PNAS

PERSPECTIVE

Challenges to sustainable large-scale shale gas development in China

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Edited by Hongwu Xu, Arizona State University, Tempe, AZ; received December 12, 2024; accepted March 3, 2025 by Editorial Board Member Alexandra Navrotsky

China's shale gas production has grown annually by 21% since 2017 with long-term national energy strategy calling for continued expansion. This large-scale shale gas development is challenged by constraints on water supply. It requires over 6,000 new wells to be drilled within the Yangtze River Basin in South China—one of China's most populated regions with sensitive ecological and geological conditions, posing significant environmental threats to the hydrosphere, atmosphere, and biosphere. Hydraulic fracturing-induced seismicity also adds to the existing earthquake risk for the Sichuan/Chongqing region. These potential negative impacts challenge both China's and the United Nations' sustainable development goals. We explore China's current shale gas operations in the Yangtze River Basin and their interaction with the environment from these multiple perspectives. We then suggest future improvements to practice that will promote sustainable development to jointly satisfy China's burgeoning energy needs. We conclude that China's shale gas industry would benefit from an innovation ecosystem that involves companies and research institutions, and that there is an urgent need to implement environmental regulations for shale gas extraction.

shale gas | environmental risks | water stress | GHG emissions | induced seismicity

Shale gas is the most abundant source of natural gas, with an estimated 196,915 billion cubic meters (bcm) of technically recoverable reserves on Earth (1). The potential of shale gas is of international interest because sources of conventional gas are being steadily depleted (2). Natural gas is often regarded as a cleaner and more efficient energy source than oil and coal and is widely seen as a crucial bridge for the energy transition in China. For example, carbon dioxide and nitrogen oxide emissions can be reduced by half and three-quarters, respectively, if natural gas replaces coal (3). However, for natural gas to be a climate-effective option for electricity generation, methane emissions must be kept below ~3% from well through power plant delivery (4). In the wake of the shale gas revolution at the beginning of the 21st century, shale gas production in the United States has surged to 807 bcm, comprising ~78% of total production in 2023 (5). This newfound abundance rapidly changed the United States from a net importer of natural gas to an exporter. China is believed to have the largest national shale gas reserves, according to world shale resource assessments (1). As reported by the Chinese Ministry of Land and Resources, China has 134 trillion cubic meters (tcm) of geological reserves and 25 tcm of technically recoverable reserves (6), but commercial exploitation of shale gas began in 2012—more than a decade later than in the United States.

Coal comprises over half of China's energy use with net imports comprising 6.8% of 2022 total coal supply and contributing 79% of China's total CO_2 emissions from fuel combustion (7). In recent years, China has steadily enhanced the security of its energy supply and improved energy system infrastructure; however, the dependence on imported energy remains high. A faster and more thorough transition to clean energy is required to meet the self-prescribed 2030 carbon emissions peaking and 2060 carbon neutrality goals announced in the 75th United Nations General Assembly.

The "14th Five-Year Plan" presents a national strategy for promoting regional economic and social development and calls for accelerating the exploration, development, and utilization of shale gas. National and provincial policies have been announced to encourage shale gas production (Table 1). Following breakthroughs in fundamental research, production technologies, and management over the past decade, China's shale gas production has grown annually at 21% since 2017 (8)—it is now the second-largest shale gas producer after the United States. In 2022, shale gas accounted for ~10% of China's total natural gas production at 24 bcm, over 1000% more than merely a decade ago (9). Nevertheless, China's shale gas exploration and development face greater

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Author contributions: J.W., J.T., and L.L. designed research; J.W., J.T., J.X., and L.L. performed research; J.W., J.X., and B.C. analyzed data; and J.W., J.T., J.X., L.L., G.C.B., K.G.M., C.V.D.V., and D.E. wrote the paper.

The authors declare no competing interest.

This article is a PNAS Direct Submission. H.X. is a guest editor invited by the Editorial Board.

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Published April 28, 2025.

Table 1. National and provincial policies supporting shale gas development in China

Level	Policy	Date	Content
National	*Announcement on the Continued Implementation of the Resource Tax Reduction Policy for Shale Gas*	2023/09	Continue reducing the shale gas resource tax (6% statutory rate) by 30% until December 31, 2027.
	The 14th Five-Year Plan for Modern Energy System Development	2022/03	Increase natural gas production to >230 bcm by 2025. Planned active expansion of unconventional resource exploration and development.
	Notice on the Action Plan for Carbon Peaking Before 2030	2021/01	Accelerate the large-scale development of unconventional oil and gas resources such as shale gas. Promote natural gas consumption and actively promote the integrated development of natural gas with various other energy sources.
	Shale Gas Development Plan (2016–2020)	2016/09	By 2030, annual shale gas production is expected to reach 80 to 100 bcm.
Provincial	*Enshi Prefecture Major Industry Development Plan (2022–2035)*	2022/09	Shale gas development has been designated as a key focus in the clean energy sector, with plans to build a full industrial chain. The goal is to achieve a total output value of 10 billion yuan by 2026 and 90 billion yuan by 2035.
	The 14th Five-Year Plan for Hubei Province Energy Development	2022/05	Accelerate shale gas exploration and development in the Yichang and Enshi regions, for annual shale gas production of 2 bcm by 2025.
	The 14th Five-Year Plan for Guizhou Province Energy Technology Innovation and Development	2022/05	Strengthen research and technological breakthroughs in unconventional gas exploration and development (e.g., hydraulic fracturing). Utilize cloud computing, big data, and the Internet of Things to establish intelligent development and utilization technologies.
	The 14th Five-Year Energy Development Plan for Sichuan Province	2022/03	Implement the national action plan for the construction of a 1 bcm-level production base for natural (shale) gas, to establish the largest modern shale gas production base in the country.
	Guiding Opinions on Accelerating the Development of the Shale Gas Industry by the Guizhou Government (2019–2025)	2020/01	Establish shale gas as an important component of natural gas supply. By 2025, confirm 50 bcm of shale gas reserves and achieve an annual production capacity of 2 bcm, with an annual output of 1.2 bcm.

