communications earth & environment

ARTICLE

https://doi.org/10.1038/s43247-023-00859-6 OPEN

Projected increases in emissions of high global warming potential fluorinated gases in China

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China is the largest greenhouse gas emitter in the world and has committed to mitigating global warming through achieving carbon neutrality by 2060. However, detailed information on China's historical and projected emissions of fluorinated greenhouse gases, with high global warming potentials, is lacking. Here we establish a comprehensive and up-to-date inventory of China's fluorinated greenhouse gas emissions and find that they show an accelerating growth rate, increasing from 5.5 to 221 million tons CO_2-equivalent per year from 1990 to 2019. China has become the world's largest emitter of fluorinated greenhouse gases and contributed 93% of the global emission increase during the period 1990−2019. We find that total emissions of fluorinated greenhouse gases from China are projected to increase to 506–1356 million tons CO_2-equivalent per year in 2060 if there is no regulation, which is larger than the projected CO_2 emissions under China's carbon neutrality commitment for 2060.

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Sulfur hexafluoride (SF_6), nitrogen trifluoride (NF_3), and 4 perfluorocarbons (PFCs-CF_4, C_2F_6, C_3F_8, and c-C_4F_8) (the fluorinated greenhouse gases abbreviated as F-GHGs) studied here, are all potent GHGs, with long atmospheric lifetimes and high global warming potentials (GWPs) (shown in Supplementary Table 1)[1]. Hydrofluorocarbons (HFCs) are also potent greenhouse gases containing fluorine. Their emissions from China are not considered here, since they already have been discussed extensively in Fang et al.[2] and Li et al.[3]. Li et al.[3] shows that HFCs emissions in 2017 reached 108 million tons CO_2-equivalent $year^{-1}$ (Mt CO_2-eq yr^{-1}), accounting for 59% of total F-GHGs emissions (182 Mt CO_2-eq yr^{-1} in 2017 in this work) in China. The emissions of SF_6, NF_3, and PFCs are incorporated in the greenhouse gas commitments of Kyoto Protocol[4,5] and in the long-term temperature goal of the Paris Agreement[6] under the United Nations Framework Convention on Climate Change (UNFCCC). Unlike methane (CH_4) and nitrous oxide (N_2O), which have both natural and anthropogenic sources, these F-GHGs, except for CF_4, are emitted only from anthropogenic activities and as chemical products[7].

Most of the developed countries are required to submit their annual emission estimates to the United Nations Framework Convention on Climate Change (UNFCCC; so-called "Annex I" countries) and have shown emission reductions[8]. However, developing countries are not required to report their emissions to UNFCCC (so-called "non-Annex I" countries) annually. China is one of these "non-Annex I" countries. Emissions of F-GHGs in four individual years (2005, 2010, 2012, and 2014) have been reported officially by China as a "non-Annex I" country to the UNFCCC[9–12]. Other published studies also report F-GHGs emissions from China, either bottom-up inventories[13–16] or top-down observation-based emission estimates[17–26]. However, all of these estimates of F-GHGs emissions from China have problems with missing species, incomplete source sectors, and limited target years (see details in Results and Discussion), which prevents a comprehensive, accurate understanding of the historical F-GHGs emissions from China and their contributions to global emissions, atmospheric radiative forcing and temperature rise. In September 2020, China announced at the United Nations General Assembly that it would strive to peak carbon dioxide emissions by 2030 and achieve carbon neutrality by 2060, while the neutrality goal is generally ambiguous about the inclusion of non-CO_2 greenhouse gases (e.g., CH_4, N_2O, HFCs, SF_6, NF_3, PFCs), meaning that it is not officially clear whether SF_6, NF_3, and PFCs are included in this carbon neutrality goal so far.

This study investigates the historical production and consumption of the six F-GHGs in China from all source sectors for 1990–2019, providing the latest and most comprehensive bottom-up emission estimates for China, with validation by top-down estimates. Compared to previous bottom-up inventory studies, this study improves estimations of historical F-GHGs emissions from China by including all the six most important F-GHGs as target gases and historical years since 1990. These emissions are then compared to global emissions, emissions from Annex I countries, and from other countries, to assess the contribution that China's emissions make to observed global emissions. Finally, China's F-GHGs emissions throughout 2020–2060 are projected and evaluated in terms of the role that F-GHGs play in achieving China's carbon neutrality by 2060, and in affecting the global atmospheric radiative forcing and temperature rises.

Some other fluorinated species (such as HFCs, SO_2F_2, less abundant PFCs, and fluorinated anesthetic gases) were not covered in our work according to the following analysis (see Supplementary Table 2). Emissions of HFCs (214 Mt CO_2-eq yr^{-1}) were equivalent to 74% of the total emissions of HFCs, SF_6, and PFCs (291 Mt CO_2-eq yr^{-1}) in 2014 based on China's 2nd Biennial Update Report[12]. Historical emissions of HFCs from China during 1980–2014 and 1995–2017 have been well investigated by Fang et al.[2] and Li et al.[3], respectively. Thus, this study does not include relatively well-understood emissions of HFCs but focuses on the poorly understood emissions of SF_6, NF_3, and PFCs. Meanwhile, emissions of SO_2F_2 in China were estimated to be 2.3 ± 2.3 Mt CO_2-eq yr^{-1} during 2011–2016 and 1.5 ± 1.5 Mt CO_2-eq yr^{-1} during 2017–2019 by a tracer-ratio method[27]. This represents approximately only 1% of total emissions of SF_6, NF_3, and PFCs estimated in this study. As for low-abundant PFCs (such as C_4F_{10}, C_5F_{12}, C_6F_{14}, C_7F_{16}, and C_8F_{18}), there are no reported emissions for China. However, according to the latest EDGAR v7.0 emission inventory[28], the global emissions of less abundant PFCs (C_4F_{10}, C_5F_{12}, and C_6F_{14}; 1.6 Mt CO_2-eq yr^{-1}) in 2019 was only 2.9% of the global total PFCs emissions (56 Mt CO_2-eq yr^{-1}) and only 0.72% of the total SF_6, NF_3, and PFCs emissions (221 Mt CO_2-eq yr^{-1}) for China in 2019. As for fluorinated anesthetic gases (such as sevoflurane, desflurane, isoflurane), no emission reports of these gases in China were readily available for review. According to Varughese et al.[29], the contributions of inhaled anesthetics (desflurane, isoflurane, and sevoflurane; 5.6 Mt CO_2-eq yr^{-1}) to total GHG emissions during 2011–2013 in the United States was less than 0.1%. Note that the activity data (production, consumption, and disposal) for SO_2F_2, lower abundant PFCs, and fluorinated anesthetic gases in China are currently unavailable. However, considering the minor emission rates of these gases, the omission of these gases from this study does not affect the results.

