data for 2,816 coal mines in 2020. The data include the production capacity, mining area, and geographic location information. First, the data were digitized, and geographical coordinates were obtained through Baidu Map. Then, the coordinates and mine names were used as the key fields to manually match the mine information from different sources one by one. Finally, the information was integrated, and a dynamic time series was generated for each coal mine. Based on the time series, the operating status of each coal mine can be tracked at the mine level. According to this dataset, the objective of this study is to quantify the cumulative effect of methane emissions and the emission reduction potential after mine closure.

TREND AND PREDICTION OF METHANE EMISSIONS AFTER MINE CLOSURE

The existing production mines will gradually reach their productive age after 2020. Methane emissions from closed/abandoned coal mines will reach their first peak in 2024, when about 1,261 mines will retire, and emissions will peak at 2.63 million tons/yr. Subsequently, after a brief decline, methane emissions will peak around 2030, with a cumulative retiring of 2,084 mines, accounting for 74% of total mines, and emissions of 4.39 million tons/yr. By 2060, when all mines retire, emissions will fall to 2.31 million tons/yr (Figure1A). In terms of spatial distribution (Figure1B), methane emissions from most mines retiring before 2030 are at a high level, and only a few scattered flooded mines (about 30%) can reduce methane emissions to a low level. Shanxi, Guizhou, and Anhui have high methane emissions levels, with 706,500 tons/yr, 546,600 tons/yr, and 3,800 tons/yr, respectively. Shanxi Province ranks first nationwide, accounting for 42.97% of national methane emissions. This indicates that methane emissions will remain high for a certain period after mine closure, which is consistent with the research of Zhang et al.[8] After 2030, the other 1,613 coal mines will be phased out. By2060, methane emissions from almost all flooded mines will be significantly reduced, especially in big coal provinces in middle reaches of the Yellow River (Shanxi, Shaanxi, and Inner Mongolia). However, it is worth noting that provinces in the lower Yellow River basin and the middle and lower Yangtze River basin still have high methane emissions. Compared to other regions, there will be no significant regional methane emission-reduction benefits yielded from the exit of mines from the emission-reduction perspective.

MITIGATION POTENTIAL AND INTERPRETATION FROM MINE CLOSURE

At present, there are mainly five kinds of methane emission-reduction measures for closed mines, including gob drainage, underground in situ explosion, water injection, microbial degradation, and emission channel blocking. Among them, gob drainage refers to the process of drilling into the gob area in the roadway through sealed or bored holes in order to extract the methane gas that enters the gob area in each section. This technology is relatively mature and economically efficient and has been widely used in major coal-producing provinces such as Shanxi and Shaanxi. The water injection technology suppresses gas release by injecting water from a wellhead or other pipe into a coal mine to increase the underground water pressure. This technology has been shown to have a significant effect on inhibiting methane emission intensity. Therefore, this study discusses the potential of methane emission reduction of these two technologies in the phase-out process of existing mines. The light green line in Figure1A shows the emission-reduction potential of closed mines with the gob drainage technology. Compared with no emission-reduction measures, the peak methane emission under this emission-reduction technology will be brought forward to 2024. By 2030, the cumulative emission reduction will be 13.2 million tons,

