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Beyond CO_2 equivalence: The impacts of methane on climate, ecosystems, and health

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ABSTRACT

In this article we review the physical and chemical properties of methane (CH_4) relevant to impacts on climate, ecosystems, and air pollution, and examine the extent to which this is reflected in climate and air pollution governance. Although CH_4 is governed under the UNFCCC climate regime, its treatment there is limited to the ways in which it acts as a “CO_2 equivalent” climate forcer on a 100-year time frame. The UNFCCC framework neglects the impacts that CH_4 has on near-term climate, as well its impacts on human health and ecosystems, which are primarily mediated by methane’s role as a precursor to tropospheric ozone. Frameworks for air quality governance generally address tropospheric ozone as a pollutant, but do not regulate CH_4 itself. Methane’s climate and air quality impacts, together with its alarming rise in atmospheric concentrations in recent years, make it clear that mitigation of CH_4 emissions needs to be accelerated globally. We examine challenges and opportunities for further progress on CH_4 mitigation within the international governance landscapes for climate change and air pollution.

1. Introduction

Methane (CH_4) is a potent climate warmer: often referred to as the second most important greenhouse gas (GHG) after carbon dioxide (CO_2), it is responsible for approximately 20% of the direct radiative forcing since 1750 (Forster et al., 2021). In the first two decades after it is emitted, CH_4 is approximately 80 times more powerful than CO_2 as a GHG, but it is removed from the atmosphere much more quickly – after about a decade, whereas CO_2 remains in the atmosphere for centuries. Methane is also a precursor to tropospheric ozone (O_3), and thus contributes to air pollution worldwide. Emissions and atmospheric concentrations of CH_4 are continuing to rise (Jackson et al., 2020; Saunois et al., 2020), making action on CH_4 especially urgent. Indeed, early mitigation of CH_4 would significantly increase the feasibility of limiting global warming to 1.5 °C or 2 °C (Collins et al., 2018; IPCC, 2018).

The 1997 Kyoto Protocol established CH_4 as a GHG within the international climate policy framework of the UNFCCC. For the accounting of emissions and their reductions, standard practice is to express the effect of CH_4 and other non-CO_2 GHGs in terms of “CO_2 equivalence” – where the “equivalence” is based on a comparison of the gas’ climate effects to those of CO_2 on a 100-year timescale via the metric GWP100 (the Global Warming Potential over a 100-year time horizon). While practical in many contexts, this simplification obscures the fact that CH_4 and other non-CO_2 climate forcers are distinct from CO_2 in many ways, including their effects on climate, ecosystems, and human health.

After a brief introduction to recent trends in CH_4 atmospheric concentrations (Section 2), in this paper we examine the physical and chemical ways that CH_4 is distinct from CO_2 in terms of its impacts on climate, ecosystems, and air quality, with a focus on feedbacks and linkages between these issue areas (Section 3). We then provide an overview of the international governance landscape for CH_4 and consider to what extent its impacts are treated by existing frameworks designed to address climate change and air pollution (Section 4). We close by discussing some of the challenges around methane governance as well as opportunities for making progress on this issue (Section 5).

2. The global methane budget and recent atmospheric trends

Methane has both natural and anthropogenic sources, including wetlands (where CH_4 is produced via microbial activity), fossil fuels,

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agriculture (livestock and rice cultivation), waste management (landfills), and fires (Kirschke et al., 2013; Saunois et al., 2020). The dominant loss process (sink) is atmospheric oxidation: 88% of CH_4 is oxidized in the troposphere via the hydroxy radical (OH) and 7% is oxidized in the stratosphere (Boucher et al., 2009). In the atmospheric oxidation process, nearly 100% of the carbon from CH_4 becomes CO_2 (Heald and Kroll, 2020), with a small amount of the intermediate oxidation products (primarily formaldehyde and methyl hydroperoxide) removed by direct deposition (Shindell et al., 2017). Smaller amounts are also removed by soils (5%) (Boucher et al., 2009). Notably, the natural sources of CH_4 emissions can also be influenced by human activities (e.g., land use changes can affect CH_4 from wetlands). The atmospheric concentration of CH_4 and its trend over time depends on the balance between these various sources and sinks.