Results and discussion

Improved estimations of historical F-GHGs emissions in China. The official inventory reports from the Chinese government to UNFCCC[9–12] included SF_6, CF_4, and C_2F_6, and Fang et al.[15] included SF_6 only. Missing some of F-GHGs prevents a complete understanding of F-GHGs emission profiles and changes in China. Although the emission inventory built by the Environmental Protection Agency (EPA) of the United States[30] covered the emissions of the above six F-GHGs in China, the EPA inventory were not able to provide emission estimates for the latest years (2016–2019). Meanwhile, the national official inventory reports to UNFCCC[9–12] only provided emission estimates for four years (2005, 2010, 2012, and 2014), and Fang et al.[15] only provided emission estimates up-to 2010. Comparisons of the number of years in this study to previous bottom-up studies are shown for each F-GHG in Supplementary Fig. 1. Thus, this study provides emission estimates for all these six F-GHGs and the whole period 1990–2019.

Compared to previous bottom-up inventory studies, this study also improves estimations of historical F-GHGs emissions from China by including almost all relevant emission sectors, since a substantial number of emission sectors were missing in previous studies (Supplementary Fig. 1; see details in Supplementary Tables 3 and 4). For instance, Fang et al.[15], the EDGAR v4.2&FT2010[13,14], and the latest EDGAR v7.0[28] included four source sectors of SF_6 emissions, namely electrical equipment, magnesium production, semiconductor manufacture, and SF_6 production, and the national inventory reports only include SF_6 emissions from aggregated consumption data of halocarbons and SF_6[9–12], while this study included five additional source sectors for SF_6 emissions, namely use in medical procedures, in air-tracer experiments, as a fire extinguisher, by the military, and in refrigeration. For NF_3, CF_4, C_2F_6, C_3F_8, and c-C_4F_8, the number of emission sectors covered in this study is much larger compared to previous studies (Supplementary Fig. 1 and Supplementary Table 4).

As for the previous top-down studies using atmospheric observations and inverse modeling, the restricted number of target years for estimating emissions limited the understanding of the temporal trends in the six F-GHGs emissions from China. The previous top-down studies only presented China's F-GHGs emissions for a single year or a limited number of years[18,22,23] (Supplementary Fig. 1). For example, NF_3 emissions in the years 2014–2015 were estimated[22], CF_4 emissions (2008–2015)[22], C_2F_6 and C_3F_8 emissions (2008)[18], and c-C_4F_8 emissions (2010–2017)[26]. Emissions before 2008 have not been estimated using the top-down approach (Supplementary Fig. 2), since atmospheric observations were not available. Thus, this study provided emission estimates for more historical years compared to the top-down studies, which is beneficial for understanding historical changes in F-GHGs emissions in China.

Historical F-GHGs emissions in the current study are validated with previous top-down observation-based results according to Supplementary Fig. 2. Our bottom-up results for these F-GHGs agree with the previous top-down emission estimates, with acceptable levels of uncertainty. For example, the average SF_6 emissions during 2007–2012 estimated by this study were 1764 (1550–1978) tons per year (t yr^{-1}) and agree with the recent estimate of SF_6 emissions [1878 (1727–2029)][21]. Based on our study, the average historical emissions of CF_4 from 2014 to 2019 were 5495 (4600–6393) t yr^{-1}. This approximates the results [5973 (5766–6186) t yr^{-1}] by Kim et al.[31] over the same period. Similarly, our results for C_2F_6 emissions in 2019 [1071 (677–1466) t yr^{-1}] are in good agreement with the results by Kim et al. [1130 (1100–1150) t yr^{-1}][31].

Fast-growing F-GHGs emissions during 1990–2019 in China. The production and consumption data (consumption means the amount of F-GHGs used = production + imports – exports) for the six F-GHGs in this study (tabulated in Supplementary Figs. 3–5) were derived from sources such as yearbooks, reports, news, and interviews with industry experts. Supplementary Fig. 3 shows that the national SF_6 production and consumption data used in this study overall agrees with Fang et al.[15] (1990–2010) in terms of magnitude and temporal trend. NF_3 consumption data are consistent with those from other sources[32,33] (6% differences on average during the available years of 2004, 2006, 2007, 2009, and 2015–2019; Supplementary Fig. 4). CF_4 consumption data in this study are also consistent with those from other studies[34] (around 2% difference on average during the available years of 2011–2018; Supplementary Fig. 5a).

Throughout this manuscript, we refer to total F-GHGs emissions as the sum of emissions of SF_6, NF_3, CF_4, C_2F_6, C_3F_8, and c-C_4F_8. In terms of GWP-weighted emissions, the emissions of SF_6 in 2019 (115 ± 31 Mt CO_2-eq yr^{-1}, million tons CO_2-equivalent $year^{-1}$) were 52% of total F-GHGs emissions and were greater than those of CF_4 (48 ± 18 Mt CO_2-eq yr^{-1}; 21%), NF_3 (29 ± 12 Mt CO_2-eq yr^{-1}; 13%), c-C_4F_8 (14 ± 9.7 Mt CO_2-eq yr^{-1}; 6.1%), C_2F_6 (13 ± 4.8 Mt CO_2-eq yr^{-1}; 5.7%), and C_3F_8 (3.6 ± 2.2 Mt CO_2-eq yr^{-1}; 1.6%) (Fig. 1). Thus, in the perspective of global warming mitigation, control of SF_6 is a priority in China, followed by CF_4 and NF_3. In terms of CO_2-eq emissions of F-GHGs, the electrical equipment sector contributed most (24%), followed by the semiconductor manufacture (22.1%), primary aluminum production (13%), medical use (7.4%), and HCFC-22 feedstock use (5.7%) in 2019 (Fig. 2). As for individual F-GHG, the major emission sectors are the electrical equipment sector (for SF_6), semiconductor manufacture (for NF_3), primary aluminum production (for CF_4), semiconductor manufacture (for C_2F_6), medical use (for C_3F_8), and HCFC-22 feedstock use (for c-C_4F_8), respectively (see Supplementary Figs. 6–8).

