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RESEARCH ARTICLE
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Key Points:

- Highest uncertainty and lowest confidence levels were identified in bottom-up natural emissions in the Global Methane Budget
- High driver data uncertainties are associated with freshwater, vegetation, and coastal/ocean methane sources
- New methane source partitioning reveals 76% of global emissions are related to moderate to high levels of anthropogenic impacts

Supporting Information:

Supporting Information may be found in the online version of this article.

Correspondence to:

J. A. Rosentreter,
judith.rosentreter@scu.edu.au

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Revisiting the Global Methane Cycle Through Expert Opinion

Judith A. Rosentreter[1,2,3], Lewis Alcott[1,4,5], Taylor Maavara[1,2,6], Xin Sun[1,7], Yong Zhou[1,7,8], Noah J. Planavsky[4], and Peter A. Raymond[2]

[1]Yale Institute for Biospheric Studies, Yale University, New Haven, CT, USA, [2]Yale School of the Environment, Yale University, New Haven, CT, USA, [3]Faculty of Science and Engineering, Southern Cross University, Lismore, NSW, Australia, [4]Department of Earth and Planetary Sciences, Yale University, New Haven, CT, USA, [5]School of Earth Sciences, University of Bristol, Bristol, UK, [6]School of Geography, University of Leeds, Leeds, UK, [7]Department of Ecology and Evolutionary Biology, Yale University, New Haven, CT, USA, [8]Department of Wildland Resources, Utah State University, Logan, UT, USA

Abstract An accurate quantification of global methane sources and sinks is imperative for assessing realistic pathways to mitigate climate change. A key challenge of quantifying the Global Methane Budget (Saunois et al., 2020, https://doi.org/10.5194/essd-12-1561-2020) is the lack of consistency in uncertainties between sectors. Here we provide a new perspective on bottom-up (BU) and top-down (TD) methane uncertainties by using an expert opinion analysis based on a questionnaire conducted in 2021. Expectedly, experts rank highest uncertainty and lowest confidence levels in the Global Methane Budget related to natural sources in BU budgets. Here, we further reveal specific uncertainty types and introduce a ranking system for uncertainties in each sector. We find that natural source uncertainty is related particularly to driver data uncertainty in freshwater, vegetation, and coastal/ocean sources, as well as parameter uncertainty in wetland models. Reducing uncertainties, most notably in aquatic and wetland sources will help balance future BU and TD global methane budgets. We suggest a new methane source partitioning over gradients of human disturbance and demonstrate that 76.3% (75.8%–79.4%) or 561 (443–700) Tg CH_4 yr^{-1} of global emissions can be attributed to moderately impacted, man-made, artificial, or fully anthropogenic sources and 23.7% (20.6%–24.2%) or 174 (115–223) Tg CH_4 yr^{-1} to natural and low impacted methane sources. Finally, we identify current research gaps and provide a plan of action to reduce current uncertainties in the Global Methane Budget.

Plain Language Summary To effectively address climate change, it's crucial to gain a better understanding of the difficulties involved in estimating global methane sources and sinks. One of the key challenges in this process are the varying levels of uncertainty associated with different sectors responsible for methane emissions and methane uptake. In this study, we conducted a survey to gather expert opinions regarding the uncertainty of methane data. The experts highlighted that the Global Methane Budget has the highest uncertainty and lowest confidence levels when it comes to natural sources in the bottom-up budgets. This uncertainty primarily stems from uncertain data related to natural sources like freshwater, vegetation, and coastal/ocean areas, as well as the parameters used in wetland models. We show that 76.3% of all global methane emissions are related to human-impact or fully man-made. Additionally, we identify existing gaps in research and lay out a plan of action to reduce the current uncertainties associated with the Global Methane Budget. This effort will contribute to a more accurate understanding of methane's role in climate change mitigation.

1. Introduction

Methane (CH_4) is a potent greenhouse gas contributing 35% of the greenhouse gas-driven warming in 2010–2019 relative to 1850–1900 (IPCC, 2021). Global mean atmospheric concentrations of methane have increased by 160% since pre-industrial levels (1750: 729 ppb; 2021: 1895 ppb) and the global annual increase rate was exceptionally high in 2020–2021 (18.3 ppb yr^{-1}) (Dlugokencky, 2019). After a period of stagnation between 2000 and 2006, also termed the "stabilization period," a strong renewed increase in atmospheric methane has accelerated in recent years (Dlugokencky, 2019). It is unknown at present whether the rapid renewed growth is caused by emissions from anthropogenic or natural sources, or by the decline in the atmosphere's oxidative capacity (e.g., declining atmospheric OH concentration (Rigby et al., 2017)) or by

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a combination of all three factors (Nisbet et al., 2019). To assess the present day and future trends in global methane emissions and methane removal, a consortium of multidisciplinary scientists synthesizes and regularly updates the Global Methane Budget (GMB). The most recent and second version of the GMB 2020 (Saunois et al., 2020) integrates results from top-down studies and bottom-up estimates of global methane sources and sinks for the time frames 2000–2009, 2008–2017, and 2017. Top-down (TD) studies use atmospheric observations and calculate fluxes via the use of atmospheric inverse-modeling frameworks. In contrast, bottom-up (BU) estimates include process-based and statistical methods for estimating land surface emissions and atmospheric chemistry, inventories of anthropogenic emissions, and data-driven extrapolations (Saunois et al., 2020).

Although uncertainties have reduced since the previous GMB 2016 (Saunois et al., 2016), in the GMB 2020 (Saunois et al., 2020), there are still significant questions associated with natural and anthropogenic methane source and methane sink sectors, particularly within the "other natural emissions" sector. It is currently unknown whether the large ranges for some sectors are related to insufficient models and/or empirical data availability. For example, global uncertainties in the GMB 2020 (Saunois et al., 2020), reported as [min-max] ranges, may be associated with temporal variability (e.g., diurnal, seasonal, annual, inter-annual), spatial and/or regional variability (e.g., tropics vs. polar), biases in sampling approaches, uncertainties in global areas and geographically overlapping of sources, but also with uncertainties in TD versus BU approaches. Model-related uncertainties include, among other factors, structural and parameter uncertainty, data quality, model complexity, as well as the model type (e.g., process-based vs. empirical models). The GMB 2020 (Saunois et al., 2020) summarizes some of these substantial uncertainties by considering the source-sink imbalance which for BU estimates is 112 Tg CH_4 yr^{-1} compared to 13 Tg CH_4 yr^{-1} for TD estimates, leaving an astonishing discrepancy of 99 Tg CH_4 yr^{-1} (~3 Pg CO_2-equivalents $year^{-1}$ using the global warming potential (GWP) for 100 years time period (IPCC, 2021)) between the two approaches.