Alarmingly, CH_4 emissions and concentrations have been increasing rapidly over the past few years (Jackson et al., 2020). The recent growth in atmospheric CH_4 – which began in 2007 and accelerated beginning in 2014 – followed a brief period of stability between 2000 and 2007 (Nisbet et al., 2019). While the precise explanation for the stabilization and subsequent growth of atmospheric CH_4 over the past two decades has been a subject of debate within the scientific community (Nisbet et al., 2019; Kirschke et al., 2013; Rigby et al., 2017; Turner et al., 2019; Schaefer, 2019; Saunois et al., 2016, 2020), a new study concludes that the recent growth is due in roughly equal parts to emissions from fossil fuel sources and the combined emissions from agricultural and waste sources (Jackson et al., 2020).

The increase in atmospheric CH_4 observed over the past decade has been tracking RCP8.5, the warmest scenario assessed by the IPCC, which yields an estimated 4.3 °C of warming globally by 2100 (Jackson et al., 2020; Saunois et al., 2020; Nisbet et al., 2020). Furthermore, there is no reversal of this trend on the horizon: under current policy scenarios, by 2050 CH_4 emissions are expected to increase by 30% compared to 2015 levels (Höglund-Isaksson et al., 2020). Together with recent trends, these prognoses serve to underscore the urgency of mitigating CH_4 emissions.

3. Methane's impacts: beyond CO_2 equivalence

In Section 3, we provide an overview of methane's impacts on climate, ecosystems, and health, as depicted schematically in Fig. 1. We focus on the various ways in which methane's impacts are distinct from CO_2, and thus poorly represented by the concept of "CO_2 equivalence."

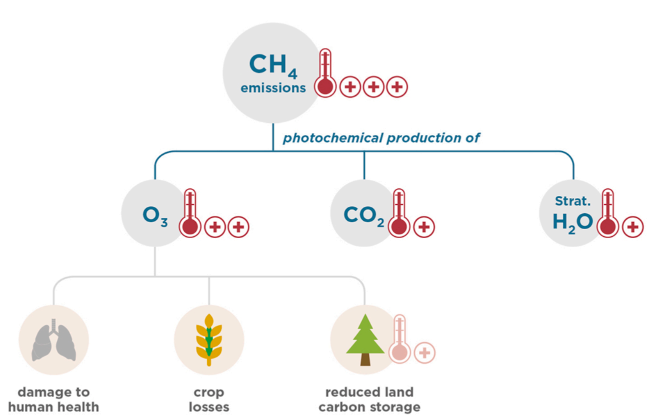

Fig. 1. Schematic overview of methane's primary impacts on climate, ecosystems, and health. Photochemical reactions of CH_4 in the atmosphere lead to the production of tropospheric ozone (O_3), CO_2, and stratospheric water vapor (Strat. H_2O), all of which are also GHGs and contribute directly to global warming (see also Table 1). Tropospheric ozone is harmful to human health and also to ecosystems, where it damages plants, leads to crop losses, and reduces the ability of the biosphere to store carbon.

3.1. *Methane's impacts on global climate*

3.1.1. *Time horizon of methane's climate forcing*

It is well established that CH_4 is a GHG with a warming influence on climate: with a 100-year global warming potential (GWP100) of 27.9 it exerts, on a per-kg basis, a radiative forcing that is 27.9 times greater than CO_2 over a 100-year time horizon (Smith et al., 2021). However, while GWP100 is the common metric used under the UNFCCC, it is not the most appropriate basis for comparison from a climate physics perspective. This is a consequence of the most significant difference between CH_4 and CO_2's climate impacts: the time frame during which they exert a warming effect. Methane has an atmospheric lifetime of ca. 12 years, whereas CO_2 stays in the atmosphere for centuries to millennia (Joos et al., 2013; Forster et al., 2021). For this reason, CH_4 is characterized as a short-lived climate-forcing pollutant (SLCP), in contrast to the long-lived CO_2. If shorter time horizons are considered, methane's potency in comparison to CO_2 is even greater: considering a 20-year timescale, methane's global warming potential (GWP20) is 81.2 times that of CO_2 (Smith et al., 2021). However, since most CH_4 becomes CO_2, CH_4 retains a non-negligible impact on global temperature for more than a century in contrast to nearly all other SLCPs (Fig. 2).