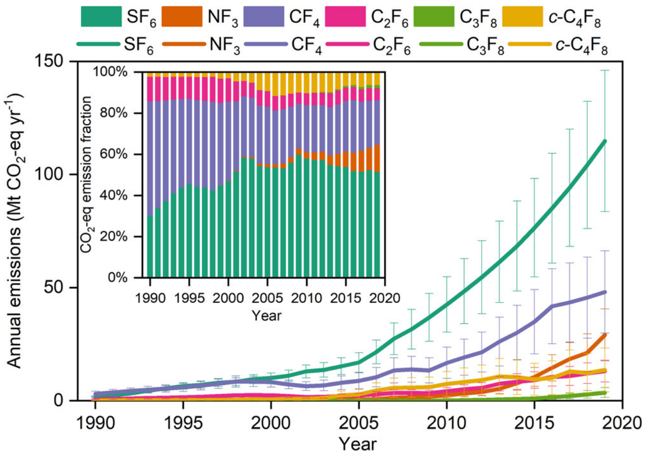

Fig. 1 The estimated historical CO_2-eq emissions of SF_6, NF_3, CF_4, C_2F_6, C_3F_8, and c-C_4F_8 from China over the period 1990–2019. GWP values over a 100-year-time horizon from IPCC's 4th Assessment Report (AR4) in 2007[51] shown in Supplementary Table 1 are used to calculate F-GHGs CO_2-eq emissions. The error bars here represent the uncertainties of F-GHGs emissions due to the uncertainties of activity data and emission factors.

The contributions to emissions growth over 1990–2019 from the perspective of species and sectors in China are also identified in this study, which implies the priority of future controls. Figure 3a shows that the increase in annual F-GHG CO_2-eq emissions during 1990–2019 were mainly driven by the SF_6 (52.7%), CF_4 (20.3%), and NF_3 (13.5%), while the other three F-GHGs totally contributed 13.5%. As for emission sectors, the increase in annual F-GHG CO_2-eq emissions during 1990–2019 was mainly driven by the electrical equipment sector (24.2%), semiconductor manufacture (22.7%), primary aluminum production (11.7%), medical use (7.6%), and HCFC-22 feedstock use (5.8%), while other 9 sectors contributed a total of 27.9% (Fig. 3b).

Contribution from China to global F-GHGs emissions. Figure 4 shows the global total emissions of F-GHGs[21,35,36], emissions of F-GHGs from China (this study), UNFCCC Annex I countries emissions (UNFCCC database[8]), and non-Annex I countries other than China (global totals minus China and Annex I countries). Global emissions of SF_6 and NF_3 are currently only available for the years before 2018 and 2017, respectively; thus, global emissions for 2019 and during 2018–2019 were obtained by extrapolation of emissions of 2014–2018 and 2013–2017, respectively. During 1990–2019, the average contributions from China to global emissions increased from 1.4 to 55% for SF_6, 0.30 to 70% for NF_3, 2.6 to 47% for CF_4, 2.4 to 49% for C_2F_6, 0 to 72% for C_3F_8, and 1.2 to 58% for c-C_4F_8, implying that China has become the largest emitter of F-GHGs, especially for C_3F_8, NF_3, c-C_4F_8, and SF_6 across the world.

Comparisons of emissions among China and UNFCCC Annex I countries show that China's total CO_2-eq emissions of the six F-GHGs (5.5 Mt CO_2-eq yr^{-1}) were only 3.8% of the total UNFCCC Annex I countries' emissions in 1990 (Fig. 4g). Then, China's total CO_2-eq emissions of the six F-GHGs (51 Mt CO_2-eq yr^{-1}) surpassed the total UNFCCC Annex I countries' emissions (49 Mt CO_2-eq yr^{-1}) in 2007 and continued to grow after 2007 (Fig. 4g). The emissions from China reached about 8 times the total UNFCCC Annex I countries' emissions in 2019 (Fig. 4g). Meanwhile, since 2018, China's total CO_2-eq emissions of the six F-GHGs (198 Mt CO_2-eq yr^{-1} in 2018) have surpassed those of total UNFCCC non-Annex I countries other than China (177 Mt CO_2-eq yr^{-1} in 2018). Between 2000 and 2019, the