Urgent and rapid action is needed in order to achieve the goal of limiting global warming to 1.5°C. In November 2021, over 100 countries joined "The Global Methane Pledge" and committed to a collective goal of reducing global methane emissions by at least 30% by 2030 and moving towards using best available inventory methodologies to quantify methane emissions ("IEA (2022), Global Methane Tracker 2022, IEA, Paris https://www.iea.org/reports/global-methane-tracker-2022," 2022). An elicitation of scientific and technical judgment from experts is required to go beyond well-established knowledge and can provide additional evidence to support the decision making for public policy (Morgan, 2014). Several studies have provided valuable insight into current climate change related issues by using expert elicitation (Macreadie et al., 2019; Schuur et al., 2013). In this analysis, we use expert opinion based on a questionnaire to assess the prevailing views of experts in the scientific community on the magnitude, distribution, and types of uncertainties behind global methane sources and sinks in the GMB 2020 (Saunois et al., 2020) based on scientific evidence and/or expert opinion. We developed an online survey that was completed by 53 experts on the various aspects of the global methane cycle, to establish a standardized means of assessing the uncertainty across sectors. This study aims to provide guidance on how to further reduce uncertainties in global methane source and sink estimates by describing uncertainties in each sector and by listing specific recommendation (Table 1) and most-pressing questions (Box 1) based on an expert assessment. Using data from our survey, we provide a novel perspective and a plan of action to reduce uncertainties in the GMB 2020 (Saunois et al., 2020). We further suggest a new partitioning of natural and anthropogenic source sectors and identify current research gaps in the GMB 2020. A fundamental understanding of the distribution and drivers of methane uncertainties in global sinks and sources is imperative for achieving our global ambitions to rapidly reduce methane emissions in the near-term future and to develop effective climate mitigation strategies.

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Table 1
Methane Source and Sink Uncertainties, Types of Uncertainties, and Current Limitations Identified Through Expert Assessment, a Proposed Plan of Action to Reduce Uncertainties in Sectors, and Anticipated Uncertainty Evaluation After Action Taken

Sector	Uncertainty evaluation *this study* (Figure 1a)	Uncertainty type most uncertain *this study* (Figures 4b–4d)	Current limitations	Plan of action	Uncertainty evaluation after action taken
Sources					
Other natural sources	HIGH	• Driver data uncertainty	• Inadequate spatial and temporal coverage of data.	• Need for more systematic measurements, in particular from understudied regions, to develop reliable biogeochemical models. For example, high resolution temporal data for small and dynamic systems (e.g., ponds, coastal systems) and high spatial resolution for large-scale multinational systems (e.g., forests, oceans).	MEDIUM/LOW
		• Parameter uncertainty	• Inadequate empirical knowledge of methane processes, pathways and environmental controls.	• Constrain the global role of woody vegetation.	
			• Response to climate feedbacks unclear.	• Advance fundamental understanding of methane production and consumption/oxidation processes and transport pathways (diffusion, ebullition, plant-fluxes).	
			• Risk of double counting of inland/coastal waters and wetlands.	• Improve model and scaling efforts through better integration of physical and hydrological parameters (e.g., flow volume, residence time). • Need to account for lateral fluxes along the land-to-ocean aquatic continuum. • More research on direct and indirect emissions from permafrost thawing. • Improve classification of wetland, freshwater, and coastal area by using advanced satellite remote sensing.	
Wetlands	HIGH	• Parameter uncertainty	• Risk of double counting of inland/coastal waters and wetlands.	• Use advanced satellite remote sensing to finalize global high-resolution classification of wetlands.	MEDIUM/LOW
			• Inadequate knowledge of temporal variability of global wetland extent and methane emissions within and across years.	• Increase understanding of the landscape connection between wetlands and inland/coastal waters.	
			• Wetland response to climate feedbacks (e.g., warmer temperature, change of inundation patterns) unclear.	• Greater temporally (inter-annually) and spatially resolved models to identify peak fluxes and to identify local hot spots. • Improve integration of new and updated understanding of biogeochemical processes (e.g., redox reactions), environmental drivers, and extent of inundation into relevant models. • Evaluation/validation of land surface models against in situ observations.	

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Table 1
Continued

Sector	Uncertainty evaluation *this study* (Figure 1a)	Uncertainty type most uncertain *this study* (Figures 4b–4d)	Current limitations	Plan of action	Uncertainty evaluation after action taken
Agriculture and waste	MEDIUM	• Parameter uncertainty	• Lack of sustained measurements of industrial agriculture and landfill operations. • Inaccurate ruminant emissions from Tropics and Sub-tropics.	Constrain regional and global inventories of methane from agriculture and cattle farming. • Improve knowledge of spatial and temporal variations of $\delta^{13}CH_4$ signatures of different methane sources. • Extend methane networks to poorly monitored regions (e.g., Tropics, high latitudes).	LOW
Fossil fuel	MEDIUM	• Parameter uncertainty	• Uncertain partitioning between anthropogenic and geological fossil sources. • Potential underreporting of oil, gas, and coal extraction in national inventories.	• Advance satellite monitoring to resolve fossil fuel emissions and methane leaks related to fracking more spatially and temporally. • Improve knowledge of $\delta^{13}CH_4$ signatures and radiocarbon to better distinguish between anthropogenic and natural geological fossil sources (and biogenic vs. thermogenic).	LOW
Biomass and biofuel burning	LOW/MEDIUM	• Parameter uncertainty	• Inadequate modeling parameters, lack of comprehensive data.	• Develop better tracking programs of methane emissions from biomass burning. Improve biomass burning emission factors.	LOW
Sinks					
Total chemical loss	MEDIUM	• Driver data uncertainty	• Global OH variability in the troposphere is unresolved. • Inadequate knowledge of the controls on chemical loss.	• Improve model representation of spatiotemporal and inter-annual OH variability. • Advance understanding of the mechanisms and controls on OH concentrations. • Improve quantification of oxidation by Cl. • Requirement for an established effort in the development of a new OH tracer.	LOW
Soil uptake	MEDIUM	• Driver data uncertainty	• High structural uncertainty in models.	• Need for more empirical data on soil sinks (and sources), globally. • Need for complex models to simulate soil water content and shifts from soil sinks to sources.	MEDIUM/LOW

Note. Uncertainty evaluation: HIGH = Large knowledge gaps, low agreement of studies, limited evidence. MEDIUM = Good knowledge but medium agreement and medium evidence. LOW = Well known, high agreement of studies, robust evidence.

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Box 1. The Six Most Pressing Questions Related to Global Methane Budget Uncertainty.

The most pressing questions related to methane uncertainties in the Global Methane Budget identified by experts correspond to wetland and freshwater sources (18%), climate feedbacks (13%), fossil fuel sectors (10%), and ∼equally (9%) to topics such as TD versus BU, anthropogenic versus natural sources, OH sinks, and unknown factors. Other topics raised by experts are related to permafrost thawing (7%), negative emission technology (5%), and the atmospheric growth rate (3%). In the following, we systematically summarize the responses raised by experts of the top six topics in our own words beginning with the most pressing question in a descending order.

1. Can we improve the accuracy, reduce the uncertainty, and better account for spatiotemporal variations of wetland and inland water methane emissions? How will wetland and freshwater emissions change in response to warmer temperatures, increased fertilizer runoff, and changing patterns of inundation and precipitation under future climate change?
2. Are (positive) climate feedbacks on natural sources and sinks already contributing to the atmospheric increase of methane? If yes, what are the relative contributions from different sectors (e.g., permafrost, wetlands, clathrates)? If not, then why not?
3. Globally, how accurate are fugitive emissions from the fossil fuel industry? Are emissions from oil, gas, and coal mining sectors from regions that are relatively well-monitored comparable to regions where data are less available or data sources uncertain? Are super-emitters responsible for the current increase of fugitive emissions?
4. What drives the large discrepancy of TD and BU estimates? Can we reconcile TD and BU estimates, particularly of "other natural sources," through further observations and more careful upscaling?
5. Are there any unknown or overlooked sources or sinks that contribute to the increase of atmospheric methane? An improved monitoring of generally understudied regions and ecosystems, explorations of new avenues, and better insight into microbial pathways is needed.
6. Is the OH sink capacity changing over time or relatively constant in the troposphere? If it is changing, how large is the inter-annual variability in OH concentrations and what controls it?