New emission metrics, including GWP* and Combined-Global Temperature Potential (CGTP), use an alternate approach to assigning "equivalence" between SLCPs and CO_2, specifically relating changes in the emission rate of SLCPs to cumulative emissions of CO_2 (Forster et al., 2021; Cain et al., 2019; Allen et al., 2016; Collins et al., 2020). Ultimately, the utility of these and all metrics are strongly dependent on the scientific or policy contexts in which they are applied (Forster et al., 2021).

3.1.2. *Radiative forcing by CH_4 and its oxidation products: tropospheric O_3, stratospheric H_2O, and CO_2*

Methane is a GHG and thereby a direct climate forcer; that is, it absorbs and re-radiates thermal radiation, contributing directly to the greenhouse effect. Unlike CO_2, CH_4 is chemically active, with atmospheric oxidation accounting for approximately 95% of its loss. Among other things, reactions of CH_4 lead to the production of tropospheric O_3 and stratospheric water vapor, and the end product of CH_4 oxidation is

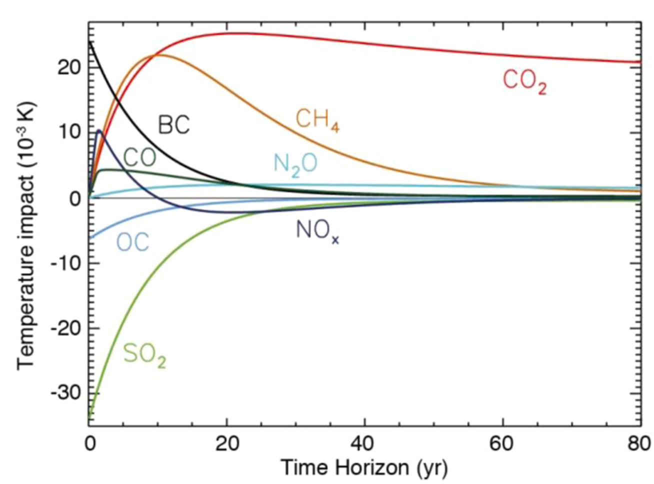

Fig. 2. Global temperature impact as a function of time for emissions of different anthropogenic climate forcers. The temperature impact is calculated based on the metric AGTP (Absolute Global Temperature change Potential) (Shine et al. 2005), defined as the change in global mean surface temperature at a chosen point in time in response to an emission pulse. Here, a one-year pulse of emissions representing the year 2008 was used for the calculation. In addition to CH4 and CO2, the evolution of AGTP with time is shown for anthropogenic emissions of black carbon (BC), organic carbon (OC), carbon monoxide (CO), nitrogen oxides (NOx), sulfur dioxide (SO2), and nitrous oxide (N2O). Reproduced from Myhre et al. (2013) (Figure 8.33).

CO_2 itself (Forster et al., 2021). In this way, CH_4 also acts as an indirect climate forcer because it leads to the production of other GHGs (Fig. 1). A quantitative overview of radiative forcing due to CH_4 and its associated photochemical products is provided in Table 1.

The chemical reactions of CH_4 also alter the atmospheric concentration of oxidants, especially the OH radical. This in turn has an indirect effect on the abundance of other trace gases and aerosols in the troposphere. In particular, increased atmospheric CH_4 provides an increased sink for OH, reducing the formation of sulfate aerosol (via SO_2 +OH). Since sulfate aerosol has a cooling effect on the climate (see also Fig. 2) its reduction can be seen as an additional, indirect positive radiative forcing attributable to CH_4 (Shindell et al., 2009). Shindell et al. (2009) calculate that this effect is equivalent to a radiative forcing of approximately + 0.1 W m^{-2} (Table 1), comparable to the CH_4-induced radiative forcing due to stratospheric water vapor.