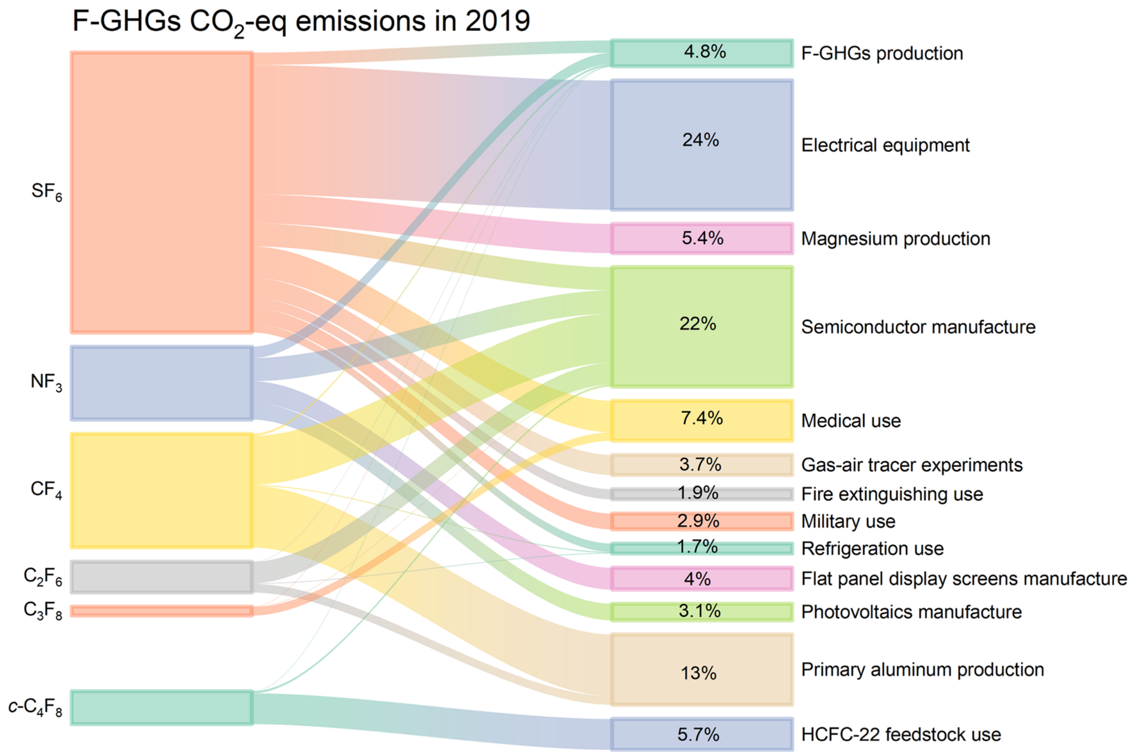

Fig. 2 F-GHGs CO_2-eq emission contribution of different sectors from China in 2019. The percentages represent ratios of the F-GHGs emissions from a single source sector in 2019 to the total F-GHGs emissions from all source sectors in 2019.

increase in global F-GHGs emissions was 160 Mt CO_2-eq, the increase in China's emissions was 201 Mt CO_2-eq, the increase in non-Annex I countries other than China was 16 Mt CO_2-eq, and the decrease in Annex I countries was 57 Mt CO_2-eq. Thus, the increase in China's emissions explained most (93%) of the global increase.

For individual F-GHG, emissions of six F-GHGs except for c-C_4F_8 from China all surpassed emissions from the Annex I countries during 2007–2012, and surpassed emissions from non-Annex I countries other than China during 2017–2019 (Fig. 4a±e). c-C_4F_8 emissions in China were nearly always larger than those from the Annex I countries and larger than those from non-Annex I countries other than China after 2010 (Fig. 4f). This might be caused by HCFC-22 feedstock use (the main emission sector for c-C_4F_8) largely occurring in China compared to other countries[37] and also caused by the fact that emission estimates of c-C_4F_8 were only reported by some Annex I countries, e.g. only 9 countries compared to 43 Annex I countries for c-C_4F_8. China's production of electronic components is on the rise. The report 'Government Incentives and US Competitiveness in Semiconductor Manufacturing' states that China's share of the global semiconductor manufacturing capacity has grown rapidly from 1% (1990–2000) to 15% (2010–2020)[38]. The report also indicates that during the next decade China is expected to increase its new capacity by approximately 40%, thereby becoming the largest global semiconductor manufacturing location[38]. Moreover, this report shows that the semiconductor manufacturing capacity of US has decreased from 37% in 1990 to 12% in 2018[38]. In addition, the International Aluminum Institute (IAI) shows that the primary aluminum production in China has continued to climb since 1999, reaching 5547 thousand metric tons (kt) in 2003, surpassing the primary aluminum production in other regions, such as North America (5495 kt), Western&Central Europe (4068 kt), and Russia&Eastern Europe (3996 kt)[39]. Moreover, the contribution of primary aluminum production in China to the global total primary aluminum production nearly reached 50% in 2013 and rose to 56% in 2019[39]. The industry-associated F-GHGs emissons are determined collectively using direct emissions from industrial processes and the subsequent application of mitigation measures. Several other regions of the world have developed mitigation measures for F-GHGs. For example, the US EPA has operated voluntary action programs to reduce SF_6 and PFCs emissions in the electrical equipment, semiconductor manufacturing, and magnesium production industries[40,41]. However, industry-related F-GHGs mitigation measures are inadequate in China. Thus, the increasingly dominant manufacture of these products and China's current circumstances of mitigation collectively account for the associated F-GHGs emissions in China. Overall, China became the most important contributor to global F-GHGs emissions in the past 30 years. Thus, China will play an inevitable role in global F-GHGs mitigation in the future, considering the accelerated increase in China's emissions and the rapid increase in China's contributions to global totals in the past 30 years.

Impacts of F-GHGs emissions on China's greenhouse gases mitigations. This study shows that F-GHGs emissions can not be ignored in China's total historical and future GHG emissions (Fig. 5). Total CO_2-eq emissions of the F-GHGs in China grew from 5.4 Mt CO_2-eq yr^{-1} in 1990 to 221 Mt CO_2-eq yr^{-1} in 2019, with the ratio of total F-GHGs CO_2-eq emissions relative to China's CO_2 emissions[42] exponentially growing from 0.23% in 1990 to 2.2% in 2019 (Fig. 5a). Although the historical F-GHGs total emissions accounted for only 2.2% of China's CO_2 emissions, China's F-GHGs total emissions were close to the national CO_2 emissions of Spain (251 Mt CO_2-eq yr^{-1}), and Ukraine (223 Mt CO_2-eq yr^{-1}), and larger than those of the Netherlands (153 Mt CO_2-eq yr^{-1}), Czechia (101 Mt CO_2-eq yr^{-1}), and Belgium (100 Mt CO_2-eq yr^{-1}) derived from the National Inventory Reports submitted to UNFCCC[8].