2. Materials and Methods

2.1. Survey Design and Justification

We developed the written survey questions (Supporting Information S1) using the Qualtrics Survey Tool with an enterprise license held by Yale University (https://yale.service-now.com/it?id=service_offering&sys_id=5b584dcd6fbb31007ee2abcf9f3ee4e3). We interactively revised background information, response formats, and survey questions based on our discussion with leading scientists in uncertainty quantification and expert opinion analyses. Survey respondents did not include experts involved in survey development or testing. From July to August 2021, the survey questions were further refined for readability, clarity, and scientific rigor following a pilot interview with several scientists.

All authors involved in the development of the survey completed human subjects' protection training offered at Yale University. The survey was approved by the Yale University Institutional Review Board (Yale IRB) and included a risk statement as follows: "You will not directly benefit from participation in this research study, but we hope that the input we receive from all our experts will advance public policy in this area. Your responses will not be linked to your name. Your participation in this study is completely voluntary and the limited amount of personal information collected will be dissociated with your answers prior to data analysis. We are required to inform you that the only risk the Yale IRB review has identified is a possible loss of confidentiality of your answers."

The survey was finally distributed to experts through emails on 19 August 2021 with an accessible link and closed on 31 December 2021. To better help survey participants access all information and questions while filling out the survey, we also distributed a pdf document containing the questionnaire (Supporting Information S1). The final survey consists of three sections: Introduction, Pre-survey, and the Main Questionnaire containing 16 questions related to uncertainties in the Global Methane Budget. The questionnaire includes a mix of quantitative survey questions to answer initial research and qualitative survey questions that are open-ended and designed to uncover thoughts and opinions. Open-ended questions can be viewed as expert opinion. Therefore, we refer to our survey as an expert opinion analysis.

2.2. Survey Responses and Quality Controls

We selected potential participants based on their contribution to the understanding of one or more sources and sinks in the global methane cycle. We identified potential participants in three ways: (a) nomination by lead scientists in the global methane cycle; (b) authors of the GMB 2016 (Saunois et al., 2016) and GMB 2020 (Saunois et al., 2020) publications; and (c) querying Google Scholar with applicable search terms (e.g., wetland AND methane) and selecting the first and/or corresponding authors of influential peer-reviewed literature and filtering based on applicability. Overall, we invited 201 experts with expertise covering all sources and sinks in the global methane cycle.

We received a total of 53 responses (including two responses referred by participants) (27% response rate), of which 45 completed the entirety of the survey. We note throughout how many respondents (n = number of respondents) answered specific questions in our analysis. Participants come from various disciplines, career stages, and geographical locations (Figure S1 in Supporting Information S1).

Our pre-survey analysis revealed that participants ranked (on a score from 1 to 10) their highest (median) expertise in wetlands (7) and inland waters (6), followed by oceanic sources (5), landfill and waste (5), coal mining (5), tropospheric OH sinks (5), oil and gas industry (5), soil uptake (5), biomass burning (5), rice cultivation (4), enteric fermentation and manure (4), tropospheric Cl sinks (4), wild animals (3), termites (3), permafrost (3), vegetation (3), geological onshore sources (3), transportation (3), biofuel burning (3), and methane sinks through stratospheric loss (3). While we acknowledge the varying levels of our participants' expertise across methane sectors, we were able to have at least one participant with a high level of expertise (8+) for each sector. Note that several participants had expertise in more than one sector (Supplementary Figure 1a). More than 96% of the participants were either senior scientists (40%), early career researchers (34%), or mid-career researchers (23%), with the remaining 4% were PhD students or retired/emeritus researchers (Figure S1b in Supporting Information S1). More than 88% of participants have more than 10 years research experience in the methane cycle (Figure S1c in Supporting Information S1). Participants identified as empiricists (47%), modelers (30%) or both (23%) (Figure S1d in Supporting Information S1). More than 62% of the participants use BU methods, 17% use TD, and 21% use both approaches at the local/regional (17%), local/regional to global (57%), and global (26%) scales (Figures S1e and S1f in Supporting Information S1). Participants' affiliations were from 17 countries with the majority based in the US (42%), Australia (8%), France (8%), and Canada (6%) (Figure S1g in Supporting Information S1).

2.3. Evaluation of Uncertainty

To evaluate uncertainty, we followed the guidance on consistent treatment of uncertainties of the IPCC assessment report (Mastrandrea et al., 2010) that relies on two metrics for communicating the degree of certainty: confidence and likelihood. Each survey question includes a clear statement/definition of the type of uncertainty, confidence, and/or likelihood referred to.

Confidence is based on the type, amount, quality, consistency of evidence and the degree of agreement (e.g., expert judgment, mechanistic understanding, models), and expressed using up to five qualifiers in relation to evidence and agreement statements: "very low," "low," "medium," "high," and "very high." Confidence in this study is used distinctly from statistical confidence and should not be interpreted probabilistically.

Very low confidence = low agreement/limited evidence
Low confidence = low agreement/medium evidence or medium agreement/limited evidence
Medium confidence = medium agreement/medium evidence

