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Doomed to fail? A call to reform global climate governance and greenhouse gas inventories

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Abstract

Commitments to emissions reductions following the landmark Paris Climate Change Agreement have proliferated. Though it is promising that 145 countries have declared a net-zero emissions target, with 33 enshrining this goal into law, comparison of country-level emissions inventories can only be effectively carried out with uniform and consistent data. The extent to which greenhouse gas (GHG) inventory comparison is possible, and the ancillary climate governance implications, are the motivation for this article. Based on time-series correlation analyses over 32 years and 43 Annex-I countries, we uncover issues that are likely to inveigh against country-country comparison of GHGs—with the potential to weaken climate governance systems that are based mainly on emissions inventory tracking. First, the Global Warming Potentials (GWPs)—which convert each respective GHG into carbon equivalents (CO_2-e), and are revised with each IPCC report—are not immediately or consistently integrated into GHG inventories. Second, GHGs apart from carbon dioxide, based on the data analysis, do not appear to be tracked uniformly. Should comparison of emissions remain a cornerstone of global climate governance, an overhaul of country-level GHG inventories is called for, specifically to enable effective reporting and tracking of GHGs apart from only carbon dioxide.

Keywords Carbon governance · Methane emissions · Nitrogen dioxide emissions · Global warming potentials · Post-Paris climate

Abbreviations

Acronym	Definition
CH_4	Methane
CO_2	Carbon dioxide
CO_2-e	Carbon dioxide equivalents
CM	Compliance mechanism
COP	UNFCCC conference of parties

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ETF	Enhanced transparency framework
FAR	IPCC first assessment report
GHGs	Greenhouse gas emissions
GS	Global stocktake
GWPs	Global warming potentials
HFCs	Hydrofluorocarbons
IPCC	Intergovernmental panel on climate change
KP	Kyoto protocol
NDCs	Nationally determined contributions
NF_3	Nitrogen trifluoride
NO_2	Nitrogen dioxide
PA	Paris agreement
PFCs	Perfluorocarbons
SAR	IPCC second assessment report
SF_5CF_3	Trifluoromethyl sulphur pentafluoride
SF_6	Sulphur hexafluoride
TFI	Task force on national greenhouse gas inventories
UNFCCC	United Nations framework convention on climate change

1 Introduction

Global climate change governance, in the formative years of the UNFCCC (United Nations Framework Convention on Climate Change) (1990–2005), sought to integrate top-down and command-and-control mechanisms (Cole, 2011; Hare et al., 2010)—even though this characterisation is recently called into question (Depledge, 2022). In this period, greenhouse gas emissions (GHGs) monitoring and measurement systems were initiated (Nukusheva et al., 2021). Since the Copenhagen Conference of Parties (COP-15), and certainly after the Paris Climate Agreement (PA) (COP-21), however, instead of top-down climate governance, greater emphasis was placed on the power of bottom-up and flexible approaches (Falkner, 2016)—as reflected in the NDCs (Nationally Determined Contributions) (van Asselt et al., 2015; Winkler et al., 2018). The PA stipulates that comparison of the NDCs will take every five years through the "Global Stocktake"—to help "institutionalise aggregate tracking of 'where we are'" (Hale et al., 2020: 409). The expectation is that the post-PA climate governance regime will lead to greater transparency and effort-sharing for the reduction of global GHGs (Backstrand et al., 2017; van Asselt et al., 2018; Hale, 2020).

NDCs have already been submitted by 193 countries, with 153 updating those by September 2023, providing further details at UNFCCC (COP28) in Dubai. As of November 2023, 145 countries have declared a net-zero emissions target, with 33 enshrining this goal into law (Climate Action Tracker, 2024), covering 95% of the world's total GHGs (UNFCCC, 2023a). The main barometer for climate performance at the country level—supported by the NDCs and the Global Stocktake (GS)—therefore rests on measuring, monitoring, and *comparing* GHGs (Banda, 2018; du Pont & Meinshausen, 2018; Milkoreit & Haapala, 2019; Pauw et al., 2018; Rowan, 2019).

Consequently, even more than prior climate governance mechanisms at the global level, the accuracy of emissions inventories is now paramount for the post-Paris framework (Kuyper et al., 2017; Coen et al., 2020a, 2020b). Nevertheless, climate governance scholars tend to focus more on the mechanisms for GHG inventory submissions rather than the accuracy of the data (Swart et al., 2007). Bearing in mind the important role of tracking and comparing emissions, against this backdrop, this article addresses the following research questions: Are GHG inventories submitted to the UNFCCC readily comparable? If not, then what is impeding such comparison? Finally, how can the system be reconfigured to ensure that the post-PA climate governance regime is effective, and help to enable more robust tracking of country-level GHG inventories?

To respond to these questions, we evaluate time-series GHG data submitted to the UNFCCC by 43 Annex-I countries,[1] from 1990 to 2021. We argue that, based on the empirical data analyses, GHG inventories are not currently comparable, with consequences for global climate governance. We first draw attention to the varied carbon conversion metrics used by different parties—the Global Warming Potentials (GWPs)—which are used to convert each respective GHG into carbon equivalents (CO_2-e). GWPs are periodically revised as science improves, yet some countries do not immediately apply new GWP conversion rates (Höhne et al., 2017), reducing GHG comparisons. Second, through cross-correlation analyses, we demonstrate nearly perfect correlation between carbon dioxide (CO_2) and total GHGs. While this might come as little surprise since CO_2 represents about 75% of total GHGs worldwide (Ritchie et al., 2020), it is known that countries have vastly different industrial structures (Höhne et al., 2006, 2011; Jung et al., 2000)—e.g., countries with a large agricultural or natural gas sector tend to have much higher methane emissions—meaning that not all countries should exhibit such high correlation (Janssens-Maenhout et al., 2017, 2019; Zheng et al., 2019). Given the different industrial makeup of these countries (Crippa et al., 2019), we did not expect such uniform consistency in correlations between gases. On the other hand, we fail to find similarly high correlations between methane (CH_4) and total GHGs, which could well be due to the changing GWPs and country's decision to use different conversion metrics—oscillating from 21 to 83 CO_2-e. Finally, with respect to nitrous oxide and other GHGs, related but less fundamental issues warrant attention.

This is not the first study to draw attention to GHG emissions inventory issues, however (Rypdal, 1999; Rypdal & Winiwarter, 2001; van Amstel et al., 1999). For example, focusing on two GHGs (CO_2 and CH_4) and two GHG databases (Edgar and the UNFCCC), van Amstel et al. (1999) find significant inconsistencies for CH_4, and slightly less discrepancies for CO_2 data. In relation, researchers show that, even among the Annex-I countries—which have the most advanced economies—GHG inventories exhibit substantial uncertainties between 5 and 20 percent (Rypdal, 1999; Rypdal & Winiwarter, 2001). Specifically, the US, Norway, and the Netherlands demonstrate, on average, 20 percent uncertainty for methane emissions (Rypdal & Winiwarter, 2001). Though our findings are consistent with earlier investigations, which raise awareness to the underlying GHG data issues (Marland et al., 1999; van Amstel et al., 2000; Macknick, 2011), we go further to explore the ramifications for global climate change governance. By drawing attention to the GWPs, moreover, we suggest that these issues should be rectified if the post-Paris governance mechanisms are to have their intended climate governance impacts.

[1] Annex-I parties: Australia, Austria, Belarus, Belgium, Bulgaria, Canada, Croatia, Cyprus, Czechia, Denmark, Estonia, European Union, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Japan, Latvia, Liechtenstein, Lithuania, Luxembourg, Malta, Monaco, Netherlands, New Zealand, Norway, Poland, Portugal, Romania, Russian Federation, Slovakia, Slovenia, Spain, Sweden, Switzerland, Türkiye, Ukraine, United Kingdom of Great Britain and Northern Ireland.

In short, this article makes three contributions. First, we provide deeper insight into the governance and policy implications of emissions data inventories. Second, given that the PA stipulates that GHGs must be submitted to the UNFCCC, we explicitly call for immediate attention to be drawn to the UNFCCC database and inventory compilation processes. Third, and more specifically, this is the first study to demonstrate strikingly high correlations not only between CO_2 and total GHGs, but also between total GHGs and three other specific gases. These contributions, in aggregate, suggest that, although "carbon-based" governance systems now play a central role in global climate governance (Coen et al., 2020a, 2020b; Dubash, 2021; Guy et al., 2023; Pan et al., 2021), the enthusiasm for bottom-up emissions-based climate governance should be tamed since there remains substantial work to be done to refine country-level GHG inventories (Biermann, 2010; Hickmann et al., 2017; Walker, 2011).

This article proceeds as follows. Section 2 begins with a review the history of scientific estimations of GHGs, extending the analysis under the UNFCCC and the IPCC (Intergovernmental Panel on Climate Change) up to the present day. We then provide background to emissions-centric policies and agreements made through the UNFCCC process, many of which have cemented the central role of emissions inventories as key comparative metric. Section 3 introduces the UNFCCC emissions database data, country sample, and correlation methodologies, and closes with results. Section 4 discusses the findings and policy implications. The final Sect. 5 is the conclusion.

2 Background and literature

This section provides an overview to measuring GHGs, followed by a brief history of the IPCC and the UNFCCC, paying attention to the climate governance mechanisms which revolve around emissions data measurement, reporting, and comparison. The section closes by introducing the publicly available UNFCCC emissions database and the role of these data in the post-Paris climate governance regime.

2.1 The pre-UNFCCC period: GHGs are a major threat (prior to 1980)

Fourier (1827) was the first to show that the Earth's atmosphere traps heat through the "greenhouse gas" effect. Thereafter Tyndall (1861) discovered that different types of GHGs can accelerate these impacts, with the first accurate measurement of GHGs in the atmosphere conducted by Savant Arrhenius in 1889 (Arrhenius, 1889). These earlier GHG calculations provided the foundations for global climate change policy based on the measurement of emissions (Stern, 2008).

Throughout the twentieth century, various revisions to atmospheric carbon dioxide concentrations were carried out (Callendar, 1940; Plass, 1956; Keeling, 1973; Rotty, 1973). For instance, Rotty (1973) included methane emissions to these datasets demonstrating that, importantly, natural gas methane immediately oxidises to carbon dioxide. Following Keeling's dataset, Marland and Rotty (1984) used energy data from the UN to extrapolate GHG levels. These GHG measurement conventions were carried forward to most GHG data repositories (Marland, 2001), providing the foundations for country-level emissions inventories under the UNFCCC and the IPCC (Macknick, 2011).