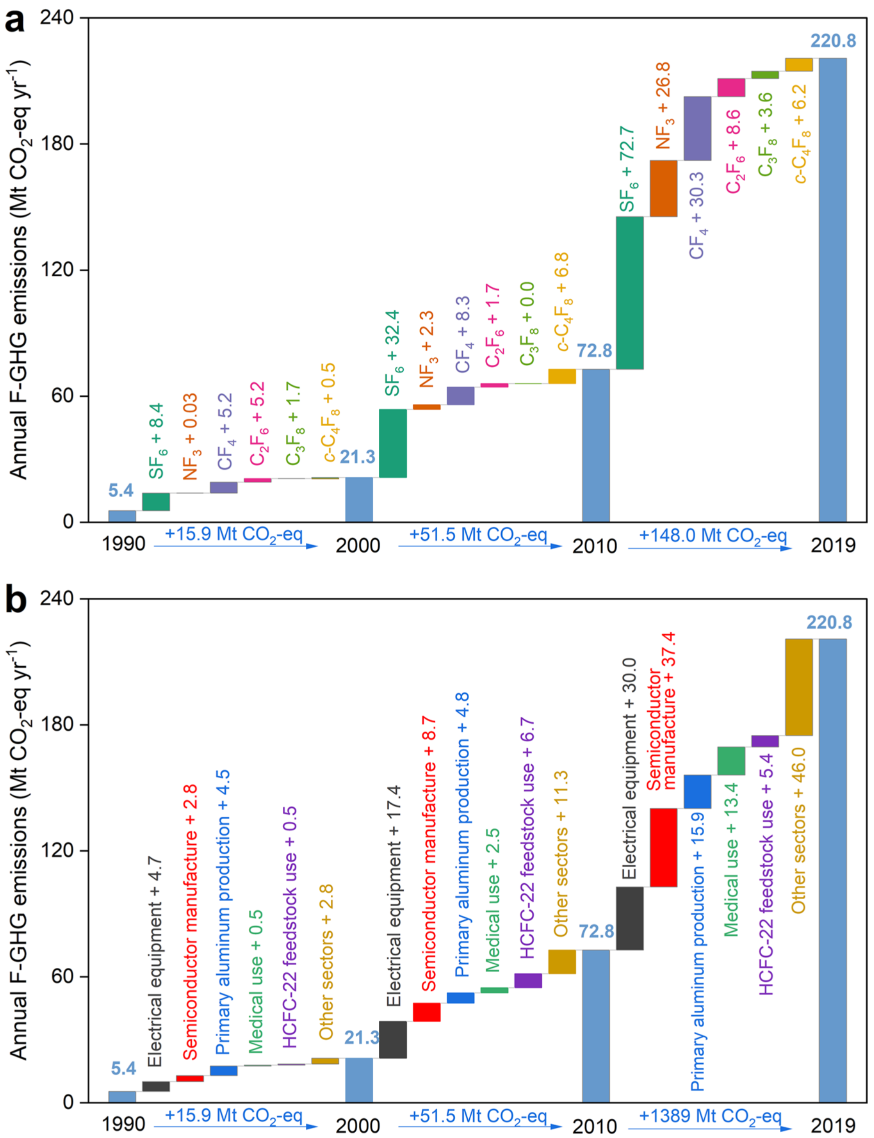

Fig. 3 Contribution of each F-GHG and sector to the change in annual F-GHG CO_2-eq emissions in the period of 1990–2000, 2000–2010, and 2000–2019. **a** Contribution of F-GHG to changes in total F-GHG CO_2-eq emissions. **b** Contribution of each sector to changes in total F-GHG CO_2-eq emissions.

China's future emissions of the six F-GHGs from 2020 to 2060 are projected based on China's future gross domestic product (GDP; Supplementary Fig. 9)[43–45] and the relationship between historical GDP[46] and historical F-GHGs production/consumption data (see Methods for details). Although the economic situation and consumption pattern of China might change in the future, the projections present a set of future scenarios based on the very good agreement between historical GDP and F-GHG consumption in each sector. Some other studies also used GDP to predict the future growth of F-GHG emissions. For example, Lin et al.[47] assumed growth rates of C_2F_6 emissions in semiconductor manufacturing from 2020 to 2050 based on national GDP growth rates through 2050. In the work of Teng et al.[48], they assumed that the usage of F-GHGs each year in semiconductor manufacturing would be proportional to semiconductor matrix production, and set the rate of increase in semiconductor matrix production after 2020 to be equal to the rate of increase in GDP. Similarly, the EPA projection report shows that the semiconductor manufacturing capacities for a specific country from 2020 through 2050 are estimated by growing the manufacturing capacity at a rate equivalent to the growth in the GDP of that country over the same period[30]. The total F-GHGs emissions in China are projected in this study to increase to 506–1356 Mt CO_2-eq yr^{-1} (reflecting the variance in China's F-GHGs emissions in 2060 caused by the difference in GDP growth rates among different GDP projection scenarios) in 2060 assuming zero mitigation of these F-GHGs emissions in the future (Fig. 5b). CO_2 emissions from China are projected to decline to 600–1090 Mt yr^{-1} by 2060 under the carbon neutrality target[49,50] (Fig. 5b). Note that both two studies did not exactly interpret the goal as CO_2 neutrality or GHG neutrality. Thus, the projected F-GHGs emissions (506–1356 Mt CO_2-eq yr^{-1} in 2060), if unabated, will equal or even exceed the CO_2 emissions (600–1090 Mt yr^{-1}) in 2060. In other words, an extra 506–1356 Mt CO_2-eq yr^{-1} of F-GHGs will be emitted into the atmosphere in 2060 if carbon neutrality only applies to CO_2 emissions. We also show that future increasing F-GHGs will lead to an increase in global atmospheric radiative forcing of 16.5–32.2 mW m^{-2} (Fig. 5c), and cause a temperature increase of 0.013–0.025 °C (Fig. 5d). Emission mitigation actions should be