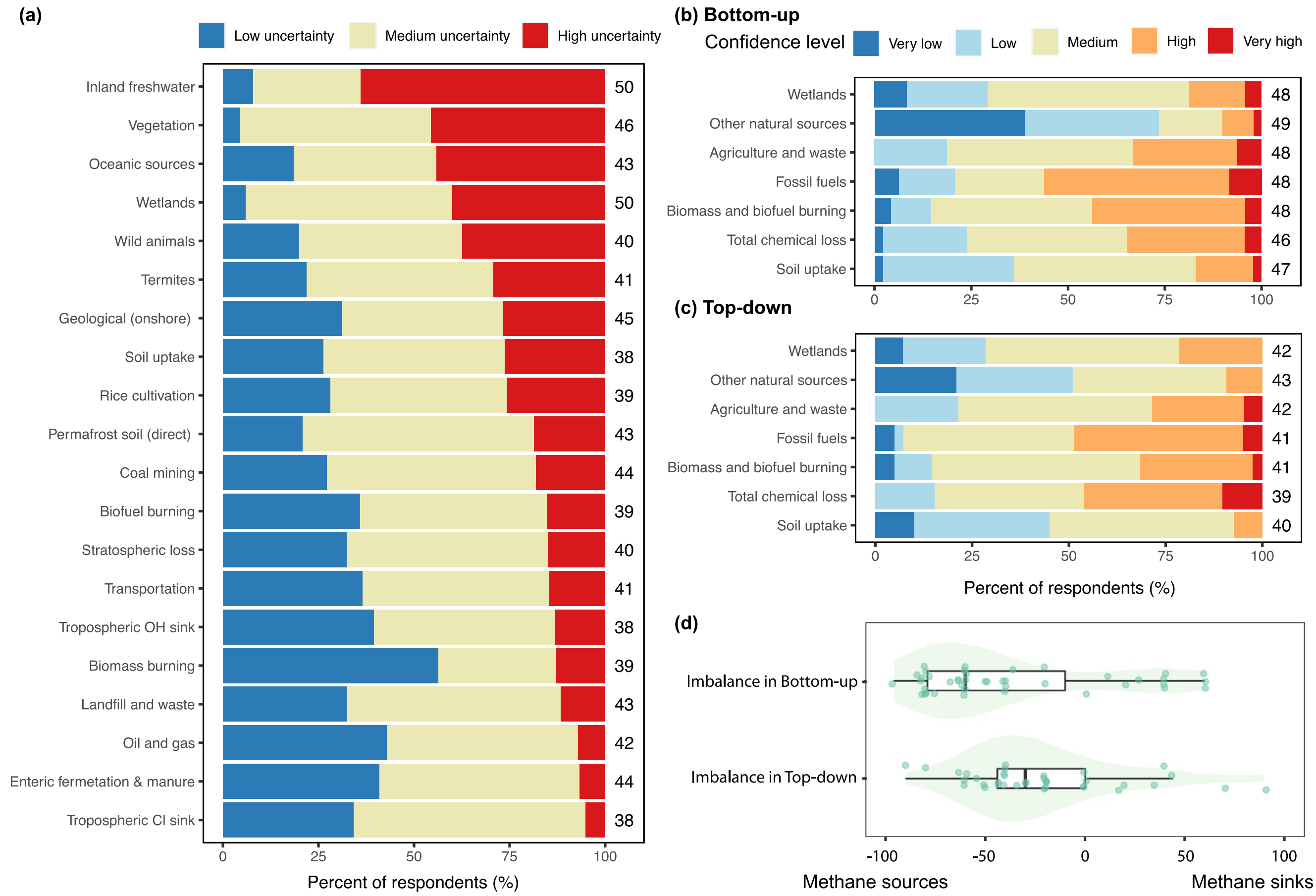

Figure 1. Uncertainty and confidence levels in bottom-up and top-down estimates based on expert opinion analysis. Stacked bar plots show the relative percentage of (a) high, medium, and low uncertainty, (b) confidence level of bottom-up estimates, (c) confidence level of top-down range estimates, of methane sources and sinks rated by experts. The number (n) of expert responses is shown to the right of each sector. (d) Box and violin plots showing median, interquartile range, and the distribution of numerical data (kernel density plot) of experts' ranking of how much of the imbalance in bottom-up and top-down budgets they relate to uncertainties in methane sources or methane sinks, with the score −100 meaning the imbalance is related to uncertainty only in methane sources and 100 meaning the imbalance is related to uncertainties only in methane sinks. Highest uncertainty and lowest confidence levels in both TD and BU approaches are associated with other natural sources (including inland freshwater, vegetation, and oceanic sources) and soil uptake.

High confidence = high agreement/medium evidence or medium agreement/robust evidence
Very high confidence = high agreement/robust evidence

Alternatively, confidence is used to describe the confidence in the range of an estimate:

Very low confidence = very low confidence that the range represents the true range
Low confidence = low confidence that the range represents the true range
Medium confidence = medium confidence that the range represents the true range
High confidence = high confidence that the range represents the true range
Very high confidence = very high confidence that the range represents the true range

Likelihood provides calibrated language for quantified uncertainty that may be based on elicitation of expert opinions, statistical, modeling, or other analysis. We used the following likelihood scale:

Very likely = 90–100% probability
Likely = 66–100% probability
About as likely as not = 33–66% probability
Unlikely = 0–33% probability
Very unlikely = 0–10% probability

3. Current Uncertainties in Global Methane Sources and Sinks

Our expert opinion analysis demonstrates that higher uncertainties are attributed to natural sources than anthropogenic sectors in the GMB 2020 (Saunois et al., 2020) (Figure 1a). This rather expected finding is in accordance with the uncertainty evaluation of the GMB 2020 (Saunois et al., 2020) that attributed the most important source of uncertainty to wetlands and other inland waters. In this study, using expert opinion analysis, we further reveal the specific types of uncertainties related to each sector by introducing a systematic ranking system, present a new partitioning of anthropogenic versus natural methane emissions, and discuss present and future methane trends based on the current view of experts. We find that uncertainties are ranked highest for inland waters (64% of experts ranked as a sector of high uncertainty) due to a combination of poor spatiotemporal coverage of sampled water bodies from which global estimates are upscaled and from which models are calibrated, uncertainties related to importance of ebullition compared with diffusion (Deemer & Holgerson, 2021; Rosentreter et al., 2021), as well as difficulties related to the spatially variable classification of inland water body types and sizes (Deemer & Holgerson, 2021; Peacock et al., 2019), and their locations within terrestrial landscape and river network (Borges et al., 2019). Interestingly, we find that experts rank uncertainties in vegetation (46%) and oceanic/coastal sources (44%) higher than in wetlands (40%). Previous assessments of natural methane sources have focused primarily on reducing uncertainties in wetland methane (Ganesan et al., 2019) because of their relatively high contribution (149 Tg CH_4 yr^{-1}, 20%) to BU global sources (Saunois et al., 2020). Nevertheless, lakes, river, and coastal/oceanic systems have substantial contributions to global aquatic methane emissions of 35%, 6%, and 8%, respectively (Rosentreter et al., 2021). Here we show that the prevailing view of experts is to uncover unknown methane pathways and to establish better confidence around magnitude and variations of methane fluxes in freshwater and coastal/oceanic aquatic and vegetated ecosystems. Methane emissions from vegetation include plant-mediated emissions through aerenchyma of vascular plants (Chanton et al., 1989; Jeffrey, Maher, et al., 2019), and tree stem-based methane fluxes from both living and dead trees (Jeffrey, Reithmaier, et al., 2019; Zhang et al., 2022). While emissions are potentially large, global estimates of these pathways remain highly uncertain (Barba et al., 2019; Jeffrey et al., 2023). Oceanic sources comprise coastal and open ocean methane fluxes from brackish and marine sediments. Existing global and regional estimates are highly variable because of the high spatiotemporal variability within and between systems and because of the overall global paucity of data, making global estimates sensitive to statistical assumptions (Rosentreter et al., 2021; Weber et al., 2019). In contrast, anthropogenic defined sectors such as biomass burning (12%), oil and gas industry (7%), and enteric fermentation and manure (7%) are identified as sources of lower uncertainty that are relatively well-known and associated with high agreement of studies and robust evidence (Figure 1a). The relatively lower uncertainty of these sectors may be attributed to a better understanding of processes that drive anthropogenic methane emissions. For example, methane emissions from biomass burning can be derived from a variety of satellite data (e.g., the Global Fire Emissions Database, 2024, the Quick Fire Emissions Dataset, 2024, or the Global Fire Assimilation System, 2024).

Although uncertainties have been reduced since the GMB 2016 (Saunois et al., 2016), in the GMB 2020 (Saunois et al., 2020) global means and ranges from BU approaches differ quite significantly from TD approaches. Total mean BU methane sources (737 Tg CH_4 yr^{-1}) are 28% larger than TD sources (576 Tg CH_4 yr^{-1}) (Saunois et al., 2020). Total mean BU sinks (625 Tg CH_4 yr^{-1}) are 12% larger than TD sinks (556 Tg CH_4 yr^{-1}) for the time period 2008–2017 (Saunois et al., 2020). The discrepancy of the two approaches continues to stimulate debate in the scientific community (Kirschke et al., 2013; Saunois et al., 2016, 2020).