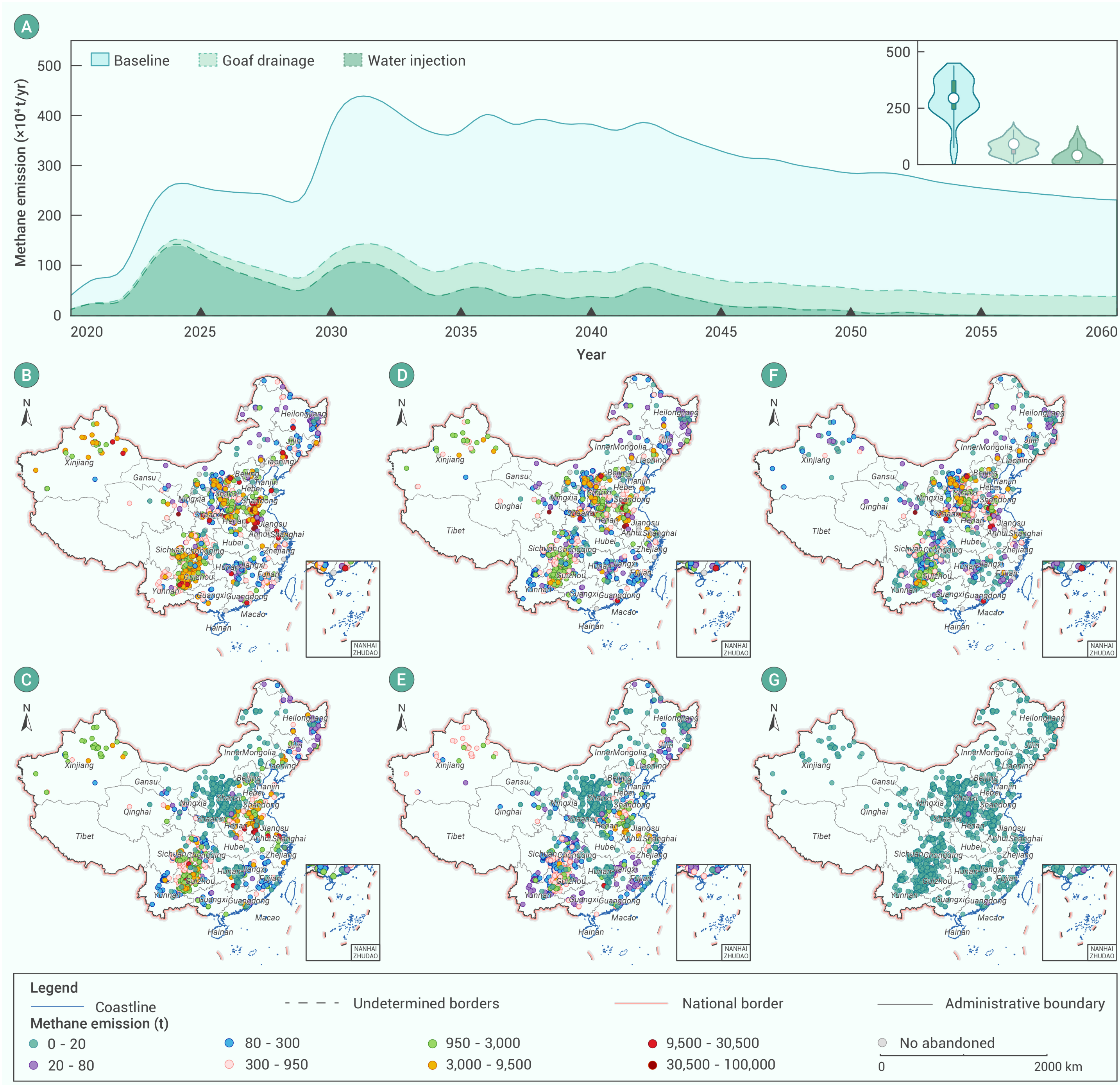

Figure 1. The trend and projected methane emissions from mine closure under the three scenarios The mitigation potential and interpretation from mine closure under different scenarios (A); Spatial distribution of projected methane emissions from mine closure in 2030 (B) and in 2060 (C) for the baseline scenario; Spatial distribution of projected methane emissions from mine closure in 2030 (D) and in 2060 (E) for the goaf drainage scenario; Spatial distribution of projected methane emissions from mine closure in 2030 (F) and in 2060 (G) for the water injection scenario.