challenges than in the United States. The main reasons are i) the geological conditions in the principal reservoirs of southwest China are more complex, with diverse sedimentary types, intense tectonic degradation, and generally greater depths of burial; ii) most of China's shale gas reserves are located in areas with severe water shortages and with ecologically fragile environments; iii) the most productive shale gas fields are within the collision zone between the Indian and Eurasian Plates and thus near seismically active zones; and iv) China is the largest national emitter of greenhouse gases (GHG), so there is an urgent need to develop new, green, and low-carbon technologies for shale gas production that can reduce life cycle GHG emissions, optimize water use and management, and minimize ecological disturbances.

China currently has >2,600 active shale gas wells (9), with the vast majority distributed in the drainage area of the Yangtze River. The Yangtze River region accounts for >60% of China's total shale gas reserves (10) and almost 100% of the currently produced shale gas. The Yangtze watershed covers ~18.8% of China's total land area in 11 provinces with ~43% of the nation's inhabitants and contributing ~46.4% of its GDP (11). By 2030 to 2040, the Chinese government plans an annual production of 80 to 100 bcm (12), requiring >6,000 new wells in the Yangtze River Basin. Thus, the rapid growth of shale gas extraction and related hydraulic fracturing brings with it significant environmental concerns, including water shortages, GHG emissions, induced seismicity, groundwater contamination, and deforestation (Fig. 1). The Yangtze River watershed is home to hundreds of ecological conservation areas, thousands of wildlife species, and 100s of millions of residents. Potential negative impacts are either directly or indirectly related to several of the United Nations Sustainable Development Goals (UNSDG) (e.g., 6. Clean water and sanitation; 7. Affordable and clean energy; 13. Climate action; 14. Life below water; 15. Life on land) with global implications. The Yangtze River Basin serves as a principal economic belt connecting the megacities of Chengdu, Chongqing, Wuhan, and Shanghai. Thus, the protection and restoration of its ecological environment is a high priority for the central government (13). This emphasis aligns with nationwide goals for sustainable economic and social development. Therefore, understanding and navigating trade-offs between environmental sustainability and long-term energy security pose unique challenges over the coming decades—addressed in the following discussion.

Methane Is a Greater Contributor to GHG Emissions

The systems-level GHG footprint of shale gas production through utilization consists of the direct emissions of CO_2 from combustion, indirect emissions from fossil fuels used in the development process, and fugitive methane emissions (17–19). To achieve the dual 2030 and 2060 peaking and neutrality goals, China has pledged to reduce the use of coal as the primary energy source in favor of options to lower carbon emissions related to combustion, such as shale gas. Most of China's shale gas reservoirs, however, are deeper than 3.5 km