We asked a variety of experts that identified as modelers (47%), empiricists (30%), or both (23%), using BU (62%), TD (17%), or both (21%) approaches in their work, to rate their level of confidence in BU and TD range for global methane sources and sinks. Surprisingly, their confidence rankings were similar for the two approaches across different sectors (Figures 1b and 1c). Experts have very low confidence that the range in other natural sources and soil uptake represents the true range in BU and TD assessments but have less confidence in BU estimates (39% of experts ranked sector as very low confidence) compared to TD estimates (21%) of other natural sources. In fact, this sector shows the largest discrepancy of the two approaches, with an exceptional 185 Tg CH_4 yr^{-1} difference between BU and TD means (Saunois et al., 2020). We conclude that the scientific community has low confidence that either BU or TD approaches are currently able to capture the true range of other natural methane fluxes. Therefore, we propose a plan of action that may help reduce uncertainties and build confidence in the other natural sources sector (Table 1). In contrast, high to very high confidence in BU and TD ranges is associated with fossil fuel (BU, TD) (4.17, 4.34) (scoring system from 0 to 4.8, see Supporting Information S1

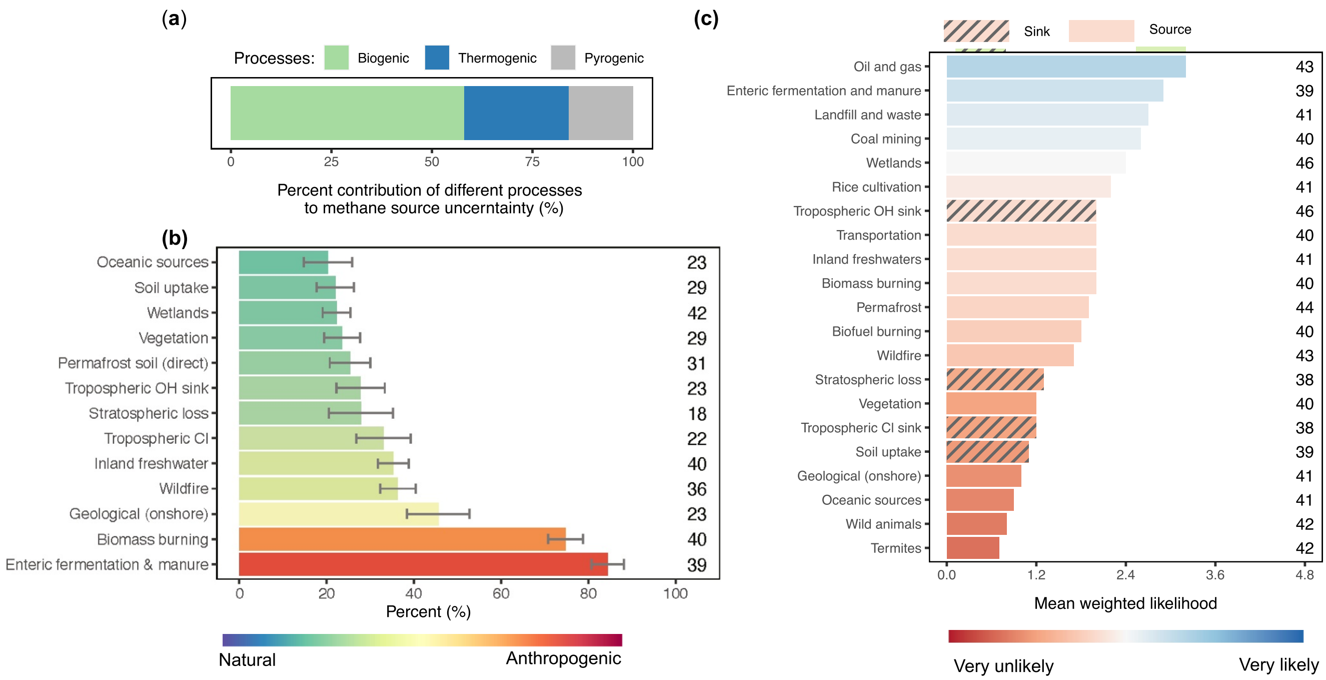

Figure 2. Uncertainties in natural and anthropogenic methane processes based on expert opinion analysis. (a) Relative contribution (percentage) of biogenic, thermogenic, and pyrogenic processes contributing to methane source uncertainty ranked by experts. (b) Experts' rating of selected methane source and sink sectors according to how much they are best described as "natural" or "anthropogenic" categories with 0% meaning sectors are solely natural and 100% meaning they are solely anthropogenic. Excluded from this assessment are obvious anthropogenic (fossil fuels, transportation, industry) and natural (termites, wild animals) sources. Error bars are the standard error. (c) Experts' rating of the likelihood of sectors being responsible for the renewed increase of atmospheric methane since 2007. For sources this refers to the likelihood of increased emissions since 2007. For methane sinks this refers to the likelihood of decrease of the sink capacity since 2007. For (b) and (c) the number (n) of expert responses is shown to the right of each sector.

Question 8), biomass and biofuel burning sources (4.15, 4.00) and total chemical loss in the atmosphere (3.89, 4.26) (Figures 1b and 1c). This is likely because inventory models commonly follow the IPCC guidelines which suggests a uniform methodological approach to their quantification. Nevertheless, we show in the following that there are open questions also related to these sectors.

In the GMB 2020 (Saunois et al., 2020), uncertainties in global estimates result in a budgeted imbalance of methane sources and sinks in both BU (112 Tg CH_4 yr^{-1}) and TD (13 Tg CH_4 yr^{-1}) approaches. Based on our survey, we find that the imbalance is generally believed to be more related to uncertainties in methane sources than in methane sinks, especially in the BU budget (Figure 1d). This suggests that uncertainties in methane emissions, especially in natural sources, need to be significantly reduced to accurately balance methane sinks in BU approaches.

Relative contributors to methane sources can be further differentiated into three classes, that is, biogenic, thermogenic, and pyrogenic (see Glossary). Experts rank biogenic methane as the largest source of uncertainty (58%) toward overall methane source uncertainty, followed by thermogenic (26%) and pyrogenic (16%) methane release (Figure 2a). This compares well with previous experts' rankings that other natural sources currently have the highest uncertainties in the GMB 2020 (Saunois et al., 2020), because most of the methane produced in natural environments is of biogenic origin. This also suggests that a better understanding of biogenic methane sources and pathways will greatly help reduce uncertainties in the other natural sources sector (Table 1). Biogenic methane is one final product of the decomposition of organic matter by methanogens in anaerobic environments such as water-saturated soils in wetlands and inland waters. At present, little is known about other biogenic methane pathways such as aerobic methane production, methane from non-archaeal sources involving cyanobacteria, phytoplankton, fungi, or methane formation as a by-product of bacterial degradation (Bižić et al., 2020; Ernst et al., 2022; Whiticar, 2020). In addition, natural sources can release thermogenic methane through onshore or offshore geological gas seeps, formed on geological timescales. Large quantities of methane are stored in marine hydrates at the continental shelf and deep ocean, and there is an ongoing debate whether seafloor and gas hydrate

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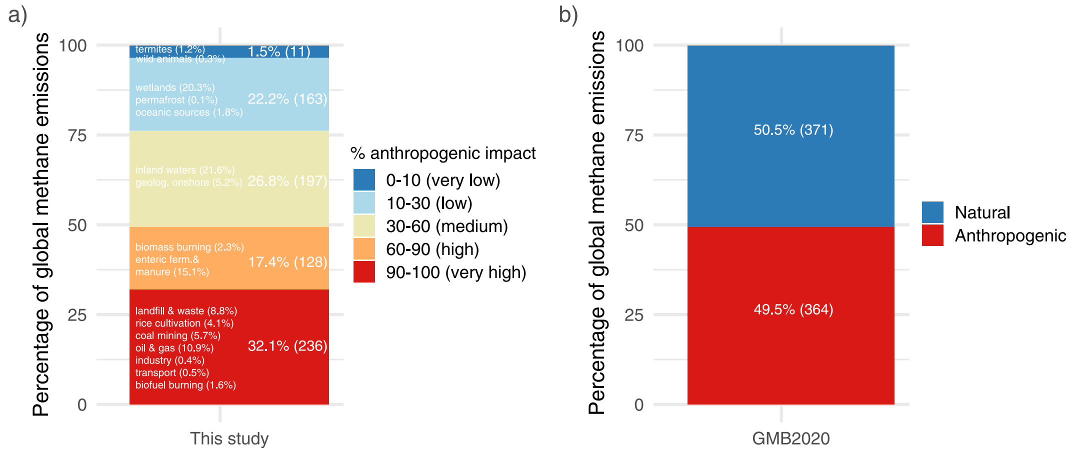