3.1.3. *Impacts of tropospheric O_3 on ecosystems and reduced land carbon storage*

Methane is an important contributor to the formation of tropospheric O_3. In addition to acting as a greenhouse gas and being directly harmful to human health (see Section 3.3), it also harms plants by causing cellular damage within the leaves, adversely affecting plant production, reducing the rate of photosynthesis, and requiring increased resource allocation to detoxify and repair leaves (Ashmore, 2005; Sitch et al., 2007). This results in an estimated $11-$18 billion worth of global crop losses annually (Avnery et al., 2011). Beyond this, however, O_3 damage to plants may significantly reduce the ability of terrestrial ecosystems to absorb carbon, negating some of the enhanced carbon uptake due to CO_2 fertilization that is expected to partially offset rising atmospheric CO_2 concentrations (Sitch et al., 2007; Ciais et al., 2013; Arneth et al., 2010; Ainsworth et al., 2012). However, the magnitude of this effect remains the subject of scientific debate, largely due to the complexity of interactions between plant response to O_3 and other environmental variables, including other air pollutants, CO_2 concentrations, temperature, precipitation, and nitrogen availability (Ainsworth et al., 2012; Kvalevåg and Myhre, 2013; Sitch et al., 2007; Simpson et al., 2014). For instance, Sitch et al. (2007) estimated that the present-day indirect radiative forcing due to O_3-induced plant damage could be as high as 0.21–0.38 W m^{-2}, comparable to the direct radiative forcing of tropospheric O_3. However, Kvalevåg and Myhre (2013) argue that this estimate is far too high and that accounting for nitrogen limitation on plant growth reduces the expected impact; they estimate an indirect radiative forcing due to O_3-induced plant damage of 0.03–0.11 W m^{-2} (Table 1).

Table 1
Present-day anthropogenic radiative forcing directly and indirectly attributable to CH_4 and its chemistry.

Mechanism for radiative forcing	Radiative forcing, pre-industrial to present (W m^{-2})
CO_2: total direct forcing	2.16 [1.90–2.41] (Forster et al., 2021, Table 7.8)
CH_4: total direct forcing[a]	0.54 [0.43–0.65] (Forster et al., 2021, Table 7.8)
Tropospheric O_3: total direct forcing	0.40 [0.20–0.60] (Myhre et al., 2013, Table 8.3)
Component of tropospheric O_3 forcing attributable to CH_4 emissions	0.241 (Myhre et al., 2013, Table 8. SM.6)
Component of CO_2 forcing attributed to CH_4 oxidation	0.018 (Myhre et al., 2013, Table 8. SM.6)
Stratospheric water vapour: total direct forcing(100% attributed to CH_4 oxidation)	0.05 [0.00–0.10] (Forster et al., 2021, Table 7.8)
Reduction in sulfate aerosol formation due to increased sink for OH, caused by increased CH_4 emissions	0.1 (Shindell et al., 2009)
O_3-induced[b] plant damage resulting in a reduced land carbon sink	0.03–0.11 (Kvalevåg and Myhre, 2013; includes effects of C-N coupling) 0.21–0.38 (Sitch et al., 2007; excludes effects of C-N coupling)

[a] Based on the total atmospheric concentration of CH_4. This is largely determined by CH_4 emissions, but emissions of other trace gases (CO, NMVOCs, and NO_x) also affect the atmospheric concentration of CH_4; see, e.g., Myhre et al. (2013), Table 8.SM.6.

[b] Estimates are for total tropospheric O_3, not just O_3 attributable to CH_4 oxidation.

3.2. *Climate change-driven feedbacks on atmospheric methane*

3.2.1. *Feedbacks on natural emissions of methane*

Changes in GHG concentrations, global temperature, and other environmental conditions that are affected by climate change all influence the natural emissions of CH_4 (Dean et al., 2018). This leads to a complex web of interdependencies and feedbacks, many of which are characterized by large uncertainties. Consequently, the changes in natural CH_4 emissions under climate change scenarios are generally poorly constrained; the largest climate change-induced feedback on CH_4 emissions is expected to come from wetlands (Ciais et al., 2013; Comyn-Platt et al., 2018; Dean et al., 2018; Gedney et al., 2004; O'Connor et al., 2010; Zhang et al., 2017). Wetlands are currently the largest natural source of atmospheric CH_4 (Saunois et al., 2020), with emissions controlled by environmental factors including the soil temperature, water table depth, and vegetation cover and composition (Dean et al., 2018; Gedney et al., 2004); all of these variables are affected by climate change. Zhang et al. (2017) calculate that increased CH_4 emissions from wetlands under climate change scenarios could result in an increased radiative forcing ranging from 0.08 W m^{-2} for RCP2.6 (strong climate mitigation with the possibility of reaching the 2° target) to 0.19 W m^{-2} for RCP8.5 (business-as-usual). Beyond 2100, climate change-induced CH_4 emissions from marine and freshwater systems and permafrost could also become important (Arneth et al., 2010; Dean et al., 2018; O'Connor et al., 2010).