2.2 Phase I: Emergence of the UNFCCC Regime (1992–1997)

Global climate change governance initially garnered international policy attention in the 1980s, due in large part to the alarming acceleration of emissions discovered by the seminal studies discussed above. In 1988, the IPCC became the first international organisation to scientifically address climate change at the international level. Its First Assessment Report (FAR) concluded, unequivocally, that "emissions resulting from human activities are substantially increasing the atmospheric concentrations of the greenhouse gases" and leading to climate change (IPCC, 1990: 63)—sounding the first alarm to the causes and consequences of GHGs, and catalysing UN member states to initiate climate change negotiations and a climate treaty.

The UNFCCC was established as a global climate treaty at the Rio Earth Summit in 1992 (Weart, 2008a, 2008b). Article 2 of its founding documents explicitly outlines its purpose: to help Parties stabilise "greenhouse gas concentrations in the atmosphere" at a level that would "prevent dangerous anthropogenic interference with the climate system" (UN, 1992, 2). Governing emissions, consequently, emerged as a central tenet of multilateral climate change governance systems from the beginning (Rogelj et al., 2011), with the IPCC providing emissions measurement guidelines since 1996 (Houghton, 1996; IPCC, 1996).

2.2.1 Phase II: The Kyoto protocol and global warming potentials (1997–2013)

Under the UNFCCC's Kyoto Protocol (1997) (KP), Annex-I countries were meant to track six GHGs. The "six Kyoto gases" are as follows: carbon dioxide (CO_2), methane (CH4), nitrous oxide (N_2O), and F-gases (hydrofluorocarbons and perfluorocarbons, and sulphur hexafluoride) (IPCC, 2021; Eurostat, 2015). Every four years Annex-I countries were to submit emissions inventories—including emissions removals, policies and measures—as well as financial and technical capacities to support developing countries (UNFCCC, 1998). In first decade of the 2000s, Annex-I parties, accordingly, set up their national institutional arrangements to measure and report emissions (Pattberg & Stripple, 2008).

The IPCC (2006) updated the 1996 guidelines for GHG data collection and submission (Eggleston et al., 2006; IPCC, 1996), with the following GHGs under its remit: carbon dioxide (CO_2); methane (CH_4); nitrous oxide (N_2O); hydrofluorocarbons (HFCs); perfluorocarbons (PFCs); sulphur hexafluoride (SF_6); nitrogen trifluoride (NF_3); trifluoromethyl sulphur pentafluoride (SF_5CF_3); halogenated ethers[2] (IPCC, 2006). The IPCC also delineated between four sectors: Energy, Industrial Processes and Product Use (IPPU), Agriculture, Forestry and Other Land Use (AFOLU), and Waste (IPCC, 2006: 1.3). To streamline and refine GHG inventories, Annex-I countries relied on the Task Force on National Greenhouse Gas Inventories (TFI) (IPCC, 2023a). The TFI updates agreed-on international methodologies, with the aim to ensure consistency for reporting and removal of GHGs (Treanton et al., 2006). GHG inventories then proceed to a UNFCCC panel and are reviewed by elected members of the Task Force Bureau (TFB).

To help reduce policy uncertainty and ensure that each respective GHG can be effectively monitored, researchers created the Global Warming Potentials (GWPs)—which were integrated into GHG databases (Eggleston et al., 2006; IPCC, 2019; IPCC, 2022).

[2] (e.g., C4F9OC2H5, CHF2OCF2OC2F4OCHF2, CHF2OCF2OCHF2); and other halocarbons not covered by the Montreal Protocol including CF3I, CH2Br2 CHCl3, CH3Cl, CH2Cl2).

Table 1 Changes to Global Warming Potentials (GWPs) from 1995 to 2023

Gas (species)	Formula	SAR-20	TAR-20	AR4-20	AR5-20	AR6-20	SAR-100	TAR-100	AR4-100	AR5-100	AR6-100
Methane	CH4	56	62	72	84	*83, 81	21	23	25	28	*30, 27
Nitrous oxide	N2O	280	275	289	264	273	310	296	298	265	273
Trichlorofluoromethan	CFC-11				6900	8321	4500	4600		4660	6226
Fluroform	HFC-23	9100	9400	1200	10800	12400	11700	12000	14800	12400	14600
Tetrafluoroethane	HFC-134a	3400	3300	3830	3710	4140	1300	1300	1430	1300	1530
Nitrogen trifluoride	NF3	NA	7700	12300	12800	13400	NA	10800	17200	16100	17400
Perfluoromethane (pfc	CF4	4400	3900	5210	4880	5300	6500	5700	7390	6630	7380
Sulfur hexafluoride	SF6	16300	15100	16300	17500	18300	23900	22200	22800	23500	25200

Source Author's compilation from UNFCCC Assessment Report. Carbon always "1." SAR = 1995; TAR = 2002; AR4 = 2007; AR5 = 2013; AR6 = 2023. *Fossil and non-fossil methane emissions. *100 refers to the 100-year atmospheric concentration, while *20 refers to the the 20-year atmospheric concentration

GWPs convert each GHG into "carbon equivalents" (CO_2-e) (Eggleston et al., 2006); they are therefore "an index, describing the radiative characteristics of well mixed GHGs, that represents the combined effect of the differing times these gases remain in the atmosphere and their relative effectiveness in absorbing outgoing infrared radiation." Stated differently, "The greater the GWP of a GHG, the greater its ability to cause global warming. A GWP for CH4 of 21, for instance, means that 1 kg of CH4 causes 21 times more effect on global warming than 1 kg of CO_2 (which has a GWP of 1)" (UNFCCC, 2004: 3). The UNFCCC and the IPCC officially endorsed using the GWPs in 2006, defined as "the radiative forcing of a tonne of a greenhouse gas over a given time period (e.g., 100 years) to a tonne of CO_2" (IPCC, 2006: 1.5). Table 1 outlines the revisions to the GWPs starting from the IPCCs' Second Assessment Report in 1995 through its Sixth Assessment Report in 2023.

One main consequence of the GWPs is, however, that with each subsequent IPCC report, the GWPs undergo revision as climate change science evolves (Hiraishi et al., 2014; Penman et al., 2014). This has stirred some confusion because, as GWPs are updated, some countries do not immediately update their inventories—with nontrivial implications for climate governance (Montzka et al., 2011). For instance, the UK still uses the GWP conversion from 2013 (ONS, 2023), Romania uses both the 2007 AR4 and 2014 AR5* GWP conversion rates (UNFCCC, 2024a), while the EU continues to use GWPs from AR4 (UNFCCC, 2024b). The US is an outlier since it uses the latest guidelines provided in AR6 (2023) (EPA, 2024). In addition, GWPs can be converted according to 20, 100, or 500-year time horizons. Of the countries that used the 100-year horizon in their latest inventory submissions, further complicating matters, 47% used AR5, 26% used AR4, and 25% used AR2; in addition, 82% of parties used guidelines for estimating emissions and removals from the 2006 IPCC Guidelines, while 7% used the 1996 IPCC guidelines (UNFCCC, 2023a).

Adding further complexity—though the UNFCCC has endorsed the 100-year timeline for GWP conversion—researchers argue that 20-year rather than 100-year GWP conversion timelines should be used since most NDCs target net-zero by 2050 or 2060 (e.g., 25 to 35 years in the future) (Bond et al., 2013; Howarth & Jacobson, 2021; Allan et al., 2016). In addition, using the 100-year time horizon fails to properly account for short-lived GHGs (Cain et al., 2019), and can also render climate mitigation strategies "unfair, inefficient, and dangerous" (Lynch et al., 2020: 12). Irrespective of these counterarguments, Annex-I parties agreed in 2023 to use 100-year GWP by the end of 2024, and to update the metrics by 2028 (UNFCCC, 2023b: Decision 7CP.27). The multifarious effect that revisions to the GWPs have on GHG inventories and climate governance are revisited in the discussion and conclusion sections.

2.2.2 Phase II: Building momentum for climate governance under the Paris Agreement (2013–2017)

The 2015 Paris Agreement (PA) was heralded as a major stepping-stone for global climate governance and, given the slow rate of progress since the first Kyoto Commitment period expired in 2012, was seen as an important re-design of the global climate governance architecture (Backstrand et al., 2017; Hale, 2020). Like the KP, the PA also focuses on monitoring emissions Perugini et al., 2021). The key difference is that the PA allows countries to set their own GHG reduction goals and timetables. Table 2 below documents the PA's stipulations for the measurement and reporting of GHGs. We draw attention to no less than six articles dealing squarely with tracking, measuring, and/or reporting emissions.

2.2.3 Phase III: Embedding emissions-based climate governance (2017–2024)

In general, the PA specifically calls for parties to "identify qualitative and/or quantitative indicators for tracking progress (e.g., net GHG emissions and removals)" (Weikmans et al., 2019: 6). Tracking progress on emissions reductions, consequently, requires "recent information on these indicators and comparing this with baseline information […] and describe the methodologies and accounting approaches used for the targets, baselines and indicators" (ibid). The post-Paris "climate governance regime" (Backstrand et al., 2017) established four main governance pillars, each of are fundamentally based on carbon-based governance mechanisms (Biermann, 2010), as follows:

(1) The Nationally Determined Contributions (NDCs) (Article 4)
(2) The Global Stocktake (GS) (Article 14)
(3) The Enhanced Transparency Framework (ETF) (Article 13)
(4) The Compliance Mechanism (CM) (Article 15)

The NDCs are meant to help constituents track climate performance across countries and lead to collaborative policy efforts (Doukas et al., 2018; van Asselt et al., 2015). While the NDCs are seen as the most important mechanism in the PA (UNEP, 2020), the Global Stocktake will help to "assess collective progress, including on mitigation, and can be understood as a process of mutual accountability" (Winkler et al., 2017: 863). Periodic stocktake of emissions should provide timely policy feedback while helping to reconfigure actions to align better with the 2-degree goals (Milkoreit & Haapala, 2019; Rowan, 2019). Stated differently, the NDCs are the plan while the Global Stocktake is a comparison of progress on these stated goals; the Enhanced Transparency Framework (ETF), in concert with the Compliance Mechanism (CM), are to enable better execution of the plan, and to engender greater transparency on emissions profiles (IPCC, 2023c). Surprisingly, even amongst developed economies—which have reported GHG inventories since 1990–the NDCs are alarmingly dissimilar (Rowan, 2019), and emissions profiles are difficult to compare as a result (Carraro, 2016). These four mechanisms are depicted in Fig. 1 below.