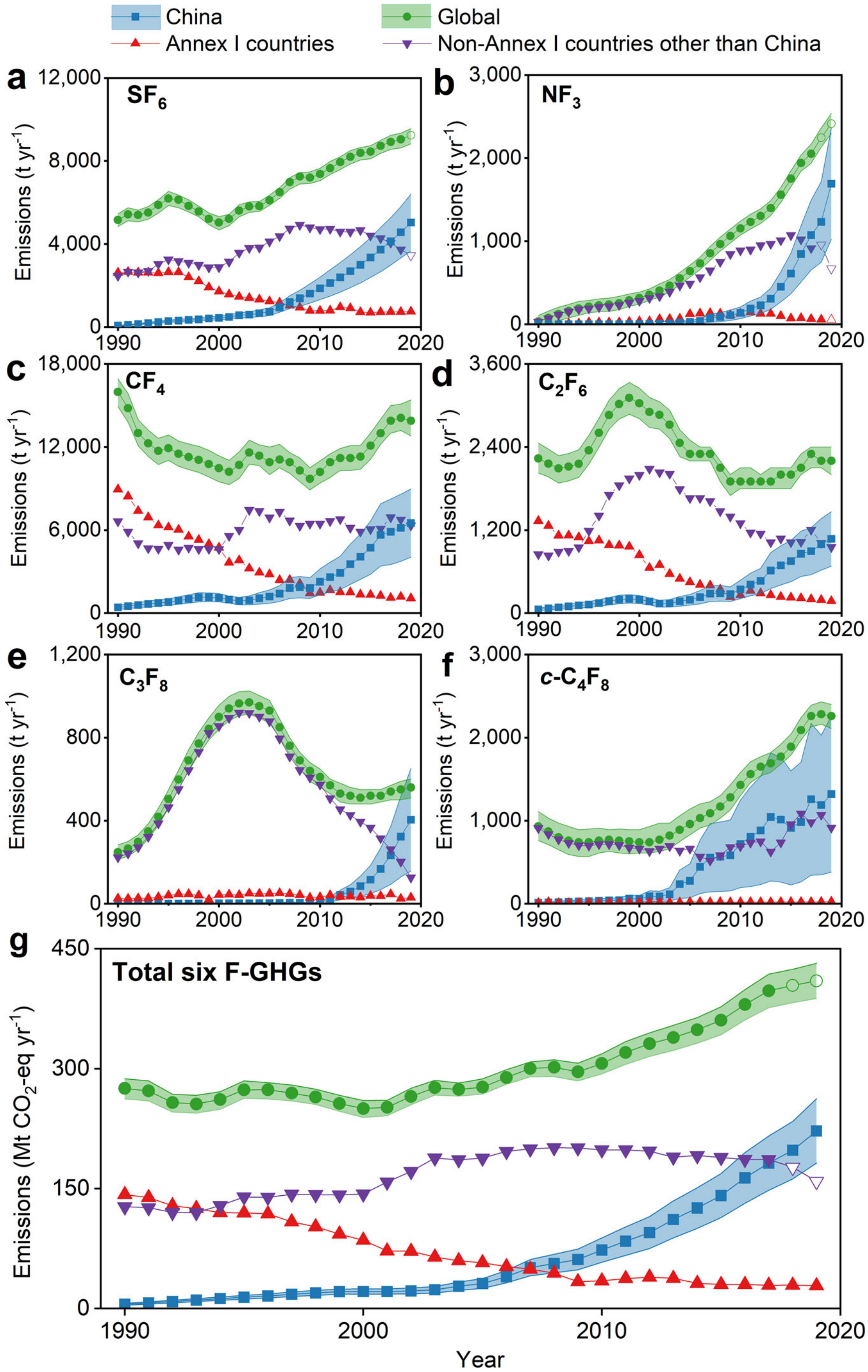

Fig. 4 F-GHGs emissions from China (this work), the global totals derived from Simmonds et al.[21], Say et al.[35], and updates of Rigby et al.[36]; the Annex I countries from UNFCCC[8], and non-Annex I countries other than China during 1990–2019. a–g are the global emissions, emissions from China, emissions from Annex I and non-Annex I countries for SF_6, NF_3, CF_4, C_2F_6, C_3F_8, c-C_4F_8, and the sum of all F-GHGs, respectively. The hollow symbols represent extrapolated emissions according to emissions of the recent 5 years (see main text).

targeting the major sectors for future F-GHGs emissions such as the electrical equipment (contribution of 24% of total emissions in 2060), semiconductor manufacture (22%), primary aluminum production (11%), and medical use (8%) (Supplementary Fig. 10d). These source sectors are important for China's F-GHG emission mitigation strategies in the future.

China has announced the goal of carbon neutrality by 2060, but it is not officially clear whether non-CO_2 greenhouse gases like the F-GHGs are included in this goal. Total F-GHGs emissions if unabated (506–1356 Mt CO_2-eq yr^{-1} projected in this study) are close to CO_2 emissions (600–1090 Mt yr^{-1}) in 2060 (Fig. 5b), revealing the potential importance of these F-GHGs emissions from China. Therefore, China's F-GHGs emissions have been increasing rapidly in the past 30 years, contributed largely to the global F-GHGs emissions, and showed a potentially increasing impact on national and global GHGs mitigations. In the future, the collection of activity data and emission factors along with an investigation into the implementation of mitigation measures for F-GHGs are required to make a continuous, timely, and accurate assessment of F-GHGs in China. This will guide China's future emission reduction of F-GHGs.