3.2.2. *Climate change impacts on methane loss processes*

Most atmospheric CH_4 is lost in the troposphere via oxidation by the OH radical. Even without considering the effects of climate change, CH_4 has a feedback on its own lifetime via atmospheric chemical cycles: increased CH_4 concentrations lead to less OH (as it is consumed in reaction with CH_4), resulting in less CH_4 destruction (O'Connor et al., 2010; Voulgarakis et al., 2013). Climate change adds another layer of complexity when considering the effects on the relevant chemical cycles: climate change is expected to increase the concentration of atmospheric water vapor, the emissions of biogenic volatile organic compounds (VOCs), and the rate of the CH_4 +OH reaction. All of these effects have competing influences on the CH_4 atmospheric lifetime and it is uncertain what the net effect will be (O'Connor et al., 2010). The oxidation of CH_4 by soils only represents about 5% of its loss, but it is also sensitive to environmental conditions. Soil oxidation is projected to increase under climate change due to rising CH_4 concentrations, higher soil temperatures, and lower soil moisture (Ciais et al., 2013; Curry, 2009). Taking this into consideration, O'Connor et al., 2010 conclude that the potential for increased emissions under climate change is larger than the potential for increased sinks. That is, considering changes in both emissions and loss processes, climate change is expected to amplify atmospheric concentrations of CH_4.

3.3. *Methane's impacts on air pollution and human health*

Methane is not typically counted as an air pollutant, since this term is usually reserved for substances that are directly harmful to human health (i.e., via inhalation). However, as a precursor to tropospheric O_3, CH_4 contributes to air pollution worldwide.

A recent model study estimated that CH_4 contributes to approximately 35% of the present-day tropospheric O_3 burden (Butler et al., 2020). Tropospheric O_3 is a purely secondary air pollutant that is associated with adverse effects on human health, including asthma, reduced lung function, and chronic obstructive pulmonary disease (COPD). Both short-term and long-term exposures are associated with negative health impacts and premature mortality (Turner et al., 2016; Jerrett et al., 2009; COMEAP, 2015; REVIHAAP, 2013; Zhang et al., 2019). A recent study estimated that in 2010, 1.0–1.2 million respiratory deaths in adults worldwide were attributable to O_3 exposure (Malley et al., 2017), based on an updated risk relationship calculated by Turner et al. (2016). Notably, this represents a significant upwards revision of the earlier risk estimate by Jerrett et al. (2009), which had been used by the Global Burden of Disease (Forouzanfar et al., 2016) and others to calculate significantly lower estimates of O_3-attributable mortality.

Further attribution of O_3 mortality to CH_4 specifically is a somewhat more complex task and has been addressed less often. Fang et al. (2013) examined the mortalities associated with changes in surface O_3 from pre-industrial times to the present and found that 15% of these premature deaths (ca. 56,000) can be attributed to historical changes in CH_4 since industrialization. Van Dingenen et al. (2018) estimate that, compared to 2010, high CH_4 emission scenarios could cause up to 91,000 additional global mortalities due to O_3 exposure in 2050, whereas high CH_4 mitigation scenarios could reduce O_3 mortality by 40,000. Notably, these mortality estimates do not reflect the updated increased O_3 mortality risk factor of Turner et al. (2016), which would revise these mortality estimates upwards by about a factor of two.

Importantly, the role of methane's contribution to O_3 production is expected to increase in the future, as emissions of other anthropogenic precursors (primarily NOx and VOCs) are anticipated to decrease as a result of current and planned air quality regulations across much of the globe. For instance, Young et al. (2013) showed that rising CH_4 concentrations could be a major driver of increased surface O_3 by 2100 under the high-emission scenario developed for the IPCC 5th Assessment report. Turnock et al. (2018) showed that increased O_3 production from rising CH_4 concentrations could offset the reduction in surface O_3 due to reductions in emissions of shorter-lived O_3 precursors.

4. Methane in international governance frameworks

In the above sections, we have provided an overview of the physical and chemical impacts that CH_4 has on climate, ecosystems, and human health, with a focus on the ways in which these impacts go beyond simple CO_2-equivalence. Given the current rapid rise in atmospheric CH_4 concentrations, it is clear: action to reduce CH_4 emissions is urgently necessary, not just to address long-term climate change, but also for near-term climate and human and ecosystem health.