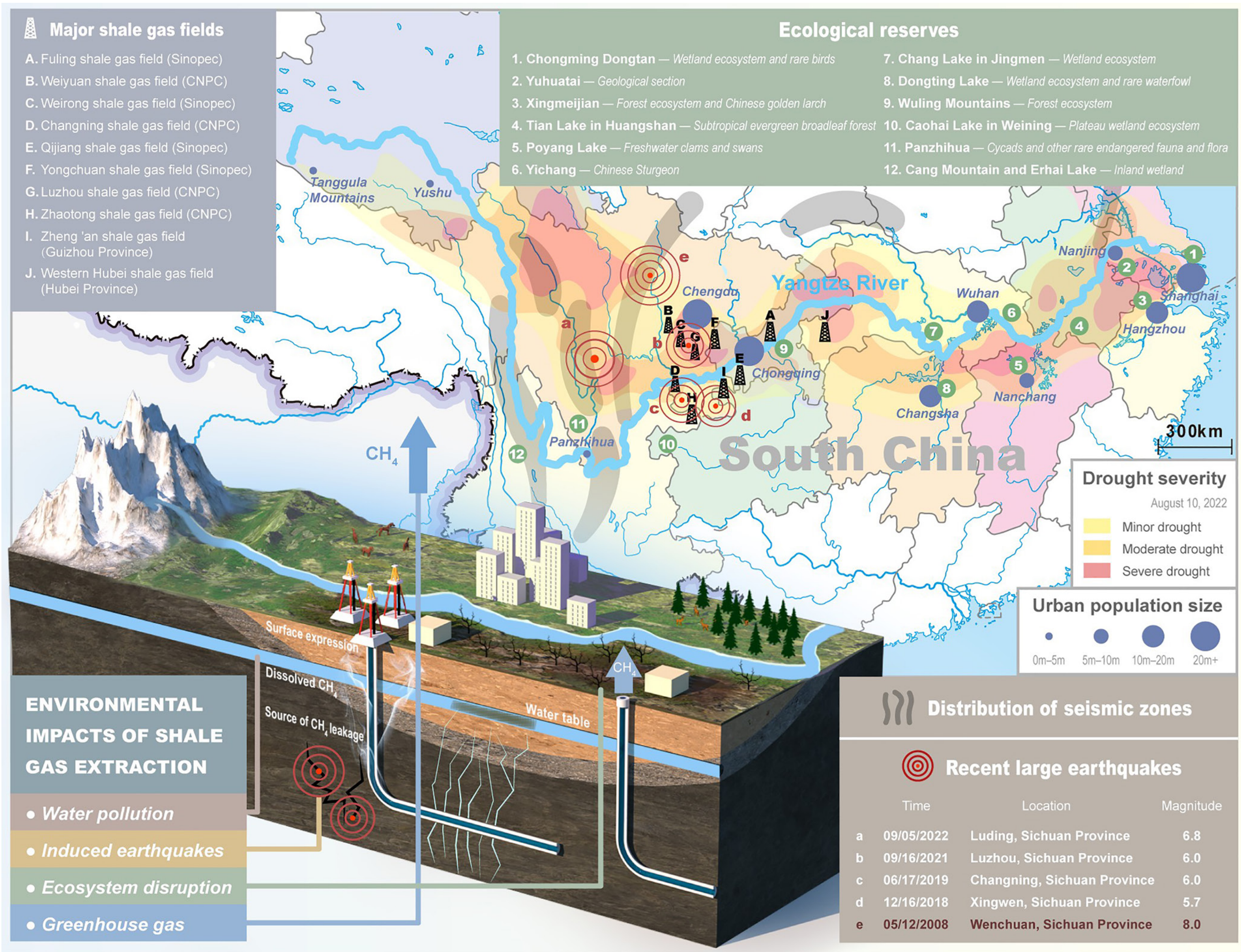

Fig. 1. Current shale gas fields (A–J) are predominantly located in the drainage area of the Yangtze River, which is home to several ecological reserves (1–12). Six megacities with over 10 million inhabitants are located along the Yangtze River: Chengdu, Chongqing, Wuhan, Changsha, Hangzhou, and Shanghai. High water stress is apparent in the region with recent minor to severe droughts. Large-scale shale gas development in the region poses severe environmental threats to water, air, plants, and wildlife and increased hazards from induced earthquakes. Several notable earthquakes are believed possibly linked to fluid-injection-induced fault reactivation (14–16). The epicenter of the 2008 Wenchuan earthquake is <300 km away from the shale gas development area. Earthquakes b–d are suspected to be some of the largest hydraulic fracturing-induced earthquakes worldwide.

in extremely low-permeability formations (20), which require advanced technologies and more intensive drilling to extract (possibly also longer duration of production). As a result, indirect carbon emissions from shale gas extraction could contribute significantly over those in recovery from conventional gas reservoirs—and thus undermine efforts to reduce carbon emissions (21). China's life cycle GHG emissions from shale gas production are summarized in Fig. 2*A* (19, 22–25). Based on data from 230 production wells, the upstream GHG emissions from shale gas development in China are 18.8 g CO_2eq/MJ (19). The preproduction phase accounts for 4.18 g CO_2eq/MJ (22.3%) of the upstream GHG emissions in China, twice as much as it does in the United States (19). In particular, well drilling and completion (the process of preparing a well into production after drilling, including hydraulic fracturing) contribute 57.4% and 41.8% of the preproduction GHG emissions, respectively (19). Several studies have suggested that the carbon footprint of shale gas is comparable to or higher than that of conventional gas sources in terms of extraction (26, 27). We estimate the annual CO_2-equivalent emissions resulting from increased shale gas production in China (Fig. 2*B*). If current well GHG emissions continue, annual GHG emissions could reach ~2×10^8 tCO_2eq by 2060 following the projected shale gas production increase.

China's total methane emissions exceed those of the United States (Fig. 2*C*), whereas methane emissions from oil and gas are higher in the United States than in China at the scale of current development. In the United States, methane accounted for 12% of human-related GHG emissions in 2012, with ~28% (the most significant contributor) from natural gas and petroleum systems (30). In China, methane emissions attributed to energy made up 44% of total methane emissions, as indicated by the 2024 International Energy Agency (IEA) methane tracker (29). China's methane emission sources have a similar composition to the global pattern, with venting accounting for the majority of emissions, followed by fugitive emissions (Fig. 2*D*). Fugitive methane emissions are detected at various stages of the shale gas development process, both upstream and downstream. A study by the Environmental Defense Fund revealed that 3.7% of the natural gas produced