Figure 3. Natural versus anthropogenic methane sources. (a) New partitioning of methane source sectors into five anthropogenic perturbation categories based on expert opinion analysis: very low (0%–10%), low (10%–30%), medium (30%–60%), high (60%–90%), and very high (90%–100%) anthropogenic impacts. The bar plot shows the percentage contribution (in brackets: Tg CH_4 yr^{-1}) of each sector in the five categories to global methane emissions (BU, 2008–2017) (Saunois et al., 2020). (b) The bar plot shows the partitioning of global methane sources (BU, 2008–2017) into natural and anthropogenic categories in the GMB 2020 (Saunois et al., 2020). While the GMB 2020 assigned ~50% to anthropogenic and ~50% to natural emissions (Saunois et al., 2020), this study suggests that >75% of global methane emissions come from sectors with moderate to high levels (30%–100%) of anthropogenic disturbance.

methane is a major contribution to global warming (James et al., 2016; Joung et al., 2022; Wallmann et al., 2018). The partitioning of total fossil emissions between natural geological and anthropogenic sources is also subject of an ongoing debate. In recent work, Hmiel et al. (2020) suggested that geological sources may be an order of magnitude lower than current BU and TD estimates (Etiope et al., 2019; Etiope & Schwietzke, 2019; Saunois et al., 2020). Thornton et al. (2021) address the discrepancy between Hmiel et al.'s (2020) lower estimate of global near-zero geological methane emissions and other estimates. They argue that this low estimate cannot be reconciled with the existence of multiple independent measurements of BU emissions from individual natural geologic seepage areas.

While the categorization of methane sources into biogenic, thermogenic, and pyrogenic is relatively straightforward, the categorization of methane sources to "anthropogenic" or "natural" classes is more complicated. For example, biogenic methane can be of natural origin when methanogenesis occurs in pristine wetland soils but must be assigned to anthropogenic origin when microbial decomposition occurs in man-made/artificial rice paddies, landfills, sewage, or wastewater facilities. Clearly, partitioning methane emissions to anthropogenic or natural sources is increasingly challenging due to the impact of human activities on "natural habitats" but of great importance given that current observational networks cannot link recent methane variations to specific sources (Turner et al., 2019). Figure 2b shows how experts define each sector in the GMB 2020 (Saunois et al., 2020) according to how much they think this sector is best described as "natural" or "anthropogenic," excluding sectors that can be clearly assigned to anthropogenic or natural sources (i.e., fossil fuel combustion). Many sectors such as geological onshore seeps, wildfires, wild animals, impacted wetlands, and impacted inland/coastal/ocean waters, as well as tropospheric and stratospheric sinks, are classified as some combination of natural and anthropogenic sources. All methane sinks were considered primarily, but not wholly, natural by experts (Figure 2b). This demonstrates an acknowledged role of human-influences on the sizes of these fluxes such as global mean OH changes (Naik et al., 2013). A quantification of pre-anthropogenic (i.e., natural) methane emissions would clearly help alleviate some of the current debates around anthropogenic versus natural methane since the industrial era. Here, we suggest that instead of partitioning sources into one or the other category, it may be more applicable to consider gradients of human disturbance, for instance, from sectors with no or very low human disturbance (0%–10%), to near-pristine, low impacted (10%–30%), moderately impacted (30%–60%), man-made and artificial environments (60%–90%), to fully anthropogenic sectors such as fossil fuel combustion and transportation (90%–100%) (Figure 3a). When applying our new partitioning (five categories) to experts' assessment of each BU methane source sector (Figure 2b), we find that 76.3% (range 75.8%–79.4%) or 561 (range 443–700) Tg CH_4 yr^{-1} of methane emissions are associated with 30%–60% moderate human disturbance activities or direct

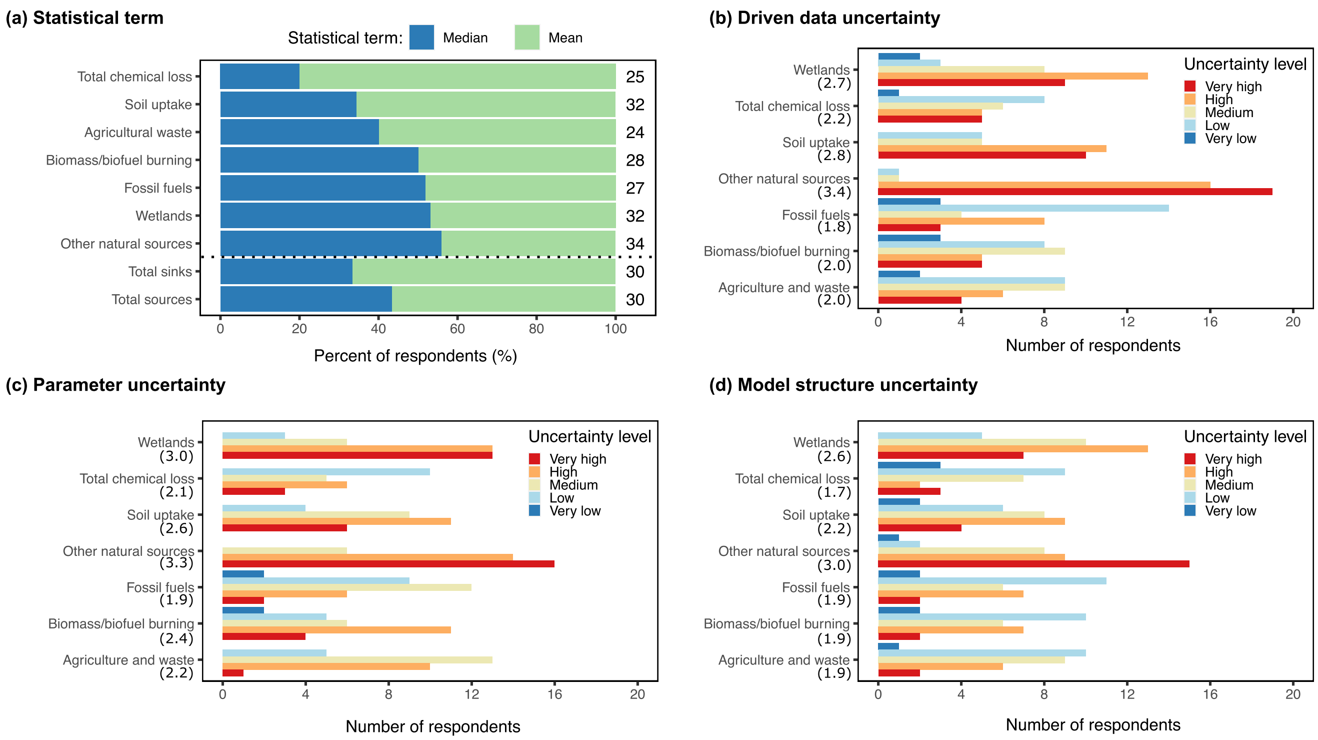

Figure 4. Experts' evaluation on statistical terms and uncertainty types. (a) Experts' opinion on the appropriate statistical measure (mean or median) of the central tendency of methane sources and sinks that they are familiar with. The number (n) of expert responses is shown to the right of each sector. (b–d) Plots showing the three types of uncertainties considered in this study. Histograms show experts' ranking of uncertainty level related to (b) driver data uncertainty, (c) parameter uncertainty, and (d) model structure uncertainty in selected methane sectors in the GMB 2020 (Saunois et al., 2020). The quoted numbers in (b–d) are weighted scores of the respective sector. See Glossary for detailed description of uncertainty types.

anthropogenic (60%–100%). In comparison, the GMB 2020 (Saunois et al., 2020) assigned ∼50% of global emissions to anthropogenic sources, which is likely an underestimate of the anthropogenic impact on methane emissions.