In Section 4, we turn from examining methane's effects on the physical earth system to examining how CH_4 is treated within legal frameworks for international climate and air quality governance. We consider the question: how are the complexity and extent of methane's climate, ecosystem, and health impacts treated by existing frameworks designed to address climate change and air pollution? We present an overview of how CH_4 is treated in international governance, followed by a discussion of the observed gaps between methane's impacts on climate, ecosystems, and health, as summarized in Section 3, and the regulatory frameworks currently in place to mitigate these impacts. In Section 5, we discuss challenges as well as opportunities for improving methane governance.

4.1. Methane in international climate policy: the UNFCCC

The United Nations Framework Convention on Climate Change (UNFCCC) is the central institution to govern climate change internationally. Its goal of preventing dangerous anthropogenic climate change is implemented via its two main treaties, the Kyoto Protocol and the Paris Agreement.

The 1997 Kyoto Protocol established CH_4 as a GHG within the purview of the UNFCCC, as part of a "basket" of GHGs that also included CO_2, N_2O sulphur hexafluoride (SF_6), and a number of halocarbons (Kyoto Protocol, Annex A). Under Kyoto, developed country parties committed to GHG reduction targets, which could be reached by combining emission reductions of any of these so-called Kyoto gases, weighted by their "CO_2 equivalence." This "comprehensive approach" was introduced into the negotiations as a way to increase flexibility, by allowing states to choose which gases to focus on and enabling prioritization of the most cost-effective measures. Environmentally, this was seen as a way to minimize the incentive to switch from one type of polluting activity to another, but with the potentially negative effect of reducing the pressure to reduce emissions of CO_2, the primary pollutant. Earlier phases of the negotiations had focused primarily on reducing CO_2 emissions and had alternately considered a gas-by-gas approach (Bodansky, 1993; Gillespie, 2003).

The Paris Agreement is structured even more broadly, applying to "greenhouse gas emissions" (Article 4(1)) without referring to a specific list. Thus, the Paris Agreement covers CH_4 as well as the other Kyoto gases, but with additional flexibility for countries to include gases beyond these (Pekkarinen, 2020).

In this section we focus on methane's treatment within the Kyoto Protocol and the Paris Agreement, as they are the most prominent of the international climate policy frameworks. Within the broader landscape of the UNFCCC, action on CH_4 can be found – and could be further advanced – within many workstreams and programs, including the Bali Action Plan, Copenhagen Accords, Cancun Agreement or under the Nationally Appropriate Mitigation Actions (NAMAs). The Agenda 2030 and the Sustainable Development Goals (SDGs) present further opportunities to foster action on CH_4, particularly via the goals on climate action, health, clean energy, and sustainable cities.

4.1.1. Equivalency, metrics and reporting

In both the Kyoto Protocol and the Paris Agreement, common practice is for parties to express GHG emissions in CO_2 equivalents (CO_2e) for the purpose of aggregating and comparing the climate impact of measures that address different pollutants. A quantity of GHG can be expressed in CO_2e by multiplying the amount of the GHG by its GWP100. For instance, if 1 tonne of CH_4 is emitted, this can be expressed as 27.9 tonnes of CO_2e (1 tonne CH_4 * 27.9 = 27.9 tonne CO_2e, using the GWP100 for CH_4 of 27.9 from Smith et al., 2021). Under the Kyoto Protocol it was specified that GWP100 values from the IPCC Second Assessment Report (IPCC, 1995) were to be used for calculation of CO_2 equivalents (Kyoto Protocol, Article 5); these GWP values have been updated in subsequent IPCC reports.