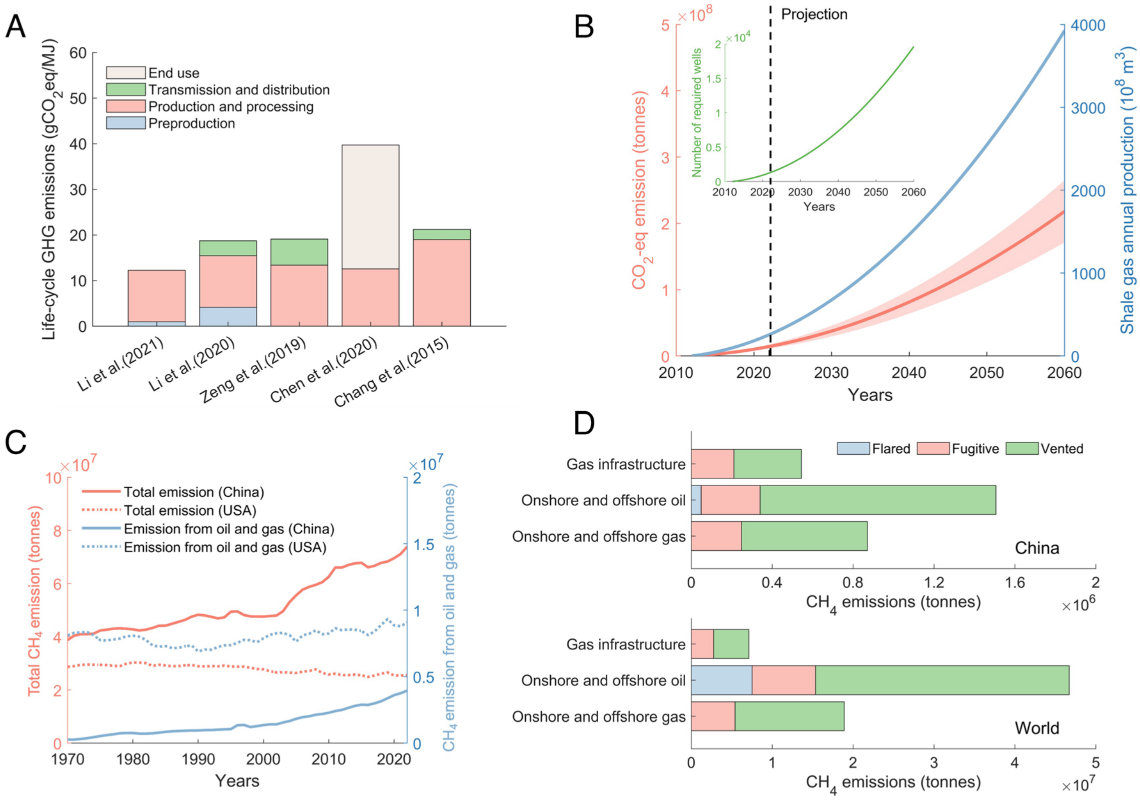

Fig. 2. (*A*) China's well life cycle GHG emissions are between 12.27 and 39.71 gCO_2eq/MJ (19, 22–25). (*B*) Estimates of China's CO_2-equivalent annual emissions from shale gas production through 2060, based on the current rate of development and well GHG emissions (preproduction, production, and processing). Annual production is expressed as a quadratic function, and per-well production rate is taken as 0.2×10^8 m^3. The red-shaded area denotes the upper and lower boundaries of the estimate. (*C*) Time series of total methane emissions and methane emissions from oil and gas in China and the United States (28). (*D*) Composition of methane emissions from oil and gas in China and the rest of the world (29).

in the US Permian Basin escaped into the atmosphere due to the lack of infrastructure to prevent extensive venting and flaring (31). Crucially, this amount is sufficient to negate the short-term GHG benefits of switching from coal to natural gas (32). Moreover, flowback fluids usually contain a significant amount of dissolved methane. When stored in open or vented tanks, methane is released into the atmosphere as liquid pressure drops (33). Compared with conventional wells, completions involving hydraulic fracturing produce more flowback due to the large volumes of water used (34). Emission data measured at 18 shale gas production sites (81 wells) in Sichuan Province suggest that flowback water tanks were the primary sources of methane emissions, with additional contributions from valves, separators, chemical injection pumps, and pneumatic controllers (35). Estimated fugitive methane emissions associated with US shale gas development are 3.6 to 7.9% of the well's lifetime production, compared with 1.7 to 6.0% for conventional gas (36). Notably, fugitive emissions at well completion for shale gas are two orders of magnitude higher than those for conventional gas (36). The difference primarily originates from emissions due to flowback and drill-out, which are larger in unconventional gas development—due to the dual necessities of large fluid volumes used in massive hydraulic fracturing and long in-reservoir drilling of horizontal boreholes. Stephenson et al. (37) reached similar conclusions, where they found the "well-to-wire (WtW)" emission intensity of shale gas is 1.8 to 2.4% higher than conventional gas because of well completion. Methane leaks from production and inactive wells, referred to as stray gas migration, are another contributor to fugitive methane emissions. During stray gas migration, leaked natural gas can pass through aquifers and emit into the atmosphere or dissolve in groundwater and later partition to the atmosphere (38). Finally, unintended methane leaks may also occur from untargeted gas-bearing zones above the production zone due to well integrity failure and disturbance during fracturing.