The first Global Stocktake concluded in 2022, with several notable observations published by the UNFCCC (2023c): the projected emissions implied by the collective NDCs, in aggregate, are short of the 1.5 degree Celsius target; there remain formidable implementation gaps; developed country parties need to take the lead; and new international platforms are needed to drastically reduce all GHGs. The latest GS occurred in 2023 in Dubai

Table 2 Stipulations for tracking emissions under the Paris Agreement

Article number	Emissions Stipulation	Main contribution
4.4	Developed country Parties should continue taking the lead by undertaking economy-wide absolute emission reduction targets. Developing country Parties should continue enhancing their mitigation efforts, and are encouraged to move over time towards economy-wide emission reduction or limitation targets in the light of different national circumstances	Developed countries need to reduce GHGs in absolute terms
4.13	Parties shall account for their nationally determined contributions. In accounting for anthropogenic emissions and removals corresponding to their nationally determined contributions [NDCs], Parties shall promote environmental integrity, transparency, accuracy, completeness, comparability and consistency, and ensure the avoidance of double counting, in accordance with guidance adopted by the Conference of the Parties serving as the meeting of the Parties to this Agreement	Emissions reductions should be reflected in NDCs, which should be accurate, complete, comparable, and consistent
4.14	In the context of their nationally determined contributions, when recognizing and implementing mitigation actions with respect to anthropogenic emissions and removals, Parties should take into account, as appropriate, existing methods and guidance under the Convention,	Providing emissions inventories should follow prior protocols
4.18	If Parties acting jointly do so in the framework of, and together with, a regional economic integration organization which is itself a Party to this Agreement, each member State of that regional economic integration organization individually, and together with the regional economic integration organization, shall be responsible for its emission level as set out in the agreement	Regional economic organizations shall follow emissions measurement in line with the agreement
6.4c	A mechanism to contribute to the mitigation of greenhouse gas emissions and support sustainable development […] To contribute to the reduction of emission levels in the host Party, which will benefit from mitigation activities resulting in emission reductions that can also be used by another Party to fulfil its nationally determined contribution	A mechanism to guide NDCs
13.7a	Each Party shall regularly provide the following information: (a) A national inventory report of anthropogenic emissions by sources and removals by sinks of greenhouse gases, prepared using good practice methodologies accepted by the Intergovernmental Panel on Climate Change and agreed upon by the Conference of the Parties serving as the meeting of the Parties to this Agreement;	NDCs shall follow good practice methods from the IPCC for emissions profiles (ETF)

Source UNFCCC Paris Agreement (2015), Additional guidance for GHG tracking under the Paris Agreement

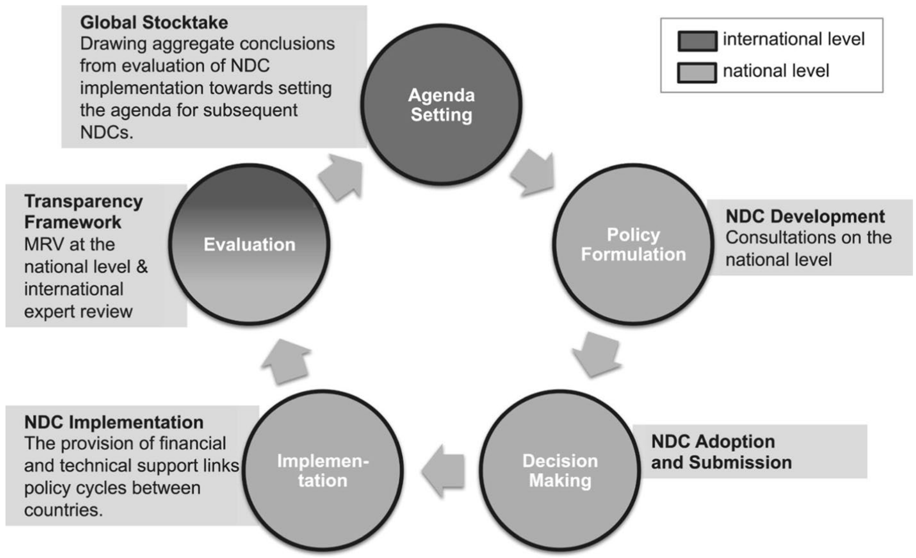

Fig. 1 Overview of the Paris Agreement governance structure. *Source* Hermwille et al. (2019)

(COP-28). There are two promising and recent developments, despite critique levied against the NDCs and the Global Stocktake. First, emissions' growth has largely subsided in the last decade (UNFCCC, 2022). The UNFCCC (2023c: 7), in addition, drew attention to the important "role of non-CO_2 emissions" as well as the importance of "mitigation measures" that "also target CH_4, N_2O and short-lived climate forcers" (UNFCCC, 2023c: 7). Collectively, the post-Paris UNFCCC framework makes clear that countries must consistently and transparently report—regardless of how they plan to reduce GHGs—their GHG inventories on a regular basis, *vis-à-vis* the Global Stocktake and NDCs (Rowan, 2019). Should GHG measurement and inventory compilation function accordingly, these processes help constituents "understand ambition and progress on climate actions and support by Parties,— – and informs the COP deliberation and guidance on these matters" (IPCC, 2023b).

Notwithstanding enthusiasm for the post-PA climate governance regime, nevertheless, emissions inventories have only modestly improved in recent years (Andrew, 2020; McLaren & Markusson, 2020). Even Annex-I countries are continuing to fall short on NDCs (Holz et al., 2018) (see Appendix Fig. 1). To date, moreover, relatively scant attention is directed towards the climate governance risks posed by emissions tracking systems (Morseletto et al., 2017; Pauw et al., 2018; Cain et al., 2019). These data anomalies do not, however, garner much attention in climate governance scholarship. In the absence of attention paid to the quality and consistency of emissions inventories, the efficacy of the post-Paris governance framework—specifically "tracking of where we are" on global emissions mitigation (Hale, 2020)—will be significantly reduced. Even more troubling, data deficiencies might reduce trust in GHG monitoring and measuring systems, which are indeed a key component of climate and "emissions" governance (Biermann, 2010).

In what follows, we conduct a time-series analysis of the UNFCCC's data repository for 43 Annex-I countries, from 1990 to 2021. The quantitative analysis exposes some excessively high correlations between different GHGs and total GHGs. Based on the analysis,

Table 3 Descriptive statistics for the UNFCCC GHG data (all countries)

Variables	(1) N	(2) Mean	(3) SD	(4) Min	(5) Max
Country	1,376	22	12.41	1	43
Year	1,376	2,006	9.236	1,990	2,021
ghgs	1,376	415,646	1.084e+06	69.76	7.511e+06
log_ghgs	1,376	11.31	2.150	4.245	15.83
co2	1,376	333,860	875,301	60.53	6.132e+06
log_co2	1,376	11.05	2.143	4.103	15.63
ch4	1,376	52,443	128,889	0.662	874,450
log_ch4	1,376	9.200	2.390	−0.413	13.68
n20	1,376	21,649	62,733	2.230	432,744
log_n20	1,376	8.346	2.255	0.802	12.98
other_gases	1,376	7,694	22,844	9.61e-05	187,292
log_others	1,376	6.604	2.730	−9.251	12.14
country_id	1,376	22	12.41	1	43
high_ghg_countries	1,376	0.512	0.500	0	1
low_ghg_countries	1,376	0.465	0.499	0	1

Source Author's calculation of UNFCCC data, without LULUCF

we follow with a discussion of climate governance going forward. Our data and analysis concur with the assertion that global climate governance, based largely on governance of emissions, deserves a radical rethink (Bernstein & Hoffmann, 2019).

3 Data and methods

This section describes the sample of countries, and correlation methods employed to assess the UNFCCC's GHG data. The sample includes the emissions inventories reported by the 43 Annex-I parties from 1990 to 2021, the latest year complete data are available.

3.1 Sample and data collection

Data were collected data from the UNFCCC GHG data repository for a 32-year period (1990–2021) over 43 countries (https://di.unfccc.int/time_series). To enable a more streamlined interpretation of the results, we have elected to split the sample into two country groupings: lower-emitting and higher-emitting countries. This was done by taking the mean total GHGs in 2005—the middle of the time-period and also the year the KP came into effect. In other words, in the median year of the dataset (2005), we divided the sample evenly between lower and higher-emitting countries. We carried out a test to split the dataset using another year (2018), and found that just one country, Hungary, would be added to the higher-emitting countries—meaning that the demarcation we have selected does more to ease interpretation of the results than it does to arbitrarily create country groupings. The analysis includes the three most prominent GHGs (CO_2, CH_4, and N_2O), and what we refer to as "other gases," which are the sum of

Table 4 Descriptive statistics for the UNFCCC GHG data (lower-emitting countries)

Variables	(1) N	(2) Mean	(3) SD	(4) Min	(5) Max
Country	672	21.81	10.31	5	39
Year	672	2,006	9.240	1,990	2,021
ghgs	672	36,072	27,695	69.76	98,910
log_ghgs	672	9.726	1.816	4.245	11.50
co2	672	26,937	20,628	60.53	76,638
log_co2	672	9.465	1.766	4.103	11.25
ch4	672	6,049	7,568	0.662	36,082
log_ch4	672	7.574	2.289	-0.413	10.49
n20	672	2,568	2,295	2.230	8,140
log_n20	672	6.803	2.132	0.802	9.004
other_gases	672	518.2	636.0	9.61e-05	5,663
log_others	672	4.987	2.321	-9.251	8.642
country_id	672	21.81	10.31	5	39
high_ghg_countries	0	0	0	0	0
low_ghg_countries	672	0.952	0.213	0	1

Source Author's calculation of UNFCCC data, without LULUCF

Table 5 Descriptive statistics for the UNFCCC GHG data (higher-emitting countries)

Variables	(1) N	(2) Mean	(3) SD	(4) Min	(5) Max
Country	736	21.74	13.98	1	43
Year	736	2,006	9.239	1,990	2,021
ghgs	736	747,108	1.400e+06	47,756	7.511e+06
log_ghgs	736	12.74	1.141	10.77	15.83
co2	736	602,013	1.131e+06	37,735	6.132e+06
log_co2	736	12.50	1.161	10.54	15.63
ch4	736	92,813	165,882	4,819	874,450
log_ch4	736	10.67	1.159	8.480	13.68
n20	736	38,334	82,209	2,854	432,744
log_n20	736	9.760	1.090	7.956	12.98
other_gases	736	13,947	29,862	0.374	187,292
log_others	736	8.068	2.135	-0.985	12.14
country_id	736	21.74	13.98	1	43
high_ghg_countries	736	0.957	0.204	0	1
low_ghg_countries	0	0	0	0	0

Source Author's calculation of UNFCCC data, without LULUCF

HFCs, PFCs, and an unspecified mix of HFCs and PFCs, SF_6 and NF_3 (UN Data, 2024). To simplify classification of high and lower-emitting countries we present and analyse the GHG data in logarithmic form. Tables 3, 4 and 5 present the descriptive statistics for the database.