4. Statistical Treatment and Types of Uncertainties

Uncertainties presented in the GMB 2020 (Saunois et al., 2020) do not reflect uncertainties of individual estimates but are expressed as the range of available average estimates across different methodologies and data sets. This is because of the inconsistent and sometimes incompatible statistical information emerging from diverse methods from across multiple scientific communities. The appropriate statistical measure of average methane fluxes may differ for specific sectors. When asked, experts propose that the median is a more appropriate statistical measure of central tendency for methane source sectors such as wetlands and other natural sources, whereas the mean may be the preferred measure for methane sinks (Figure 4a). Regarding fossil fuel and biomass/biofuel burning, there was no strong preference for one or the other statistic. This partitioned view of mean versus median is expected due to the method of data collection for the predominantly variable point-based sampling efforts. Empirical studies of methane fluxes often report anomalous high or low values (highly skewed data sets), which the median is not as heavily influenced by. TD efforts rely on modeling-based results meaning that mean values better represent regional and/or global central tendencies. Whilst we asked for suggestions from experts on additional methods to standardize and average data, the dominant response was to avoid a singular average value (mean or median), with trend-based and full statistical suites being proposed. We suggest that the choice of appropriate statistical measure depends on the methods used and data distribution in both TD and BU approaches for methane sources and sinks.

We further identify the specific types of uncertainties associated with each sector, but mostly discuss those in relation to wetlands and other natural source sectors as they have been unambiguously revealed as the greatest contributor to BU and TD uncertainty in the GMB 2020. We categorized three types of uncertainties for this study: (a) driver data uncertainty, (b) parameter uncertainty, (c) model structure uncertainty (see Glossary). As expected, wetlands and other natural sources are consistently ranked (on a scale from 0 to 4) highest in all three categories (Figures 4b–4d). Notably, of the experts who identified inland waters as an area within their expertise, 61% considered driver data the most uncertain, 19% parameter uncertainty, and 14% identified model structure as the most uncertain in the other natural sources sector. Wetlands ranked second highest in terms of parameter uncertainty and model structure associated uncertainty, with scores of 3.0 and 2.6, respectively. Experts also ranked driver data as a high source of uncertainty for wetland emissions (2.7), but interestingly ranked driver data uncertainty slightly higher for soil uptake (2.8). Of the experts who identified wetlands as an area within their expertise, 58% chose driver data as the greatest source of uncertainty in wetland emissions, followed by 21% for both parameter and model structure uncertainty. This suggests a discrepancy between experts in all fields of the methane cycle, who may perceive wetland driver data to be of lower uncertainty than those who specialize in wetland methane. More specifically, we asked about the presumable source of each uncertainty type. Experts noted that poor spatiotemporal data coverage is responsible for some of the current issues with driver data in wetlands and inland water sectors. Experts who selected parameter uncertainty as the largest source of uncertainty associated with wetlands and/or inland waters raised issues related to the absence of an appropriate, consistent, and complete database of inland water bodies as well as the absence of associated physical and hydrological parameter data (e.g., surface area, flow volume, residence times) for each water body type that are needed to constrain models and scaling efforts. These databases need to be developed alongside wetland, floodplain, and estuary databases to classify inland open water bodies without overlapping with other water body areas, including those that may be intermittent or ephemeral, which currently can lead to double-counting of methane emissions. Other experts raised issues regarding the parameterization of organic matter degradation and production rates in inland waters, and uncertainty related to methane production with temperature changes. Experts who found model structure as the largest source of uncertainty, suggested that representing wetland redox conditions in models is one of the top issues that need to be addressed. For inland waters, differentiating between ebullition and diffusion, as well as accounting for periodic or “hot spot-hot moment” emission pulses, were major issues raised.

On the other end of the spectrum, experts ranked fossil fuels as having the lowest uncertainty associated with driver data and parameter uncertainty, with scores of 1.8 and 1.9, respectively, as well as low model structure uncertainty (1.9) (Figures 4b–4d). Despite the comparatively low uncertainty, experts highlighted the need to better account for suspected underreporting of fossil methane emissions in many national inventories around the world.

5. Prediction of Future Methane Trends

Methane accounted for substantial (35%; 0.5°C) greenhouse gas-driven global warming in 2010–2019 (IPCC, 2021). Overall, experts' opinion on future atmospheric methane trends is relatively widespread (Figure 5). For example, experts are 67% certain that the contribution of atmospheric methane to global warming will increase by 2050 but their responses ranged from 25% to 100% certainty, highlighting the different views on methane trends within the community (Figure 5a). Similarly widespread was also the response of experts when asked about their concern about potential runaway feedbacks associated with the methane cycle such as the thawing of permafrost or the destabilization of methane clathrates on the ocean floor. Experts' concern ranged from 5% (almost impossible) to 100% (certain) with an average of 58% indicating divergent opinions on runaway feedbacks but overall, there is concern about potential runaway feedbacks (the probability density of their responses peaked around 75%) (Figure 5b).

Understanding the shifts underlying atmospheric methane trends and how sources and sinks respond to environmental change is necessary to mitigate anthropogenic climate change (Nisbet et al., 2019, 2020; Schaefer, 2019). Experts believe that anthropogenic sources are the most likely cause for the strong renewed increase of atmospheric methane since 2007, specifically, the oil and gas industry (3.2, on a scale of 0–4.8), enteric fermentation and manure (2.9), landfill and waste (2.7), and coal mining (2.6). Wetlands (2.4) are believed to be the most likely natural source contributing to the recent rise of methane (Figure 2c). 30% of the experts suggest that changes in the tropospheric OH sink capacity are responsible for reduced removal of methane in the troposphere. This inconclusive result highlights the uncertainty within the community associated with this renewed growth. Based on experts' feedback in this study and previous discussions (Nisbet et al., 2019, 2020; Schaefer, 2019), no single process can explain the methane rise since 2007. According to our present-day