Southwest China Faces Water Challenges

The majority of shale resources in China are located along the Yangtze River in South China in areas with high water stress (Fig. 1), including a 1,500 km corridor dominated by exogenous droughts extending along the river mainstem (39). Despite ample water resources, South China experiences seasonal water shortages primarily due to inadequate water quality (40). Since 2012, South China has experienced at least four significant droughts. In the summer of 2022, the Yangtze River experienced record-low water levels, with entire sections and numerous tributaries drying up. Water flow in the main trunk of the Yangtze was more than 50% below the average of the past 5 y. Apart from direct loss of water for use on 2.2 M hectares of agricultural land, the severe drought caused a large reduction in hydropower generation. This loss of generation capacity affected at least 2.46 million people in cities and provinces from upstream to downstream in Sichuan, Hubei, Hunan, Jiangxi, Anhui, and Chongqing (41). With the increasing likelihood of heatwave events in the mid and lower reaches of the Yangtze River under future high-emission scenarios, the risk of drought events is also likely to rise (42). It should be noted that shale gas development consumes ~4 times more water over its life cycle than conventional natural gas production (43). Thus, hydraulic fracturing could consume 35 million cubic meters (mcm) of water and produce 23.7 mcm of wastewater annually at the scale of ~4,800 wells (44)—less than the >6,000 projected. Intensified hydraulic fracturing activity associated with large-scale shale gas development will compete for limited domestic, agricultural, industrial, and environmental water resources in this most populated region of South China. To achieve an annual production of 80 bcm in 2030, up to 792 mcm of water may be required (45). This is equivalent to ~3% of the total water consumption in Sichuan in 2023 (46). Estimates suggest that water stress could intensify by more than 10% by 2035 in the Sichuan basin and other shale gas production areas (44).

Provinces in the Yangtze Basin have a high proportion of electricity delivered by hydropower generation. The proportion provided by hydropower generation in 2022 was ~40% in Hubei and Hunan and ~80% in Sichuan (47). Since China is the world's leading producer of most rare earth elements and many specialty metals, electricity generation curtailments due to drought have the potential to disrupt global supplies of essential materials, drive up prices, and intensify inflationary pressure (48).

In addition to the high demand for water resources, groundwater and surface water can be polluted from formation water and chemical additives within fracturing fluid (49). Although chemicals are usually used in small concentrations within the fracturing fluid, the total mass can be large given the large volume of fluid injected (50). Moreover, a fracturing liquid is usually a complex mixture of chemicals (51), which can cause elevated concentrations of total dissolved solids (TDS), chloride, bicarbonate, and other ions through flowback water from damaged wells or active fractures/faults, as well as from leaking wastewater storage on the surface (52). In the United States, shallow groundwater contamination has been associated with shale gas extraction at major production sites. For instance, in the Marcellus of Pennsylvania, organic contaminants from fracturing fluids were transported ~1 to 3 km along shallow to intermediate depth fractures to a potable aquifer (53). In contrast, a few studies in China show that the salinization of shallow groundwater has only a weak connection with shale gas extraction (52, 54) and can be instead attributed to the natural migration of formation brines along faults and fractures. Nevertheless, China's shale gas development is at an early stage and at a much smaller scale, and lacks systematic studies of groundwater contamination to draw definitive conclusions.

Unlike groundwater, concerns over surface water primarily arise from the management of surface operations and the handling of off-site wastes (55). Areas needed for well pads typically range from 5-10 acres, providing adequate space for pipelines, transport of materials, and handling waste generated during the drilling and hydraulic fracturing processes. Aside from sediment transport during land clearing, the large areas of impermeable surface increase surface water runoff, which may contaminate nearby water bodies (55–57). Inadequate wastewater treatment in China has led to contaminant concentrations surpassing natural background values (NBVs) by 1,000 to 10,000 times and exceeding the lowest quality standards (LQSs) by 10 to 100 times (58). A study of wastewater from the Fuling shale gas field revealed that the concentrations of several contaminants remained above drinking water and ecological standards even after treatment (59). However, dilution brought contaminant levels below regulatory limits after being discharged into a local river. This sudden change emphasizes the importance of water treatment and quality monitoring of treated wastewater from shale gas development. With the Yangtze River stretching across 6,300 km, localized direct contamination of waterways may be carried from shale production zones in the southwest to the east and become a generalized problem if not treated properly.

Stray natural gas migration due to shale gas extraction and other subsurface infrastructure can cause secondary water quality concerns in shallow groundwater and surface water due to biogeochemical reactions. Stray gas is not as well-understood as other fugitive methane emissions (e.g., emissions from surface infrastructure) and comprises only a relatively small proportion of total emissions; however, gas migration may originate hundreds to thousands of meters below the ground surface from deep wells and affect the subsurface at great depth (60). For example, high concentrations of methane have been detected in aquifers above the Marcellus and Utica shale formations in Pennsylvania due to active shale gas extraction (58, 61). Preferential flow pathways for stray gas can be created by poorly sealed new production wells or improperly abandoned preexisting gas wells (62, 63). As natural gas enters shallow aquifers and surface water through breached wellbore seals, subsurface fractures and faults, it can stimulate microbial activity that consumes methane, leading to oxygen depletion and creating anaerobic conditions (64). Under such conditions, iron and manganese oxides in the subsurface can be reduced to soluble forms, increasing their aqueous concentrations and mobility. Moreover, oxidation reactions that consume methane can produce byproducts such as CO_2, Fe(II), Mn(II), and HS^-/H_2S, which may influence groundwater alkalinity and pH and impact color, odor, and taste (60).