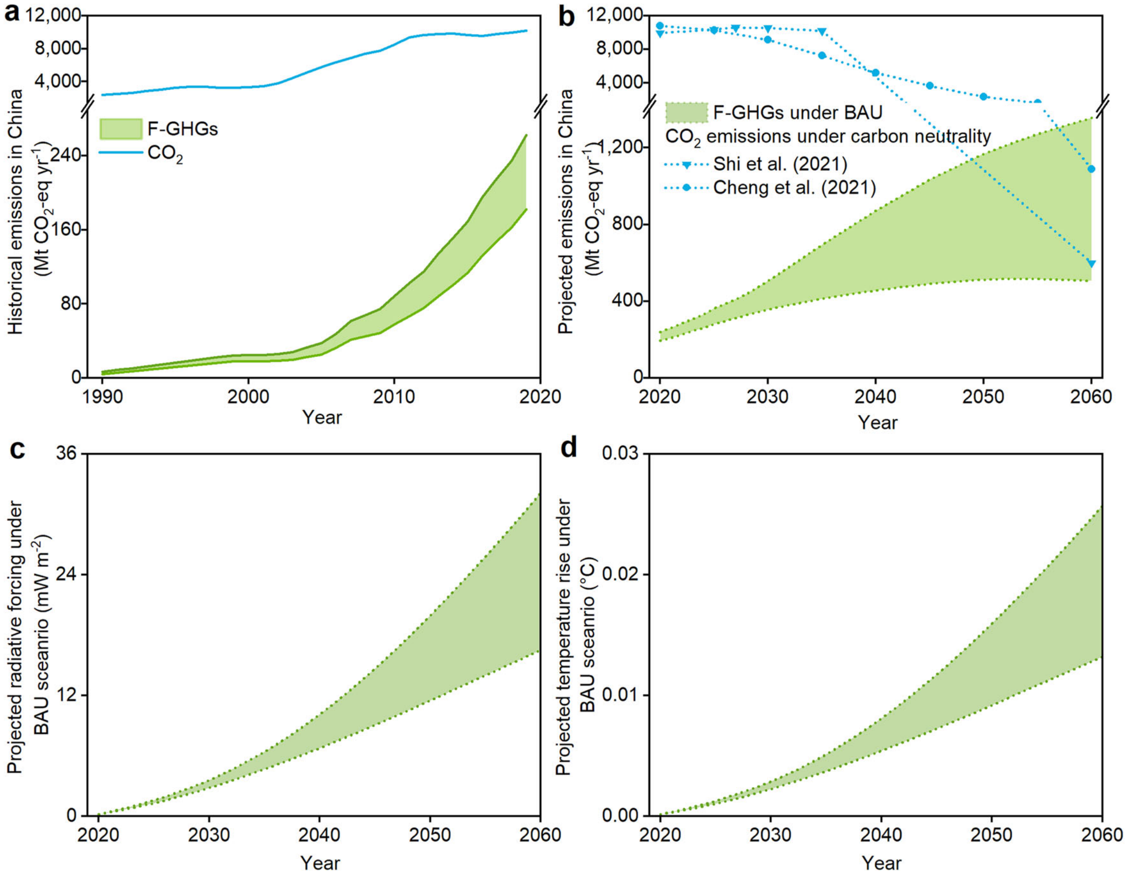

Fig. 5 Historical and projected F-GHGs CO_2-eq and CO_2 emissions. a historical F-GHGs CO_2-eq emissions in China during 1990–2019; historical CO_2 emissions from China for 1990–2019 are also shown and derived from the Global Carbon Project 2020[42]. **b** projected F-GHGs CO_2-eq emissions in China under the business-as-usual (BAU) scenario during 2020–2060 based on ten different GDP scenarios and projected CO_2 emission from China under the carbon neutrality[49,50]; projected GDP values under different scenarios are from the Shared Socioeconomic Pathways (SSPs)[43–45]. **c** projected global radiative forcing relative to 2019 due to China's F-GHGs emissions during 2020–2060 under the BAU scenario. **d** projected global temperature rise relative to 2019 due to China's F-GHGs emissions during 2020–2060 under the BAU scenario.

Methods

Estimating F-GHG emissions at sector and compound levels. In total, SF_6, NF_3, CF_4, C_2F_6, C_3F_8, and c-C_4F_8 were included in this study. Data on the chemical formulas, lifetimes, and GWPs are shown in Supplementary Table 1. In this study, GWPs over a 100-year-time horizon from the 4th Assessment Report (AR4)[51] of the Intergovernmental Panel on Climate Change (IPCC) were used because IPCC/AR4 GWPs are employed in the official national greenhouse gases reports submitted to UNFCCC by Annex I and several non-Annex I countries. Using IPCC/AR4 GWPs here would be conducive to directly comparing our GWP weight emissions with results from other countries and to conducting negotiations for future climate policy. SF_6, NF_3, CF_4, C_2F_6, C_3F_8, and c-C_4F_8 are emitted in a total of 13 source sectors in China (not including Hong Kong Special Administrative Region, Macao Special Administrative Region, and Taiwan Province in this work) (Supplementary Table 3): (1) F-GHGs production, (2) electrical equipment, (3) magnesium production, (4) primary aluminum production, (5) semiconductor manufacture, (6) flat panel display screens manufacture, (7) photovoltaics manufacture, (8) medical use, (9) gas-air-tracer experiments, (10) fire extinguishing use, (11) military use, (12) refrigeration use, and (13) HCFC-22 feedstock use. Other F-GHGs, controlled by Montreal Protocol, e.g., chlorofluorocarbons (CFCs) and hydrofluorocarbons (HFCs), were not included in this study. Methods for estimating SF_6, NF_3, CF_4, C_2F_6, C_3F_8, and c-C_4F_8 emissions from each sector were selected according to the decision trees for method choice in the 2006 and 2019 IPCC guidelines[52,53], estimation methods by Fang et al.[15], and other published references. A detailed methodology for calculating emissions of each F-GHG and each emission sector is presented in the Supplementary Methods. Briefly, F-GHGs emissions from the emission sectors were derived from installation, operation, maintenance, and disposal of products containing F-GHGs, or direct production and usage of F-GHGs. For example, fugitive emissions of SF_6 occur during the SF_6 production process.

$$E_{1,t} = EF_1 \times P_{1,t} \tag{1}$$

where $E_{1,t}$, EF_1, and $P_{1,t}$ are annual emissions (t yr^{-1}), emission factor, and production (t yr^{-1}) in this sector in the year t, respectively.

Another example is the electrical equipment sector. SF_6 is emitted during the process of manufacturing, installation, use, maintenance, and disposal of electrical equipment.

$$E_{2,t} = EF_{2i} \times C_{2,t} + EF_{2j} \times B_{2,t} + EF_{2k} \times B_{2,t} \times (1-R) \tag{2}$$

where $E_{2,t}$ is the SF_6 emissions in the year t (t yr^{-1}). EF_{2i}, EF_{2j}, and EF_{2k} represent the emission factors of manufacturing/installation, natural leakage, and annual maintenance/disposal, respectively. $C_{2,t}$ is the SF_6 consumption in the year t (t yr^{-1}). R is the recovery factor. $B_{2,t}$ is the SF_6 bank in the electrical equipment in the year t (t yr^{-1}). Please refer to Supplementary Methods for equations and parameter values for calculating emissions of each F-GHG in each emission sector.