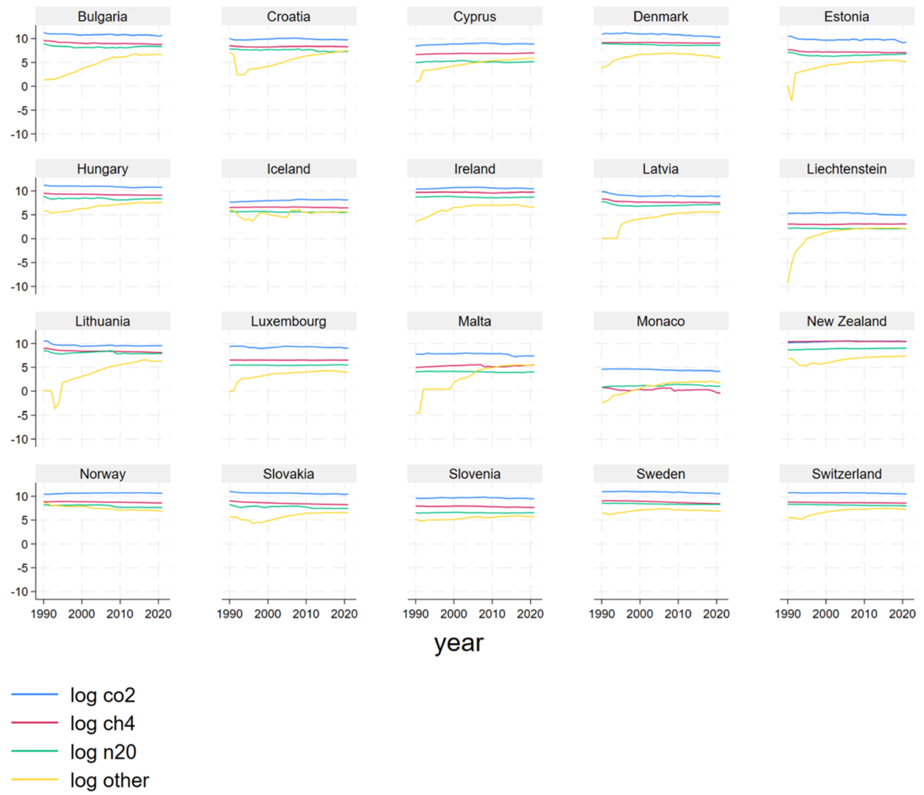

Fig. 2 Lower-emitting countries, all gases (1990–2021). *Source* Author's depiction of UNFCCC emissions inventories

3.2 Emission inventories overview

As mentioned above, we have divided the panel into lower and higher emitting countries. Below Figs. 2 and 3 depict emissions for each respective gas.

3.3 Results and analyses

To compare the respective GHG data inventories, we use Spearman Correlation analysis—widely deployed to assess underlying patterns in large datasets (De Winter et al., 2016). Since our dataset includes 1376 observations for four GHGs and total GHGs, spanning 43 countries over 32 years (e.g., a large, time-series dataset)—and the aim is to understand the comparability of country-level GHG data—we conduct Spearman Correlations (Spearman, 1904, 1910a, 1910b). The expectation is that, owing to the drastically different industrial profiles of Annex I countries (Höhne et al., 2006, 2011; Zheng et al., 2019)—notwithstanding much similarity in Western European economies—correlations between respective GHGs should not be excessively high—in other words, a nearly perfect Spearman Correlation. We present a correlation analysis in four panels, each divided between high and lower-emitting countries. Table 6 summarises our panels. The first two correlation matrices provide an overview of all gases across all years. This is followed by more granular analyses for each respective gases' correlation with total GHGs.

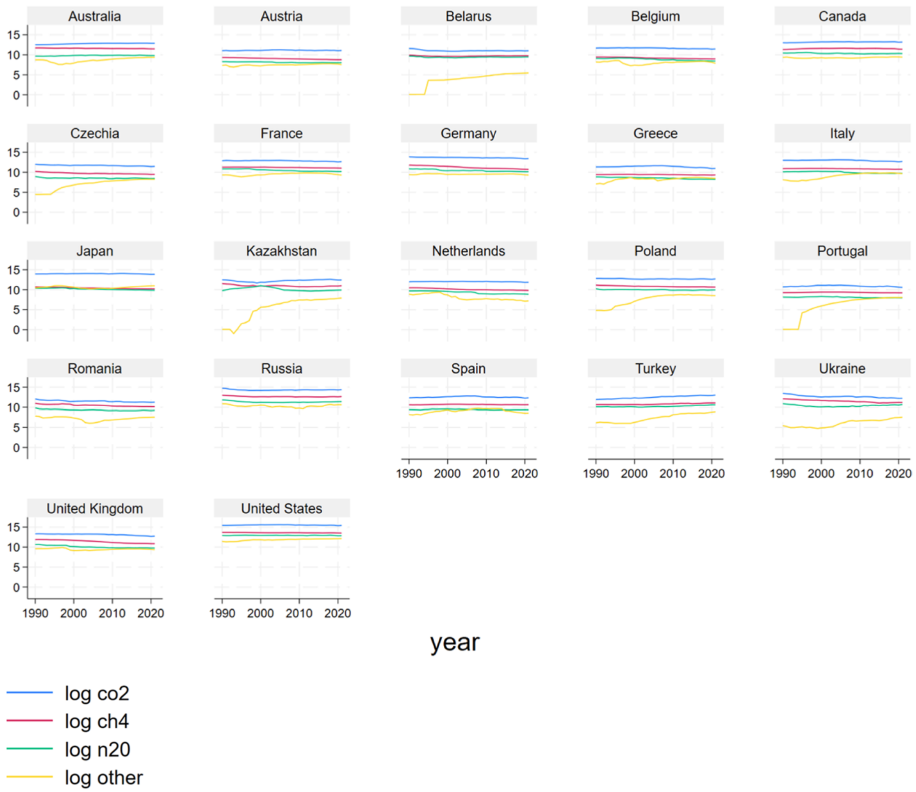

Fig. 3 Higher-emitting countries, all gases (1990–2021). *Source* Author's depiction of UNFCCC emissions inventories

Table 6 Overview of the correlation analysis panels

Panel	Analysis	GHG and sample
A-1	Numerical correlations	Lower-emitting countries, all gases (Fig. 4)
A-2	Numerical correlations	Higher-emitting countries, all gases (Fig. 5)
B-1	Graphical correlations	Lower-emitting countries, total GHGs and CO2 (Fig. 6)
B-2	Graphical correlations	Higher-emitting countries, total GHGs and CO2 (Fig. 6)
C-1	Graphical correlations	Lower-emitting countries, total GHGs and CH4 (Fig. 7)
C-2	Graphical correlations	Higher-emitting countries, total GHGs and CH4 (Fig. 7)
D-1	Graphical correlations	Lower-emitting countries, total GHGs and N2O (Fig. 8)
D-2	Graphical correlations	Higher-emitting countries, total GHGs and N2O (Fig. 8)
E-1	Graphical correlations	Lower-emitting countries, total GHGs and "other gases" (Fig. 9)
E-2	Graphical correlations	Higher-emitting countries, total GHGs and "other gases" (Fig. 9)

Source Author's calculation of UNFCCC data. *other gases: Sum of HFCs, PFCs, Unspecified mix of HFCs and PFCs, SF_6 and NF_3, in kt CO_2 equivalent

3.3.1 Panels A-1 and A-2

Figures 4 and 5.