Induced Seismicity Is Highly Concerning

Southwest China, which contains the most productive shale gas fields in the country, is also within the collision zone between the Indian and Eurasian Plates (65, 66). The geological structure in this region is highly complex, characterized by intense active tectonic deformation and active fault systems (67). The region has experienced multiple major earthquakes with magnitudes >7, making it one of the most seismically active continental areas in the world. Due to the frequent occurrence of large and major earthquakes, southwest China has long been a key focus of interest within the earthquake research community. In addition to the enormously devastating Ms 8.0 earthquake that occurred in Sichuan Province in 2008 (68), there have been several large earthquakes in southwest China during the past decade, including the 2017 Jiuzhaigou M 7.0 and 2022 Luding M 6.8 earthquakes (69). These large earthquakes can result in significant casualties and extensive damage to the environment, including buildings and infrastructure, and may trigger landslides and floods.

Hydraulic fracturing is designed to enhance reservoir permeability by both reactivating and creating artificial fractures and naturally generates abundant small earthquakes (70–73). The susceptibility to induced seismicity also depends on geological conditions, particularly the proximity to seismogenically active faults (74, 75). Large earthquakes can be induced by high-pressure fluid injection if a preexisting fault is weakened by the pressurized injection. A growing number of moderate to strong earthquakes have been observed in the nearby Changning-Zhaotong shale gas field since operations began there a decade ago (71, 76). Recent studies suggest that these earthquakes could be (partially) attributed to preexisting fault reactivation by hydraulic fracturing, either through fluid migration into the faults and/or poroelastic stress perturbations caused by the fracturing process (77–79). Several notable earthquakes, including the 2018 Ms 5.7, 2019 Ms 6.0, and 2021 Ms 6.0 events that occurred in the South Sichuan Basin, are also thought to be linked with hydraulic fracturing (14, 15, 78, 80). If so, these earthquakes would be some of the largest hydraulic fracturing-induced earthquakes worldwide. Large earthquakes (magnitude > 5.5) that occurred surrounding shale gas fields in southwest China are shown in Fig. 1. We note that the epicenter of the large (Ms 8.0) Wenchuan earthquake in 2008 is less than 300 km away from the shale gas development area. It is possible that the size of induced earthquakes might be controlled by following rigid injection guidelines and traffic light protocols; however, these regions are likely at elevated risk of encountering additional earthquakes due to the combined effect of elevated stress conditions (81, 82) and preexisting faults. The delayed and trailing seismicity associated with wastewater disposal in western Canada supports this possibility (83, 84).

Induced earthquakes are a critical concern for many underground industrial activities, such as mining, geothermal power production, wastewater disposal, and water impoundment. Many studies have revealed that the surge of seismicity in western Canada, Oklahoma, and other parts of the United States is related to hydraulic fracturing and wastewater disposal, respectively (85–89). In certain cases, issues such as ground shaking and environmental damage have led to the suspension or termination of projects, including cases in Blackpool (shale gas project in the United Kingdom), Basel (geothermal project in Switzerland), and Pohang (geothermal project in South Korea) (90, 91). The success of future projects requires that seismic risks are maintained within acceptable limits by employing state-of-the-art seismic monitoring and risk management approaches. Globally, the establishment of induced seismicity regulations and guidelines started about two decades ago and is still at an early stage (92). The Netherlands was the first nation in Europe to incorporate induced seismicity monitoring into regulations (93). In the United States, the issue of injection-induced seismicity was taken into consideration by regulators after 2011 (94). The most widely used tool for induced seismicity hazard and risk management is the traffic light protocol (TLP) (95). The Alberta Energy Regulator (Canada) introduced a TLP with yellow and red lights for magnitudes ML 2.0 and 4.0, respectively (87). Probabilistic seismic hazard analysis (PSHA) and maximum magnitude estimation are still the most common ingredients for current induced seismicity risk assessment, although they are strongly dependent on the statistical estimation of induced seismicity (96, 97). Studies in North America and Europe have advocated adaptive TLP approaches and physics-based models to better manage induced seismicity (98, 99). Practical regulations and protocols are often tailored to specific activities and regions, limiting the direct transferability of regulatory frameworks across different situations. Recent studies have demonstrated a strong connection between hydraulic fracturing and moderate to strong earthquakes in the Sichuan Basin, emphasizing the role of preexisting faults in controlling seismic behavior. This highlights the importance of understanding local geological characteristics in induced seismicity risk management for southwest China (14, 100). The proportion of flowback and produced water in shale gas production from the Sichuan Basin (e.g., 30 to 60% in the Weiyuan shale gas field) is similar to that observed in US shale gas plays (30 to 70%) (101, 102). However, most flowback water in the Sichuan Basin undergoes treatment and recycling for reuse, thereby reducing the wastewater disposal pressure compared to US shale gas operations. The fast-growing number of new wells associated with hydraulic fracturing and the disposal of partial flowback fluids from massive shale gas development are likely to make southwest China a more complicated and concerning earthquake zone in the future.