Emission uncertainty analysis. A Monte Carlo (MC) ensemble simulation was performed to calculate the uncertainties in our emission estimates. The emission model was run 1,000,000 times by randomly varying all the input data given a priori uncertainty distributions. The normal distribution was applied for both activity data and emission factors. Available uncertainties for activity data and emission factors of six F-GHGs were derived from literature[15] and IPCC[52,53]. For uncertainties of activity data, Fang et al.[15] provided values of SF_6 for electrical equipment, magnesium production, and semiconductor manufacture sectors; the 2006 IPCC Guidelines provided values of primary aluminum production and PFCs production[53]. For uncertainties of emission factors, Fang et al.[15] provided values of SF_6 for SF_6 production, electrical equipment, and magnesium production sectors; the 2019 IPCC Guideline provided values of NF_3 and CF_4 for NF_3 production[52]; the 2006 IPCC Guideline provided values of four PFCs for PFCs production[53]; the values for China PFPB technology in primary aluminum production were set as the ratio of the average of four emission factors to the standard deviation of four emission factors. Uncertainties of 50% were set for the rest of the activity data and emission factors without available values.

Projecting F-GHG emissions at sector and compound levels. Future F-GHGs emissions during 2020–2060 were projected based on historical GDP[46], historical

F-GHGs production/consumption data of recent nine years (from this study), and future GDP[43–45]. Here are the details: a linear relationship between historical GDP and historical F-GHGs production/consumption data in each sector is built respectively (correlation coefficients of 0.86–1.00; Supplementary Table 5). The future F-GHGs production/consumption data in each sector were projected according to the above linear relationship and future GDP values. Ten projected GDP scenarios (IIASA GDP-SSP1, IIASA GDP-SSP2, IIASA GDP-SSP3, IIASA GDP-SSP4, IIASA GDP-SSP5, OECD Env-Growth-SSP1, OECD Env-Growth-SSP2, OECD Env-Growth-SSP3, OECD Env-Growth-SSP4, and OECD Env-Growth-SSP5) from the Shared Socioeconomic Pathways (SSPs) were used[43–45]. Finally, emissions of each F-GHG in each sector were projected based on the projected production/consumption and the emission estimation method described above. Detailed information on the projection is presented in the Supplementary Methods.

Calculating radiative forcing and temperature change. Based on the projected F-GHGs emissions during 2020–2060, atmospheric mixing ratio, radiative forcing, and corresponding temperature change caused by F-GHGs were calculated from annual F-GHGs emissions, molecular weight, atmospheric lifetime, the number of global atmospheric molecules, and other input data according to the methodology described in Velders et al.[54] and used in previous World Meteorological Organization (WMO) assessments.

$$C_{i,t} = C_{i,t-1} \times \exp\left(-\frac{1}{\tau_i}\right) + F_i \times E_{i,t-1} \times 1000 \times \tau_i \times \left(1 - \exp\left(-\frac{1}{\tau_i}\right)\right) \quad (3)$$

Here $C_{i,t}$ and $C_{i,t-1}$ are the mole fraction of F-GHG i in the year t and $t-1$ (pmol mol^{-1}, ppt), $E_{i,t-1}$ is the annual emissions of F-GHG i in the year $t-1$ (t yr^{-1}), τ_i is the F-GHG lifetime (years), and F_i (pmol mol^{-1} kg^{-1}) is a factor that relates the mass emitted to the global mole fraction.

$$F_i = \left(\frac{N_A}{Na}\right)\frac{F_{surf}}{M_i} = 5.68 \times 10^{-9}\frac{F_{surf}}{M_i} \times 1000 \quad (4)$$

Here M_i is the molecular weight of F-GHGs i (g mol^{-1}), N_a is the number of global atmospheric molecules, N_A is the Avogadro number, and F_{surf} is a factor relating the global mean surface mole fraction to the global mean atmospheric mole fraction, which was taken to be 1.07 for F-GHGs here[54,55].

$$RF_{i,t} = C_{i,t} \times RE_i \quad (5)$$

$$\triangle T = \triangle RF_{i,t} \times \lambda \quad (6)$$

Here $RF_{i,t}$ (mW m^{-2}) is the radiative forcing of F-GHG i in the year t, RE_i is the radiative efficiency of F-GHGs i (W m^{-2} ppb^{-1}), ΔT is the temperature change compared with 2019, $\triangle RF_{i,t}$ is the radiative forcing change relative to historical values (2019 in this work) of F-GHG i in the year t, and λ is the climate sensitivity parameter, which was taken to be 0.8 °C W^{-1} m^2[56]. The molecular weight, atmospheric lifetime, radiative efficiency of the targeted F-GHGs species are shown in Supplementary Table 1.

Data availability

The datasets generated during the current study are available at https://doi.org/10.6084/m9.figshare.22670308. Global emissions of F-GHGs are derived from Say et al.[35], updates of Rigby et al.[36], Trudinger et al.[57], and Engel & Rigby[58]. Emissions of F-GHGs from Annex I countries reported to UNFCCC are available from UNFCCC Greenhouse Gas Inventory Data - Flexible queries Annex I countries (https://di.unfccc.int/). Historical GDP data are from the Organization for Economic Co-operation and Development website (OECD, https://data.oecd.org/gdp/gross-domestic-product-gdp.htm). Projected GDP data are from the Shared Socioeconomic Pathways website (SSP, https://tntcat.iiasa.ac.at/SspDb/dsd?Action=htmlpage&page=10#v2).

Received: 2 September 2022; Accepted: 19 May 2023;
Published online: 08 June 2023

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Acknowledgements

We thank anonymous reviewers for constructive comments on the initial manuscript. This work thanks to the support by the National Natural Science Foundation of China (42277084 and 22106134), Beijing Natural Science Foundation (JQ19032), and the Strategic Research and Consulting Project of the Chinese Academy of Engineering (2022-XY-47).

Author contributions

L.G.: data collection, emission analysis of PFCs, emission projections of F-GHGs, and writing the original draft with input from other authors. Y.Y.: data collection and emission analysis of NF_3. P.F., G.V., Z.L., and D.C.: results discussions and revision of this article. J.Q., Z.C.: data collection and emission analysis of SF_6. B.Y. and J.H.: results discussions and revision of this article. X.F.: supervision, funding acquisition, project administration, data collection and emission analysis of SF_6, and results discussions and revision of this article.

Competing interests

The authors declare no competing interests.

Additional information

Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s43247-023-00859-6.

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Peer review information *Communications Earth & Environment* thanks William Lamb, Luke Western, and the other, anonymous, reviewer(s) for their contribution to the peer review of this work. Primary Handling Editors: Sagar Parajuli and Joe Aslin.

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