Since introduction of the GWP100 as the standard metric within the UNFCCC (first agreed upon at COP2 in 1996), there have been numerous critiques from the academic community about the insufficiency of GWP100 as the single, stand-alone metric for climate forcing, accompanied by competing suggestions for how it could be improved (Cain et al., 2019; Allen et al., 2018, 2016; Balcombe et al., 2018; Forster et al., 2021; Shine et al., 2005). Under the UNFCCC, however, GWP100 remains the standard: according to the Paris "rulebook," GWP100 is the metric that should be used in national reporting to report aggregate emissions and removals of GHGs, expressed in CO_2e (UNFCCC, 2018). However, countries "may," in addition, use other metrics to provide supplementary information; this comes with the requirement to provide supporting documentation (UNFCCC, 2018). This provision leaves the door open for countries to additionally report aggregate emissions reductions in metrics that they find useful or favorable. Importantly, and as emphasized in the IPCC 6th Assessment report, the choice of emission metric (e.g., GWP100 or an alternative) has a significant impact on the "real world" meaning of net zero GHG emissions and the resulting temperature outcome (Forster et al., 2021); given the increasing number of net-zero pledges, this could become a topic of active political debate.

While UNFCCC reporting requirements specify that aggregate emissions and removals of GHGs are to be expressed in CO_2e (and CO_2e is also the dominant metric for expressing commitments and targets, see Section 4.1.2), GHG emission inventory reporting required under the

UNFCCC additionally requires provision of gas-by-gas information, with CO_2, CH_4, and other gases reported separately; specific requirements differ for developed and developing countries (Ellis and Moarif, 2015). Under the Paris Agreement, countries are expected to individually report on at least three gases: CO_2, CH_4 and N_2O, using common reporting tables (UNFCCC, 2018).

4.1.2. Commitments and targets

Under the Kyoto Protocol, Annex I parties committed to reduce "anthropogenic carbon dioxide equivalent emissions" by a specified percentage compared to a base year (typically 1990) (Kyoto Protocol Article 3 and Annex B; Doha Amendment to the Kyoto Protocol). That is, Kyoto commitments include an overall emissions reduction target expressed in CO_2e (encompassing the "basket" of gases listed in Annex A), but no CH_4-specific emission reduction commitments. Notably, however, the Kyoto Protocol does explicitly cover CH_4-emitting sectors, including oil and gas, agriculture, and solid waste (Kyoto Protocol, Annex A).

Under the Paris Agreement, each country determines its own mitigation pledges and submits them in the form of Nationally Determined Contributions (NDCs). The content of these NDCs is largely left up to the countries themselves, including whether they express GHG reduction targets in CO_2e, or on a pollutant-by-pollutant basis. Developed country parties are asked to specify "economy-wide absolute emission reduction targets" in their NDCs. In submitted NDCs, these economy-wide targets typically cover CH_4 and are expressed in aggregate CO_2e, without specifying which CO_2e reductions will come from which pollutant. This is the case for roughly 80% of submitted NDCs (Ross et al., 2018).

A closer look into the NDCs shows that some go beyond simply listing CH_4 under the scope of covered gases and provide more detailed information on CH_4 mitigation. For instance, a number of NDCs include sector-specific policies in the areas of agriculture, waste, oil and gas, and coal that will reduce CH_4 emissions (Ross et al., 2018; Walderdorff, 2020). An even smaller number of NDCs include a quantitative, CH_4-specific reduction target, such as Canada, Japan, and New Zealand. Table 2 provides a summary of NDCs that include a quantitative descriptor of CH_4 mitigation as of January 1, 2021. While some of the NDCs shown in Table 2 include true quantitative CH_4 reduction targets, others quantify the potential for CH_4 reductions, or specify goals expressed in terms of efficiency or intensity. In aggregate, very few NDCs provide concrete or quantitative details on CH_4 mitigation activities – indeed, the NDCs summarized in Table 2 are among those that provide the greatest amount of specificity on CH_4 mitigation, which still tends to be very little.

4.1.3. Carbon markets as policy instrument in the international climate landscape

In practice, CH_4 is tackled primarily through a diversity of sector-

Table 2
NDCs that include a quantitative descriptor associated with reduction of CH_4 emissions as of January 1, 2021. In the case of countries that have submitted updated versions, the most recently submitted NDC was considered. The underlying analysis is based on Walderdorff (2020).