The Yangtze River Basin Is China's Most Important Ecoregion

Unlike many other countries with shale gas development sites distributed across sparsely populated regions, China's major shale gas fields impinge on more than 120 national nature reserves, accounting for roughly one-quarter of the country's total reserves (103). The Yangtze is one of the most biodiverse rivers in China and home to more than 4,300 aquatic species including 29 rare fish species listed in the National Key Protected Wildlife (104, 105) roster. For example, Chongqing produced over 70% of the country's shale gas in 2013. Yet, it has five national nature reserves with 133 protected plant species and 57 protected animal species (106). Shale gas exploitation poses risks such as soil disturbance, forest degradation, a decrease in the diversity of aquatic life, and a decline in net primary productivity (NPP, a key indicator of vegetation growth and ecosystem productivity reflecting the overall health of the ecosystem and the accumulation of biomass) (107). These risks endanger ecological sustainability as they may result in habitat fragmentation or loss, disrupting critical behaviors such as bird migration patterns and leading to a decline in species populations (108). One study shows that in the Marcellus/Utica shale basin, 48.1% of the observed species in the forests distant from shale gas development sites increased in population from 2005 to 2020, while 55.6% of species proximal to sites decreased (109).

In the shale gas preproduction stage, the most immediate impact is land occupation in establishing industrial operations. Compared to conventional gas, shale gas extraction requires significantly more industrial land for infrastructure, including wells, roads, pipelines, flowback fluid treatment facilities, and mobile modular equipment (110). As a result, significant areas of surface vegetation are destroyed, and land use is changed. For instance, in the shale gas field along the Wujiang River, forested land decreased by 52.78 km^2 and cultivated land by 43.78 km^2 from 2010 to 2020, while developed land increased by 92.04 km^2. There was a concerning loss of 250 km^2 in the ecological source area, highlighting a substantially higher ecological disturbance compared to other undeveloped shale gas regions (111). Soil erosion is another common side effect of shale gas development. In Yibin of Sichuan Province, well pads have caused soil erosion outward to a distance of 90 m (112). In the shale gas production area of Fuling, Chongqing, 55.8% of the region (146.56 km^2) is at risk of soil erosion and rocky desertification (113).

In the later stages of shale gas production, significant volumes of fracturing fluid are consumed, and substantial quantities of wastewater are produced (114). Studies show that hazardous organic components in the discharged wastewater can lead to poor plant growth (115) and exhibit aquatic ecological toxicity (110, 116). The increased use of drilling fluids due to technological limitations and complicated geological conditions leads to a higher ecological risk from fracturing fluid escape and dissemination in shale gas exploitation compared to the United States. The ongoing impacts of constructing shale gas extraction platforms throughout the development stages will ultimately affect the net primary productivity (NPP) of the area, primarily due to the destruction of surface vegetation and changes in land use. In the karst areas of Sichuan, shale gas development has decreased the overall NPP by 0.35% (117). The greatest decline was as high as 63% within 30 m of well pads between 2012 and 2017. Furthermore, soil erosion, sedimentation, and groundwater contamination during the extraction phase can pose additional threats to vegetation growth and NPP.

Outlook for a Sustainable Development

In the United States, the Environmental Protection Agency (EPA) partners with states and other key stakeholders through initiatives and memoranda of understanding to enhance communication, foster mutual understanding of responsibilities, and address jurisdictional issues, driving environmental improvements and regulatory clarity while addressing the challenges of oil and gas extraction. For example, EPA studied the potential impacts of hydraulic fracturing on drinking water and released a final report in 2016. The management practices were made in partnership with states after examining different methods employed by industry to ensure the safe disposal of wastewater, stormwater, and other wastes. Such efforts extended to improving air quality by reducing methane and volatile organic compound (VOC) emissions through initiatives like the Natural Gas STAR program, where EPA has worked with industry stakeholders to identify better practices and technologies that can cost-effectively address these environmental concerns. In China, shale gas development is regulated by the Energy and Natural Resources Laws, but comprehensive and systematic regulations are lacking (118). Considering that China's energy policies actively encourage green energy exploration and the extraction of natural gas to achieve the 2030 and 2060 carbon peaking and neutrality goals, specific regulations on shale gas development need to be enacted so that environmental requirements can be enforced by oil and gas regulators for air, surface water, and groundwater pollution control. We summarize some of the prioritized recommendations in Table 2.

Methane is a more powerful GHG than CO_2 (EPA suggests CH_4 causes 28 times greater impact than CO_2 over 100 y).

Table 2. Prioritized recommendations for sustainable shale gas development

Recommendations	Potential impact	Hurdles to implementation
• Strengthening environmental regulations and operation guidelines encompassing shale gas development from exploration to abandonment • Developing stricter (post) environmental impact assessments	• Reduction in GHG emissions • Minimized risk of induced seismicity and ecological disturbances	• Enforcement challenges due to opposition from key stakeholders • Long regulatory approval process • Lack of technical expertise
• Implementing real-time detection and monitoring systems for both active and abandoned wells	• Early intervention for methane and fracturing liquid leakage and seismic activities	• High initial implementation cost • Technical complexity • Potential data accuracy issues
• Water recycling and treatment technologies • Developing nonaqueous fracturing	• Reduced water use and minimized contamination risk	• Long-term R&D process • High operational cost • Advanced infrastructure is required
• Utilizing vented and flare gases • Updating shale gas equipment • Setting equipment emission standards	• Significant reduction in GHG emissions	• Long-term R&D process • Additional cost to replace current equipment • Lack of authoritative quality standards and testing services
• Carbon capture and sequestration technologies • Carbon pricing and emission caps	• Offsetting GHG emissions and enhancing sustainability of shale gas	• Technologies are at the initial stage • Lack of fundamental understanding • Collaborative efforts and strategic investments are required from various bodies • Increased operational costs • Difficulty in accurately valuing carbon emissions • Challenges in policymaking and enforcement