which is equivalent to the total coal methane emissions of East China (8.63 million tons/yr) and Central China (6.17 million ton/r) in 2017.[8] It can achieve the target of reducing 5 million tons of emissions by 2030, as estimated by the Ministry of Ecology and Environment.[9] Subsequently, by 2060, the emission will be reduced to 83.54% of the original level (with a cumulative emission reduction of 89.05 million tons), demonstrating significant emission-reduction effects. Compared with no emission-reduction measures, the use of gob drainage technology will effectively mitigate the emission from mines that are currently experiencing high emissions levels. However, there is still a significant gap in the emission reduction potential compared with the water flooding technology, and significant low-emission areas are still dominated by major coal-producing provinces in the middle reaches of the Yellow River (Figure1D-E). According to the difference in the number of coal seams and geological conditions in the gob, combined with various factors such as the equipment and the labor force, the emission reduction cost of this technology is about CNY 1.21-13.15 billion. The dark green line in Figure1A shows the emission-reduction potential of closed mines with the water flooding technology. Peak emissions under the application of this technology also appear in 2024, slightly lower than the gob drainage technology scenario, about 1.38 million tons/yr, which is 52.47% lower than that without any emission-reduction technology. The overall downward trend is maintained until2060, reaching nearly zero emissions. From the perspective of spatial distribution, with the implementation of this technology, by 2030, in addition to water-flooded mines, emissions in Xinjiang, Jiangxi, and Fujian will also be significantly reduced. Nearly 50% of country's mines will have significant emission-reduction effects (Figure1F). In 2060, almost all mines show significant emission-reduction potential, with a cumulative emission reduction of up to 104.91 million tons, and the pressure of methane emission reduction in the lower Yellow River basin and the middle and lower Yangtze River basin is greatly reduced (Figure1G). However, assuming that a single mine has a 60m³ gob, the use of water flooding technology will consume nearly 170,000 m³ of water, so it is necessary to be vigilant about the risk of water shortage.

LIMITATIONS AND OUTLOOK

This letter highlights the need to draw attention to methane emissions from closed/abandoned coal mines in the future, which is expected to provide scientific and technological support for more effective regional emission reduction measures at local, provincial and national levels. Nevertheless, some limitations remain and deserve further study. The water injection is widely perceived as the most effective concept for suppressing methane emissions from closed coal mines, but indeed entail uncertainties. As the water injection project in closed coal mines progress, the groundwater level continues to rise, increasing the pressure of free gases in the open space above the water surface. This creates a pressure gradient, allowing methane to migrate through overlying rock layers and escape to the surface. Simultaneously, it will bring about issues of mine water pollution. Therefore, the problem is complex, and further analysis, especially for the fieldwork to accurately determine the extent of flooded conditions and parameters of decay curves.

EMISSIONS CALCULATION PROCESS AND MITIGATION SCENARIO DESCRIPTIONS

In this study, the dynamic discharge inventory of closed/abandoned coal mines was established based on the phase-out time of 2,816 mines under the assumption that no new production mines were added. Scenarios are set as follows: (1) the baseline scenario calculated the emission of water-flooded mines and dry mines separately based on emission rates.

$$E_{AMM_{dry}} = \rho \times q_0 \times (1 + b \times D_i \times t)^{\left(-\frac{1}{b}\right)} \quad (1)$$

$$E_{AMM_{flooded}} = \rho \times q_0 \times \exp((-t) \times D_i) \quad (2)$$

where, q_0 is the initial discharge from abandoned mine (m^3)， b is the rate of change in the decline rate through time; D_i is the initial decline rate; t is the elapsed time from t_0 (years). In this letter, for water-flooded mines, b is taken as 2.017 and D_i is taken as 0.302. For dry mines, D_i is taken as 0.672.[10] The Monte Carlo method was used to conduct sampling with a probability of 50% compared with the existing study,[10] and results passed the Bland–Altman consistency test. (2) the goaf drainage scenario calculated methane emissions based on a drainage rate of 40%, indicating a 40% reduction in emissions compared to the baseline scenario. (3) the water injection scenario assumed all coal mines would be adopted water flooding to methane reduction after their closure. The computational methods refer to Eq. (2).

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DECLARATION OF INTERESTS

The authors declare no competing interests.