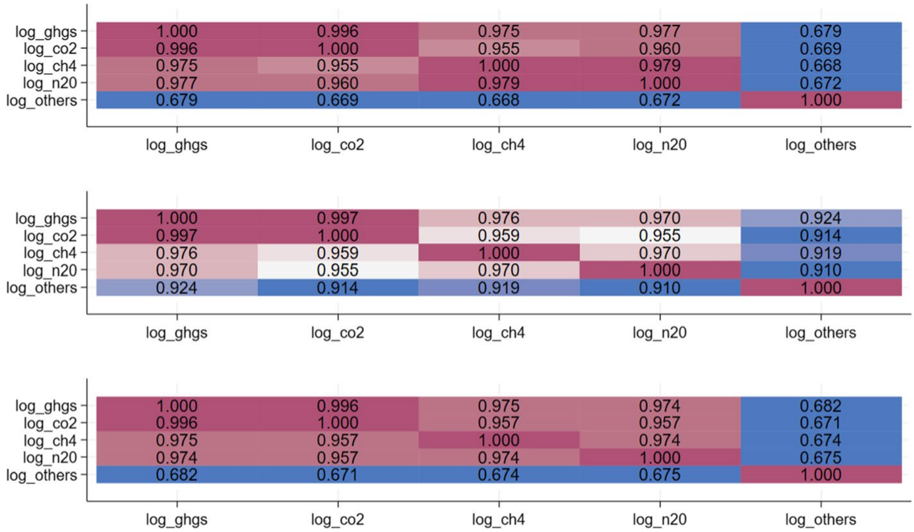

Fig. 4 Lower-emitting countries, prior 2005, post 2005, all years. *Source* Author's correlation analyses, all UNFCCC emissions inventories. Prior to 2005 (top panel); after 2005 (middle panel); all years (bottom panel)

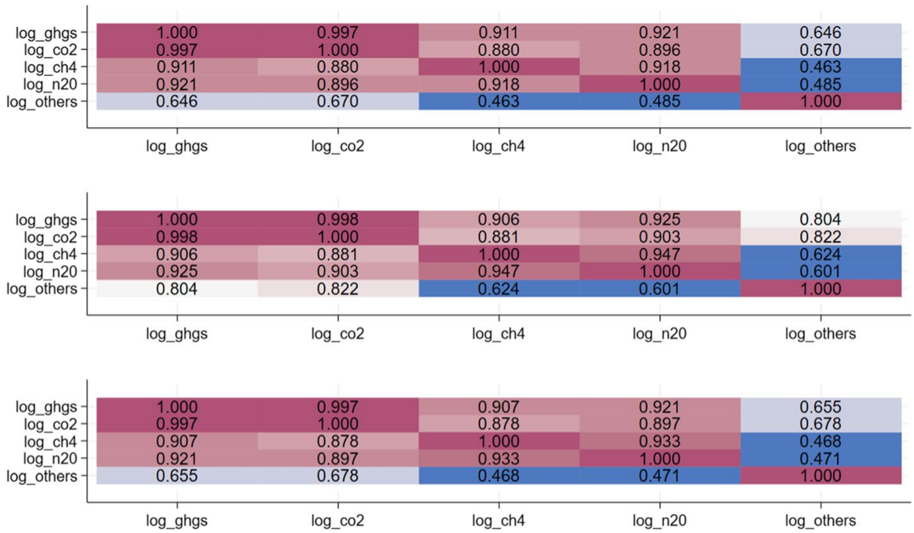

Fig. 5 Higher-emitting countries, prior 2005, post 2005, all years. *Source* Author's correlation analyses, all UNFCCC emissions inventories. Prior to 2005 (top panel); after 2005 (middle panel); all years (bottom panel)

3.3.2 Panel B-1 and B-2

Figure 6.

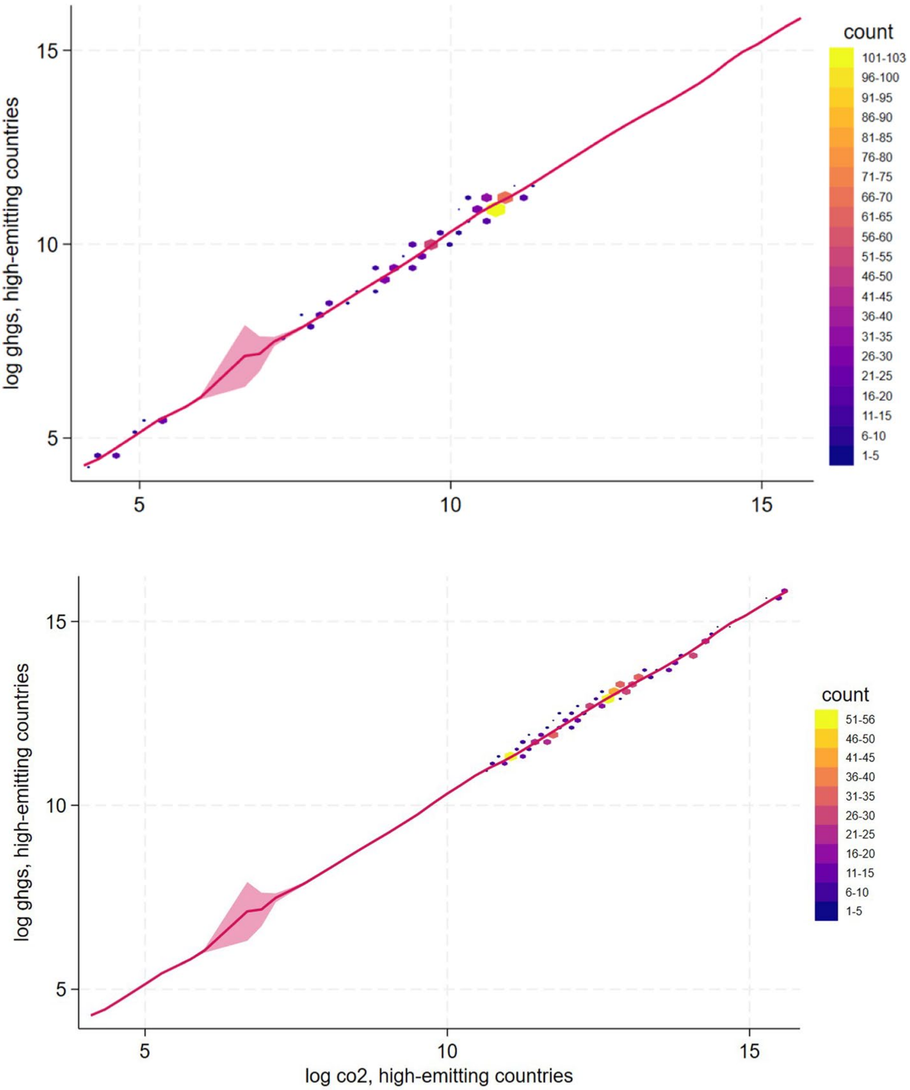

Fig. 6 Panels B-1 and B-2: Correlation between total GHGs and CO2 emissions. Lower-emitting countries (top panel); higher-emitting countries (lower panel)

3.3.3 Panel C-1 and C-2

Figure 7.

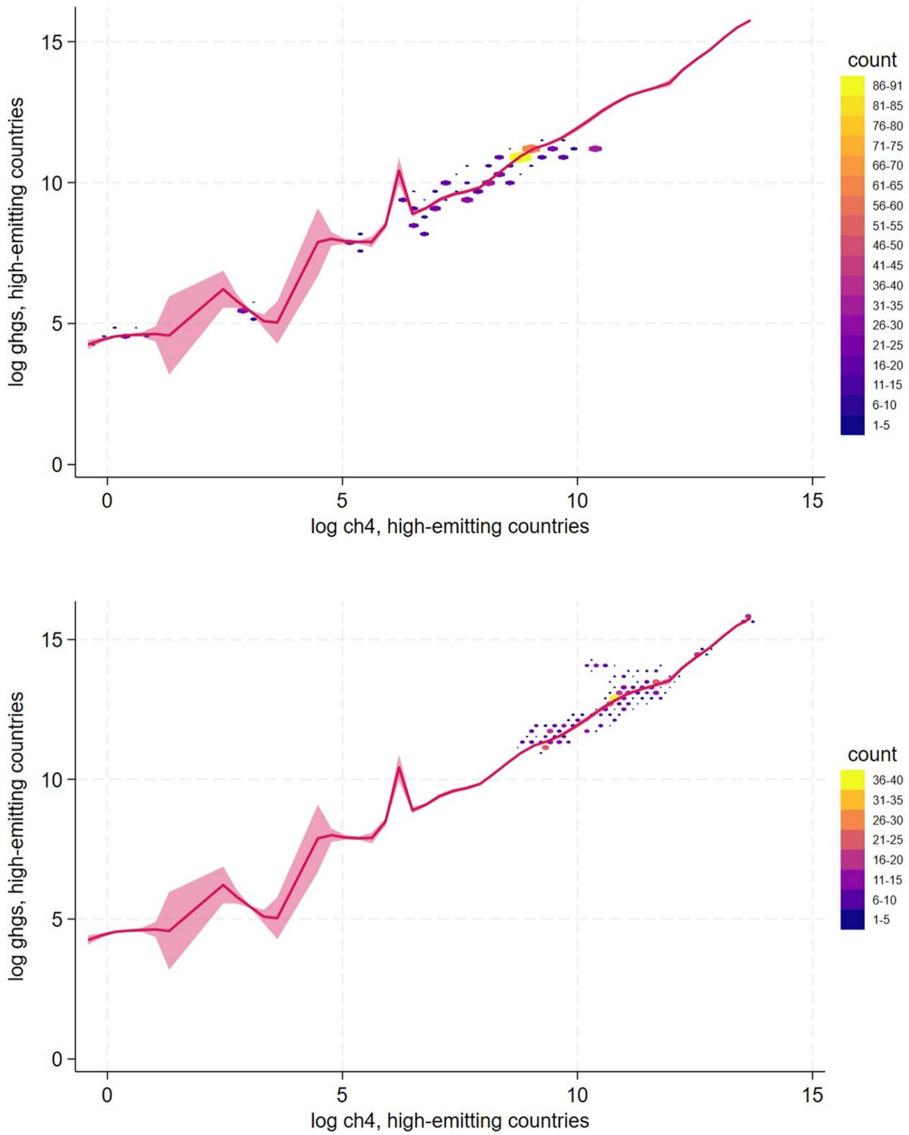

Fig. 7 Panel C: Correlation between total GHGs and methane emissions. Lower-emitting countries (top panel); higher-emitting countries (lower panel)

3.3.4 Panel D-1 and D-2

Figure 8.