The lifespan of methane in the atmosphere, however, is only about a decade on average, while CO_2 can persist for hundreds of years (119). Thus, cutting methane emissions has a more immediate impact on global warming. As fugitive gases from venting and flaring are among the most significant contributors to methane emissions in shale gas development, efforts should be made to enhance sealed gas transportation, actively recycle vented gas, and promote efficient flare gas utilization. In 2023, the Chinese Ministry of Ecology and Environment (MEE) announced the *Action Plan for Methane Emission Control*, encouraging oil and gas companies to achieve zero routine flaring in onshore oil and gas operations. If established, a methane emissions accounting and reporting system for the oil and gas industry could regularly track methane emissions and promptly address and mitigate detected leaks. Standards need to be set for mandating GHG reductions from high-emission equipment such as controllers, pumps, and storage tanks (120). Currently, most of China's shale gas equipment originates from the traditional oil and gas extraction sector. Specialized upgrades are needed in areas such as geological structure analysis, drilling, well completion, and fracturing. Setting equipment emission standards would promote the advancement and usage of innovative technologies in reducing GHG emissions. It is also recommended to establish authoritative quality standards and testing services to guide equipment manufacturers in the right direction.

China's oil and gas industry is structured in a way that fragments research efforts across different entities. The industry's innovation ecosystem lacks market-driven, open platforms where technology and knowledge can be shared freely. For oil and gas companies, fundamental research should be highly encouraged in close collaboration with universities and research institutes to understand better shale reservoirs [e.g., nanoscale gas adsorption and transport (121, 122), reducing life cycle GHG emissions, and searching for environmentally friendly or alternative fracturing fluids to replace water (e.g., CO_2 fracturing). Hazardous waste, such as drill cuttings and flowback liquids produced during exploration, must be carefully handled by qualified disposers. An initial thorough assessment of geological conditions and potential environmental risks, including local water availability, interactions with aquifers, and fault mapping, must be conducted before development. Given the high population density and sensitivity of the surrounding ecological reserves (Fig. 1) together with plans for rapid shale gas development, there is an urgent need to propose stringent induced seismicity regulations and guidelines for southwest China. A scientific assessment of induced seismicity risks should follow a deterministic and physics-based approach by integrating enhanced seismic catalogs, deterministic geological information (e.g., characterization of fractures/faults and stress), and transparent operational plans (e.g., injection rates and volumes) (79). A postenvironmental impact assessment should be promptly organized for existing projects. Furthermore, a monitoring system must be built to pinpoint leaks of methane and fracturing fluid from both active and abandoned wells. Operators should always be ready, proactively avert, swiftly respond to, and effectively recover from, emergencies and incidents. In the United States, EPA focuses its compliance and enforcement activities on addressing violations that pose significant risks to human health and the environment. They work with state and local governments to respond to incidents and promote accident prevention. Regional offices assist in implementing federal laws by offering guidance, conducting inspections, and taking enforcement actions. In 2019, EPA launched a voluntary disclosure program aimed at new owners of upstream oil and gas facilities to ensure regulatory certainty and offer civil penalty mitigation, which was later expanded to encourage existing owners to identify and correct Clean Air Act violations. Additionally, EPA provides a compliance assistance portal to help oil and gas operators navigate environmental regulations and maintain compliance with federal and state laws. By learning from the US shale gas experience on environmental management, policy enforcement, and technological advancements, China can avoid some of the drawbacks encountered by the United States and adopt best practices. It is crucial for the government, industry, and academic communities to collaborate in clarifying the key factors driving the environmental impacts associated with hydraulic fracturing to ensure its shale gas development is both environmentally sustainable and economically viable.

Conclusions

China's shale gas reserves are concentrated in water-scarce, densely populated, and environmentally sensitive areas with a major portion of these along the Yangtze River. The reservoirs are generally deeper and in more varied and structurally more complex sediments compared to US shale formations, posing greater challenges and more demanding equipment requirements. A boom in the large-scale development of shale gas is inevitable in the next few decades in line with China's national energy strategy; however, the rapid development of shale gas, coupled with the use of early-stage extraction technologies and less mature regulations, poses significant challenges to China's environmental commitments (e.g., *2030 Carbon Peaking and 2060 Carbon Neutrality*, *the Yangtze River Protection and Ecological Restoration Program*) and may have negative implications for several of the United Nations Sustainable Development Goals. We have presented potential national and global impacts that should be considered for shale gas development, including GHG emissions, water resource consumption and pollution, induced seismicity, and ecological disruption. The government and all sectors of society must actively collaborate and take the necessary measures to minimize the negative environmental impacts of shale gas development. An environmental management system encompassing research and assessment before, during, and after field exploitation is needed to pave the way for the sustainable development of shale gas production.

Data, Materials, and Software Availability. All study data are included in the main text.

ACKNOWLEDGMENTS. We appreciate support from the National Natural Science Foundation of China (U23B20155; 42488201; and 42374076), the Science and Technology Innovation Program of Hunan Province (2023RC1021), and the Central South University Innovation-Driven Research Program (2023CXQD063). We gratefully acknowledge the European Commission Joint Research Centre Emissions Database for Global Atmospheric Research as the source of the data used to produce Fig. 2*C* (https://edgar.jrc.ec.europa.eu/dataset_ghg80).

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