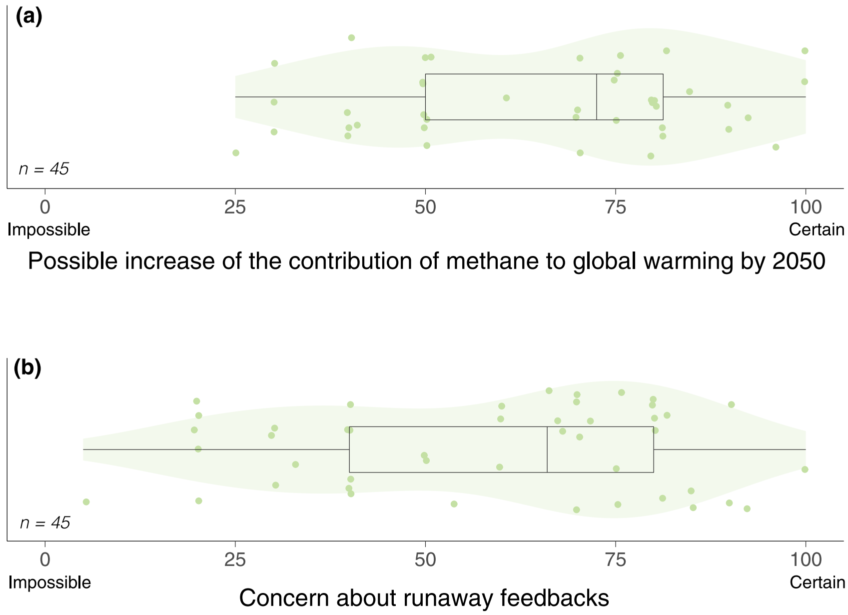

Figure 5. Experts' concern about future trends in methane. Box and violin plots show median, interquartile range, and the distribution of numerical data in a kernel density plot of (a) experts' opinion on the potential increase of the contribution of methane to global warming by 2050; (b) experts' concern about potential runaway feedbacks associated with the methane cycle, on a score from 0 to 100, 0 being impossible and 100 being certain. n refers to the number of responses.

knowledge, the dominant causes of recent trends in atmospheric methane are related to a combination of processes, most likely fossil fuel production, emissions from agriculture and waste sectors (ruminant livestock, waste management, rice farming), potential climate-methane feedbacks from wetlands, and changes of the methane sink (mainly the destruction through hydroxyl radicals). By applying our low to high anthropogenic impact categories (Figure 3) to these proposed sources, we show that processes likely responsible for the renewed increase are from across a broad range of low (i.e., wetlands) to very high (i.e., fossil fuel) anthropogenic impacted sources.

6. Reducing Methane Budget Uncertainties

To address the scientific debate on the cause of the renewed and ongoing methane rise and possible consequences from climate feedbacks, we must reduce uncertainties and build confidence in global BU and TD assessments and fill existing knowledge gaps in both empirical and modeling approaches (Table 1). Most knowledge gaps proposed by experts were related to methane emissions from wetland and freshwater ecosystems (34%). More specifically, reducing the risk of double counting of wetlands and inland waters in BU estimates should be a priority and help to greatly reduce uncertainties in the natural emission sector. Improved wetland models should aim to incorporate spatiotemporal and inter-annual variability of methane fluxes, environmental controls, and the extent of inundation. There is also a need to refine our understanding of different transport pathways (i.e., diffusion, ebullition) in freshwater and wetland ecosystems. For inland waters but also coastal waters, generally more empirical data are needed to develop reliable biogeochemical models. Knowledge gaps also exist regarding our understanding of how methane cycles through hydrologically connected wetlands, freshwater and coastal systems (rivers, lakes, ponds, reservoirs, estuaries), forests, and permafrost.

Experts raised concern about the reliability of fugitive emissions from the coal, oil, and gas industries and whether we are yet able to accurately detect methane leaks from fracking and infrastructure. Fugitive emissions may be underreported globally because data can be difficult to obtain when relying on multiple data sources or not being made available from politically “closed” areas. Increased satellite monitoring will help to resolve (inventory-based) anthropogenic emissions more spatially and temporally. Since it was launched in 2009, the Earth-orbiting Japanese Greenhouse gases Observing SATellite (GOSAT) has collected data specifically to measure atmospheric CH_4 (Palmer et al., 2021). MethaneSAT is a new and promising methane-tracking satellite program that aims to provide regular monitoring of regions accounting for more than 80% of the global oil and gas production, but also monitoring of methane from agriculture and other sources ("https://www.methanesat.org/," MethaneSAT, 2024). Another example is NASA's Earth Surface Mineral Dust Source Investigation (EMIT) imaging spectrometer that quantifies and attributes fine-scale methane (and CO_2) sources across the oil, gas, waste, and energy sectors (Thorpe et al., 2023). Such methane-tracking satellites combined with an improved knowledge of $\delta^{13}CH_4$ signatures of different methane sources will further help to fill existing knowledge gaps in methane source partitioning, and, for example, increase the accuracy of global inventories of ruminant emissions, especially in the tropics and sub-tropics. Finally, experts highlighted the need for a more accurate quantification of atmospheric methane sinks such as OH and Cl. While the global mean OH is well known from TD studies, 10% of the experts stress that we need an improved model representation of spatiotemporal and inter-annual OH variability. It remains unresolved what controls global OH variability in the troposphere. Although not explicitly linked to specific methane sources or sinks, constraints and challenges in chemical transport models in global methane inversion also contribute to the range in TD budgets (Locatelli et al., 2015; Saunois et al., 2020).

Our expert opinion analysis underlines the importance of the close and collaborative work needed across disciplines. Together, empiricists and modelers of the scientific community are encouraged to better communicate existing types of uncertainties arising from methodology in BU and TD approaches, to improve monitoring, especially in understudied regions, and to explore new and unknown avenues of methane processes, with the overall goal to better constrain methane sources and sinks in future global budgets.

Glossary

Biogenic Methane is the final product of the decomposition of organic matter by mostly methanogenic archaea in anaerobic environments such as water-saturated soils, wetlands, rice paddies, landfills, sewage, and wastewater treatment facilities, or inside animal digestive systems. Biogenic or microbial methane can also derive from aerobic methane production, photosynthesis associated methane production involving cyanobacteria, and can be formed as a by-product of bacterial degradation (non-archeal sources) depending on substrate availability.

Driver Data Uncertainty empirical uncertainties related to field and/or laboratory data, such as poor temporal and/or spatial data distribution or sparse data sets. This category also includes any lack of transparency or clarity regarding methods used to collect field data or reported data, method or instrument accuracy and/or precision, method or instrument detection limits. These types of uncertainties can impact both calibration and validation data in models as well as bottom-up empirical estimates of CH_4 emissions extrapolated from data.

Ebullition is the episodic release of gas bubbles from water-saturated sediments and sometimes stratified water columns in mostly freshwater systems and wetlands. Ebullition occurs when the dissolved methane concentrations rise above a saturation point, which leads to bubble formation and a subsequently bubble release from sediments due to buoyancy.

Model Structure Uncertainty uncertainties associated with how processes are represented in models. This includes what fundamental processes are considered, how they are represented (e.g., order of reaction kinetics), model assumptions, empirical versus process-based approaches, and the scientific community's overall understanding of how a process takes place or what conditions drive it.

Parameter Uncertainty uncertainties related to how model parameters are constrained. Examples include uncertainties associated with scaling spatially and temporally from local data to larger spatial domains and timeframes, calibration of parameters from unrepresentative or sparse data, integration of model parameters from discrete data, and application of parameters from other systems.

Pyrogenic Methane is the result of incomplete combustion of biomass and other organic matter. Pyrogenic methane sources include wildfires and peat fires, biomass and biofuel burning.

Thermogenic Methane is formed on geological timescales by the breakdown of buried organic matter due to heat and pressure in the Earth's crust and can reach the atmosphere through land (onshore) and marine (offshore) geological gas seeps. Thermogenic methane is enhanced by human activities such as exploitation of fossil fuels.

Data Availability Statement

The survey data used for expert opinion analysis in this study are available in Rosentreter et al. (2024). The questionnaire can be viewed in Supporting Information S1.

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