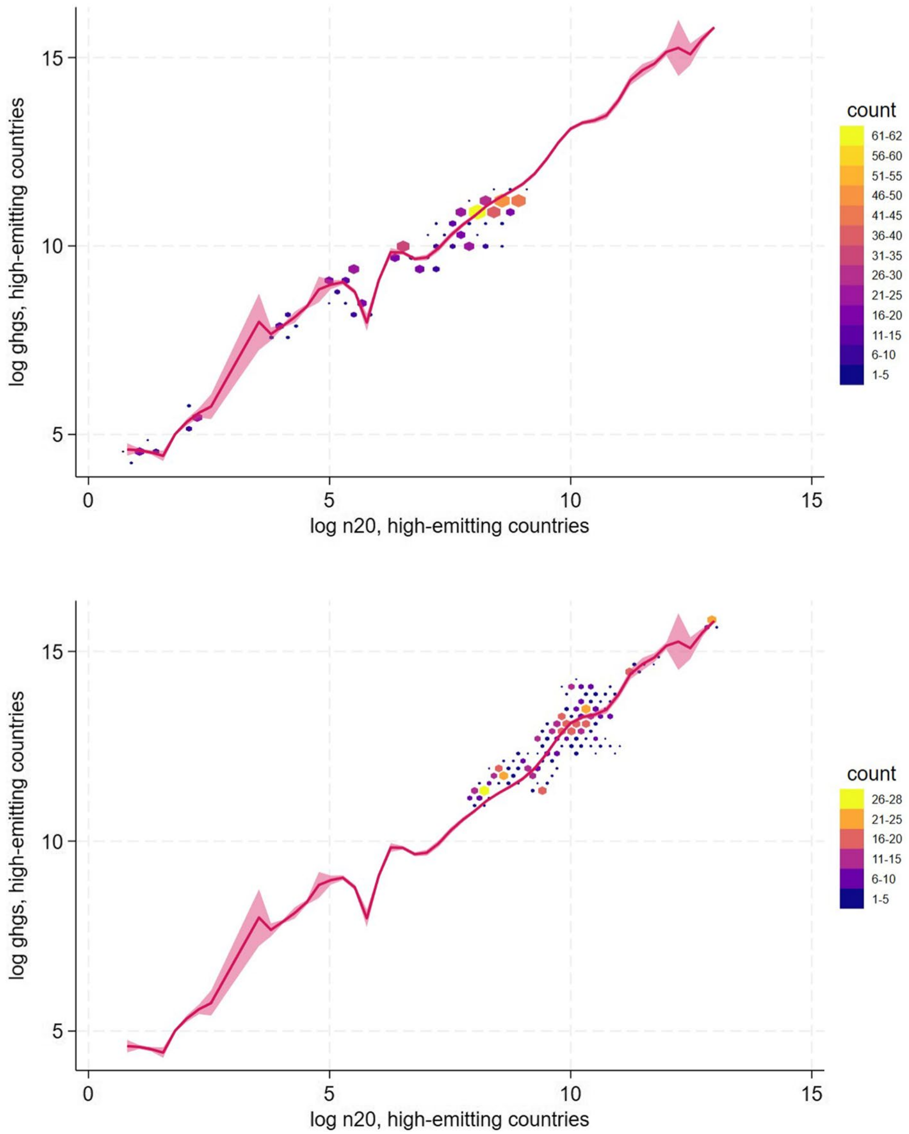

Fig. 8 Panel D: correlation between total GHGs and nitrous oxide emissions. Lower-emitting countries (top panel); higher-emitting countries (lower panel)

3.3.5 Panel E-1 and E-2

Figure 9.

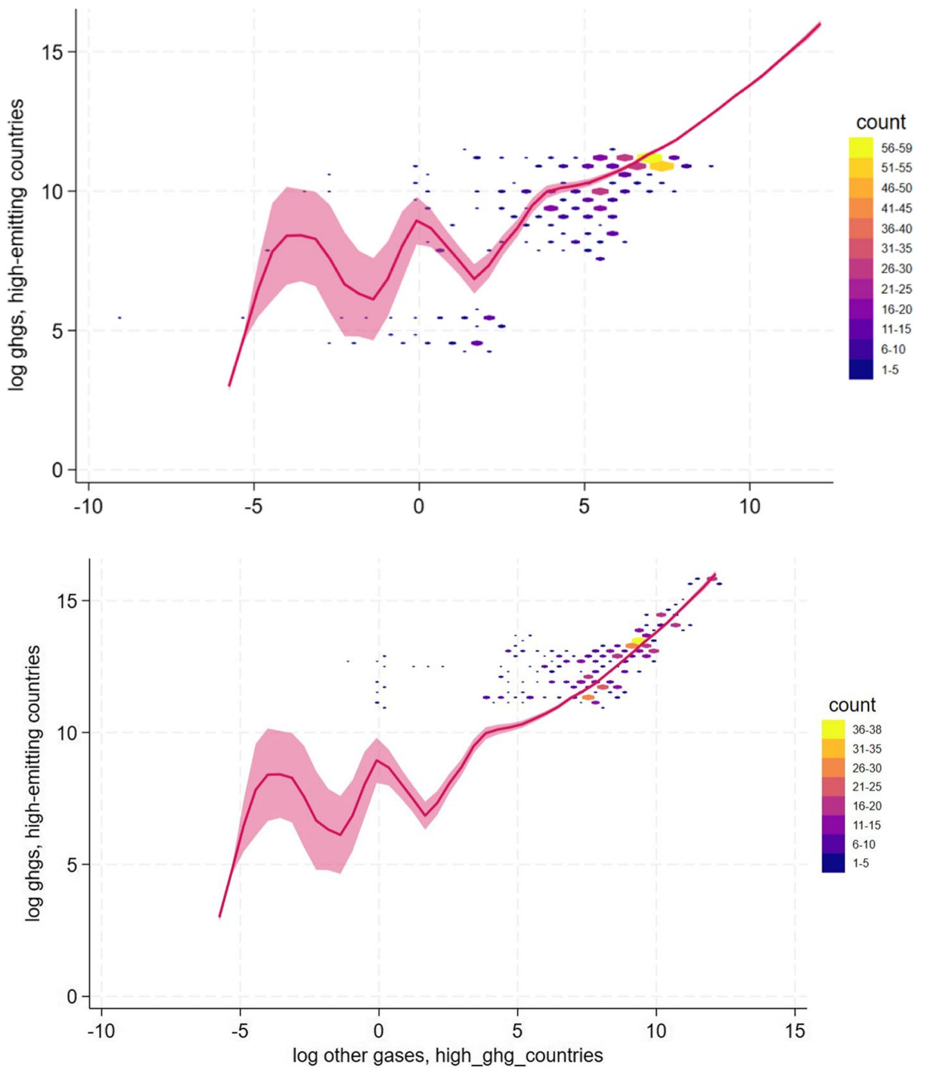

Fig. 9 Panel E-1 and E-2: correlation between total GHGs and “other” gases. Lower-emitting countries (top panel); higher-emitting countries (lower panel)

Table 7 Overview of the correlation results

Panel and description	Finding
Panel A-1: Lower-emitting countries, all gases (Fig. 5)	Correlations: CO_2 and total GHGs: 99.6% (prior to 2005); 99.7% (after 2005); 99.6% (1990–2021) CH_4 and total GHGs: 97.5% (prior to 2005); 97.6% (after 2005); 97.5% (1990–2021) N_20 and total GHGs: 97.7% (prior to 2005); 99.7% (after 2005); 97.4% (1990–2021) Other gases and total GHGs: 67.9% (prior to 2005); 92.4% (after 2005); 68.2% (1990–2021)
A-2: Higher-emitting countries, all gases (Fig. 6)	Correlations: CO_2 and total GHGs: 99.7% (prior to 2005); 99.8% (after 2005); 99.7% (1990–2021) CH_4 and total GHGs: 91.1% (prior to 2005); 90.6% (after 2005); 90.7% (1990–2021) N_20 and total GHGs: 92.2% (prior to 2005); 92.5% (after 2005); 92.1% (1990–2021) Other gases and total GHGs: 64.6% (prior to 2005); 80.4% (after 2005); 65.5% (1990–2021)
B-1: Lower-emitting countries, total GHGs and CO2 (Fig. 7)	General and moderate correlation
B-2: Higher-emitting countries, total GHGs and CO2 (Fig. 7)	Nearly perfect correlation
C-1: Lower-emitting countries, total GHGs and CH4 (Fig. 8)	Moderate correlation
C-2: Higher-emitting countries, total GHGs and CH4 (Fig. 8)	Moderate correlation
D-1: Lower-emitting countries, total GHGs and N2O (Fig. 9)	Low correlation
D-2: Higher-emitting countries, total GHGs and N2O (Fig. 9)	Low to modest correlation
E-1: Lower-emitting countries, total GHGs and "other gases" (Fig. 10)	Very low correlation
E-2: Higher-emitting countries, total GHGs and "other gases" (Fig. 10)	Moderately low correlation

Source Author's compilation of correlation results

4 Summary of the results

As Figs. 4 and 5, and Table 7 depict, across all gases apart from "other gases," the correlation with total GHGs are always above 0.9, indicative of a high correlation (Spearman, 1910a, 1910b). The correlation between total GHGs and CO_2 are the highest, specifically: 0.996 for lower-emitting countries across all years, and 0.997 for higher-emitting countries across all years. These fall somewhat with total GHG and CH_4 correlations: for lower-emitting countries, the correlation is 0.975 across all years, and 0.907 for higher-emitting countries; for N_2O, the correlations are 0.974 and 0.921 for lower and higher-emitting countries, respectively. Finally, for "other gases," the correlations are rather moderate, at 0.682 and 0.655, for lower and higher-emitting countries, respectively. Since we have elected to take the two country groupings separately, we shall now shortly discuss these independently.

For lower-emitting countries, CO_2 and total GHGs are correlated 99.6% (prior to 2005); 99.7% (after 2005); 99.6% (1990–2021), each of which are considered very high Spearman correlations (Spearman, 1910a, 1910b). The situation is much the same for CH_4 and total GHGs, 97.5% (prior to 2005); 97.6% (after 2005); 97.5% (1990–2021). That both CO_2 and CH_4 demonstrate very high correlations with total GHGs might indicate that lower-emitting countries are submitting estimations of CO_2 and CH_4 derived from total GHGs (e.g., estimating based on a percent of total GHGs, rather than compiling each gas separately). The correlations, though not as high for N_20, are still at 97.7% (prior to 2005); 97.0% (after 2005); 97.4% (1990–2021). For "other gases," finally, the correlations are unremarkable prior to 2005, at 67.9% and for all years, at 68.2%; nevertheless, from 2005 to 2021, the correlations are much higher, at 92.4%.

For higher-emitting countries, the correlations between CO_2 and total GHGs are 99.7% (prior to 2005); 99.8% (after 2005); 99.7% (1990–2021). Like the lower-emitting countries, these Spearman correlations are also very high (Spearman, 1910a, 1910b). Even though, on average, CO_2 emissions make up nearly three-quarters of total GHGs throughout the world, given the underlying differences in industrial structures, we did not expect to find correlations this high. The picture changes somewhat for the correlations between CH_4 and total GHGs: 91.1% (prior to 2005); 90.6% (after 2005); 90.7% (1990–2021). These correlations are more in line with expectations, in the sense that that GHGs should correlate moderately high with one another. It is indeed promising that the correlations have fallen after 2005, which signifies that these countries have improved upon their GHG inventory compilation methods for CH_4. For N_20 and total GHGs, for high-emitting countries, the correlations are 92.2% (prior to 2005); 92.5% (after 2005); 92.1% (1990–2021). Again, these moderately high correlations are expected. For the correlations between "other gases" and total GHGs, we observe 64.6% (prior to 2005); 80.4% (after 2005); 65.5% (1990–2021). Table 7 provides a synthesis of the findings.

5 Discussion

Researchers assert that the smooth functioning of the PA depends, to a large extent, on robust tracking and comparison of GHGs across countries and over time (Rowan, 2019). Should the underlying UNFCCC emissions data be incomparable, however, the foundations of global climate governance in the post-Paris regime are at risk (Aldy et al., 2017). This means that, while on the surface the PA appears to rest on solid footing (van Asselt et al., 2015), over time the four main pillars as detailed in Sect. 2.2.2 (NDCs, GS, ETF, CM) could fail to fully catalyse significant GHG reductions (Pauw et al., 2018).

5.1 Policy Implications

Based on the quantitative analyses, we concur with prior research which finds that the post-Paris climate governance regime did not lead to a much-needed an overhaul of the country-level emissions inventory system (Andrew, 2020; McLaren & Markusson, 2020). Despite enthusiasm for the PA in climate governance circles (Backstrand et al., 2017, Hale, 2020), key underlying and unresolved issues remain. From a policy perspective, if left unresolved, these issues could undermine the efficacy of carbon-based climate governance (Biermann, 2010), foremost among these the post-PA framework, including the NDCs and the Global Stocktake (Milkoreit & Haapala, 2019; Nielsen et al., 2021; Nukusheva et al., 2021). Broadly speaking, the GHG inventory data issues are due to impart negative implications for climate change governance—especially emissions-centric governance tools (Biermann, 2010; Coen et al., 2020b; Morseletto et al., 2017). Should comparison of emissions remain a cornerstone of climate governance under the UNFCCC within the post-Paris framework, an overhaul of country-level GHG inventories is called for. Climate governance, indeed, might deserve a radical rethink (Bernstein & Hoffmann, 2019).

Another point with respect to the GWPs warrants attention. Due to the oscillations in the GWPs, which are revised with each IPCC Assessment report, the conversion rates of CH_4, N_20, and "other gases" have undergone substantial revision in the last three decades (Tian et al., 2020) (see Table 1 in Sect. 2.2.1). This adds yet another layer of complexity when interpreting, and comparing, country-level GHG profiles. For instance, as discussed in Sect. 2, the GWPs conversion for some of the gases included in "other gases" run in the thousands (e.g., one tonne of CFC-12 is 14,400 tonnes of carbon equivalents according to AR4 and 13,900 according to AR5). Therefore, future research on climate governance in the post-Paris regime should onboard the issues that will inevitably arise as GWPs undergo future revisions.

Moreover, and what remains an important gap in the climate governance literature, the excessively high correlations in the GHG data bring to light deeper issues for carbon-centric climate governance (Biermann, 2010; Hickmann et al., 2017; Walker, 2011). Though carbon governance involves a multitude of actors, rules and regulations that monitor, verify and report *carbon emissions*—attention is still focused almost unilaterally on the governance of carbon, even though other GHGs have much higher GWPs. Moreover, using the 100-year time horizon fails to properly account for short-lived GHGs (Cain et al., 2019). This matters since some GHGs are significantly stronger than carbon. The carbon-based governance deficits surface in, for example, Ukraine and Turkey, which have experienced alarmingly upward trends for nitrous oxide in recent years (see Appendix Fig. 2). Climate governance mechanisms could mandate that submissions must immediately fall in line with the latest GWPs. Or, in the instance that substantial GWP revisions do not occur, it could nevertheless be agreed that each five years—in line with the Global Stocktake—countries would be required to revise their inventories in accord with the latest tabulations. A final option, although somewhat drastic, might be to abandon the GWPs altogether (Allen et al., 2016).

Carbon-centric climate governance, with a predominant focus on governing carbon emissions, does not sufficiently capture each country's economic and industrial structure; this means that, though some countries reduce carbon emissions, they can experience increases to other GHGs (Janssens-Maenhout et al., 2017; Nielsen et al., 2021; Sovacool et al., 2021). For example methane emissions—which stem from agriculture and also widespread deployment of natural-gas fired power stations (Mathur et al., 2022)—are only now becoming an important focus of climate governance (Sun et al., 2021). What is more, emissions from natural gas—a "bridging fuel" that has grown by 24% worldwide from 2000 to 2020–might not be accurately accounted for (https://www.iea.org/fuels-and-technologies/gas). An important dilemma is that countries can appear to be doing well to mitigate carbon emissions, while methane emissions from natural gas and agriculture are not accurately disclosed.

These issues deserve much more policy attention (McLaren & Markusson, 2020). A promising new development is the Global Methane Pledge (https://www.globalmethanepl edge.org/). Yet, emissions inventories have yet to fully revise methane GHG data (Maasakkers et al., 2019; Nisbet, 2022; Xu, 2018), as discussed in Sect. 2.2.1. One technological fix could be to begin using privately-funded satellite emissions tracking systems such as Climate Trace (Oda & Maksyutov, 2010), which are demonstrating more accurate emissions tracking (https://climatetrace.org/). Finally, recent agreements such as the Kigali Amendment, which is seen as vital to help draw down "other emissions" such as HFC-23, can also prove very important in this regard (Hoch et al., 2019).

5.2 Limitations and future research

There are several limitations to this study. First, correlations in time-series data can be spurious; this issue is particularly relevant when source data have unresolved inconsistencies (Chatfield, 2000; De Winter et al., 2016). As indicated by prior research, emissions inventory data is likely to be confronted by underlying and yet to be resolved source data issues (Marland & Rotty, 1984; Marland et al., 1985; Marland et al., 1999a; Marland et al., 1999). Indeed, this might have contributed to our findings of high correlations across different gases. In addition—and as demonstrated by the revisions to GWPs every several years—the variegated warming impact of different GHGs remains an inexact science (McArthur, 1980). To be clear, this study does not provide conclusive evidence that the UNFCCC's emissions data repository has fundamental flaws, it only suggests that, based on the preliminary findings of significantly high correlations, further research is called for. If monitoring and comparing emissions are to remain a vital part of the post-Paris climate governance framework, this is an important future research endeavour.

Finally, several counterpoints are worth discussing. Some have argued that, since carbon emissions are the most consequential GHG, monitoring and comparing other GHGs such as CH_4 and N_20 are far less important (Ritchie et al., 2020). This line of reasoning, however, does not hold much water because other GHGs—with much higher GWPs (e.g., N_20 at 298 CO_2-e)—are rising in some countries at alarming rates (Harris & Lee, 2017; Mar et al., 2022). Some troubling patterns can also be observed for "other gases" in several countries (see Appendix Fig. 2). In addition, and what has been the subject of recent research, in countries that have managed to reduce domestic emissions, it is likely that they have offshored these emissions as they have offshored industrial operations through "carbon leakage" (Nielsen et al., 2021; Sato, 2014).

Future research can extend this study in several directions. First, researchers could investigate other GHG data repositories (e.g., Edgar, BP, PIK-Potsdam) that, although they are not part of the UNFCCC governance system, are shown to be more consistent over time (Janssens-Maenhout et al., 2017; Janssens-Maenhout et al., 2019). Researchers could also conduct within-database correlations as well as across database correlations. For the latter, it is likely that some databases will not mirror others, especially since the sector-based and reference approaches are taken according to the repository method (IPCC, 2023b). In addition, stronger empirical methods might go further to provide evidence of the unrealistically high corelations found here.

6 Conclusion

Commitments to emissions reductions following the landmark Paris Climate Change Agreement have proliferated, with 145 countries declaring a net-zero emissions target. In principle, these plans are expected to help guide dramatic emissions reductions in part through knowledge sharing and comparison of emissions inventories. Nevertheless, the analyses carried out in this article call into question the extent to which GHG inventory comparison is possible. Based on time-series GHG correlation analyses covering 32 years and 43 Annex-I countries, we uncovered some troublingly high correlations, which warrant future attention, especially in climate governance research circles.

Since countries have widely different industrial and economic structures—which would mean that they have variegated and disparate GHG profiles (Crill & Thornton, 2017; Höhne et al., 2011; Sovacool et al., 2021; Zheng et al., 2019)—such high correlations are not expected, but this was indeed what was found. Broadly speaking the data suggest that, even in the most advanced economies, there are unresolved and systematic GHG inventory issues. Further complicating matters are the periodic revisions to the GWPs, which effectively amplify data inconsistencies as they are revised over time, or if countries do not update their inventories according to GWP revisions. If left unresolved, these data anomalies could well undermine the efficacy of the PA, including the NDCs, the ETF, and the Global Stocktake (Monasterolo et al., 2019).

Given the underlining data anomalies presented above, in closing, we draw attention the perilous foundations of the post-Paris climate governance system, which continues to place much emphasis on the potential to compare emissions inventories and track progress (Weikmans et al., 2020). In the absence of reliable and comparable data on GHGs, moreover, the efficacy of climate governance through emissions inventories is in jeopardy (Kingston, 2016; Rowan, 2019). In sum, while the Paris Agreement has laid down the foundations for "polycentric" and "bottom-up" climate governance (Cole, 2011; Abbot, 2018; van Asselt et al., 2018), Annex-I countries—which are expected to have the most complete and accurate GHG inventory data (Aldy et al., 2017)—continue to submit emissions inventories that are not readily comparable with respect to different GHGs and over different future timescales.

Appendix

Figures 10, 11 and 12.

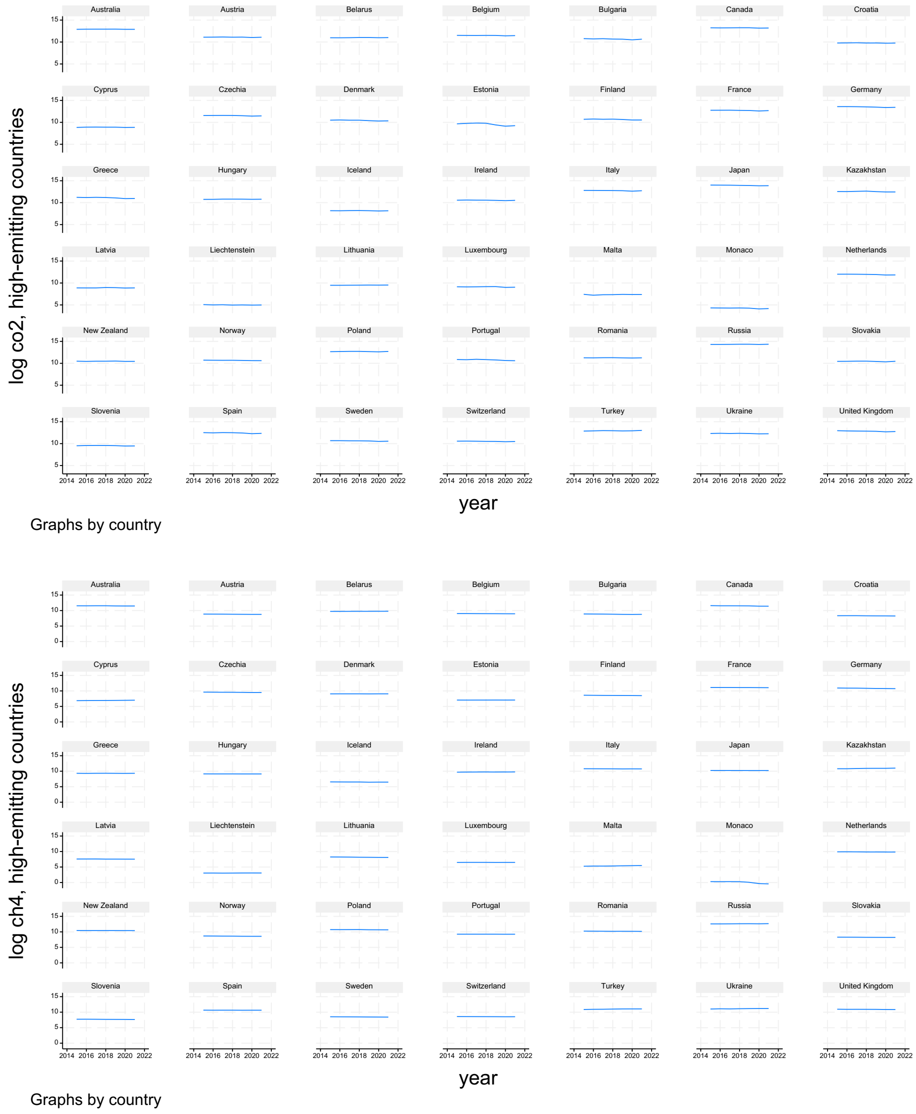

Fig. 10 Post-Paris trends in CO_2, CH_4, and N_20 (without the US as an outlier). *Source* Author's calculation of UNFCCC data

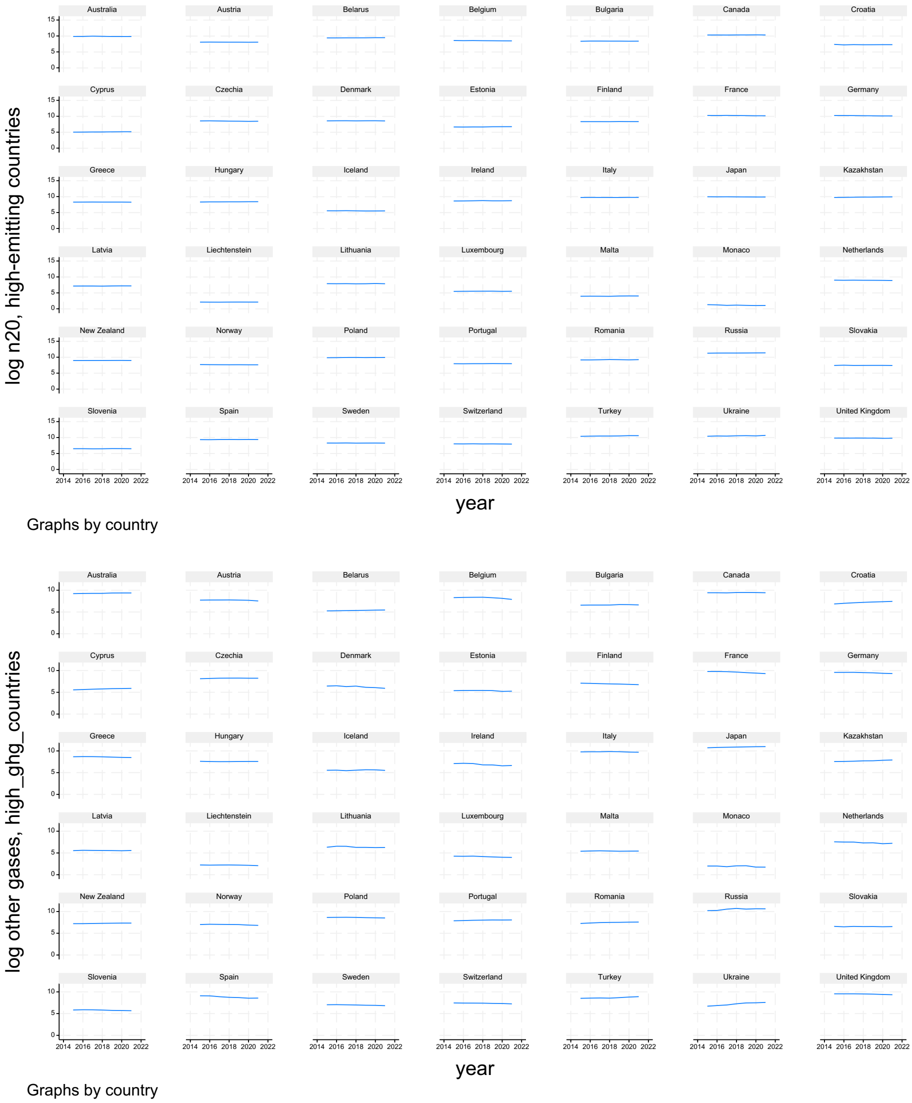

Fig. 10 (continued)

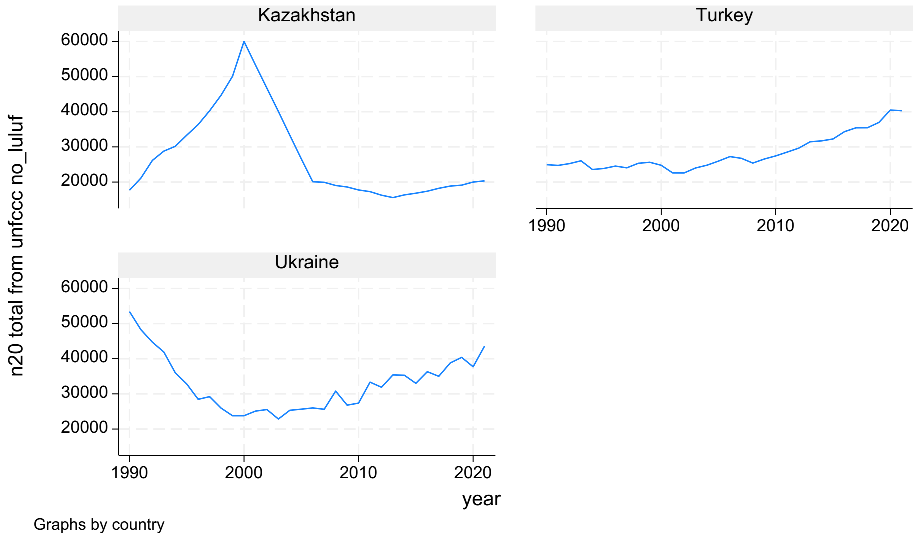

Fig. 11 Accelerating N20 emissions in several Annex I countries. *Source* Author's calculation of UNFCCC data

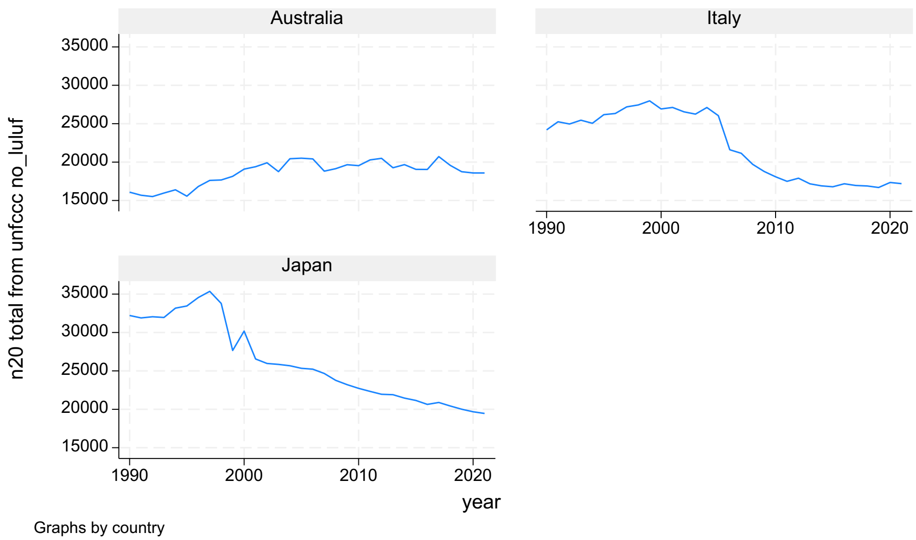

Fig. 12 Notable changes in several countries' "other gases" emissions. *Source* Author's calculation of UNFCCC data

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Data availability Data will be made available upon reasonable request. I, Kyle S. Herman, was responsible for all data collection, cleaning, and analysis. I was also responsible for all drafting of the manuscript.

Declarations

Conflict of interest I declare that there are no competing Interests.

Ethical approval This article does not require ethics approval and consent to participate. All data was collected from publicly-available sources, and does not involve human participants.

Consent for publication I give Consent for publication.

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