Country	Date of NDC submission	Relevant sector for quantitative CH_4 target	Quantitative mention of CH_4 mitigation in NDC	Comment/ characterization
Bangladesh	31.12.2020	Multi-sector	Full implementation of National SLCP Plan is expected to reduce CH_4 emissions by 17% in 2030 compared to business-as-usual.	Potential emission reductions; there is no commitment to full implementation of SLCP Plan
Benin	09.09.2018[a]	Agriculture	Developing and irrigating rice-growing areas with water control: lowering of CH_4 emissions by 8.5 tonnes CO_2e/hectare/year.	Efficiency target
Cambodia	31.12.2020	Waste Management	Construction of bio-digesters has a CH_4 reduction potential of 4 tonnes CO_2e.	Expressed as emissions reduction potential
Cameroon	29.07.2016	Waste Management	By 2035, all major cities should have landfills with at least 70% CH_4 capture.	Semi-quantitative target
Canada	11.05.2017 (updated submission)	Oil & Gas	Reduction of CH_4 emissions from the oil and gas sector, including offshore activities, by 40–45% below 2012 levels[b] by 2025.	Quantitative CH_4 mitigation target
China	03.09.2016	Coal	Making efforts to reach 30 billion cubic meters of coal-bed CH_4 production (coal-bed CH_4 recovery).	Formulated as aspirational
Colombia	30.12.2020	Waste Management	For the administrative department Santander: Capture and burn 20% of CH_4 from landfills; Avoid 7487 tonnes/year of CH_4 emissions from waste in the palm oil sector.	For one specific administrative department; formulated as goals
Cuba	10.12.2020[a]	Agricultural wastewater management	Treatment of 100% of waste waters in the Cuban swine sector, reducing 8 million kt CO_2e emissions annually in the period of 2020–2030.	Formulated as aspirational (contribution is also conditional)
Dominica	21.09.2016	Waste Management	Forecasted Emission Reductions in Landfills: > 11Gg CH_4.	Forecast rather than target
Gambia	07.11.2016	Agriculture, Waste Management	Reduce CH_4 emissions by 397.7 Gg CO_2e by replacing flooded rice fields with efficient dry upland rice; Reduce CH_4 emissions by 707.0 Gg CO_2e by through water management, less flooded areas, reduced fertilizer usage; Landfill CH_4 capture and flaring, reducing CH_4 emissions by 237.0 Gg CO_2e.	Quantitative CH_4 mitigation targets (conditional). Targets are for 2025, compared to base year 2010
Ghana	21.09.2016	Waste Management	Methane recovery from landfills: increase from 40% in 2025 to 65% by 2030.	Quantitative CH_4 mitigation target
Japan	31.03.20 (updated submission)	Economy-wide	A CH_4 target is set as 12.3% reduction compared to FY 2013 level (18.8% reduction compared to FY 2005 level); approximately 31.6 million tonnes CO_2e.	Quantitative CH_4 mitigation target
New Zealand	22.04.2020	Agriculture	To reduce emissions of biogenic CH_4 to 24–47% below 2017 levels by 2050, including to 10% below 2017 levels by 2030.	Quantitative CH_4 mitigation target
State of Palestine	21.08.2017	Waste Management	The capture of 14,000 tonnes of landfill gases per annum for use in power generation.	Quantitative CH_4 mitigation target (conditional)
Uruguay	14.11.17[a]	Energy, Agriculture, Waste Management, and Industrial Processes	57% reduction in CH_4 emissions intensity per GDP unit. (Targets for individual sectors also specified.)	Emissions intensity target covering multiple sectors

[a] Date of submission of English translation, on which our analysis is based.
[b] The mitigation target for CH_4 emissions from the oil and gas sector is based on a joint commitment made by Canada, the US, and Mexico in 2016 (*Pan-Canadian Framework on Clean Growth and Climate Change*). Note that the baseline year of 2012 as well as the target year of 2025 are different from Canada's economy-wide GHG emission reduction target (30% below 2005 levels by 2030), which also covers CH_4.

specific policy instruments at the national level. Market-based mechanisms are one example of a policy instrument that has been applied to cover GHGs in a cross-sectoral manner. Carbon markets set a monetary value (carbon price) on a unit of emissions (usually a tonne of GHG), thereby internalizing the costs of carbon pollution. Under most of these systems, participating entities have to hold (and generally purchase) one allowance per each ton of emitted GHG. This cost is supposed to incentivize reduction of GHG emissions. While a carbon price has been most commonly applied to CO_2, some carbon markets have also explicitly included CH_4.

Within the international climate landscape, CH_4 mitigation activities can produce so-called offset credits. For example, under the Clean Development Mechanism (CDM) of the Kyoto Protocol, businesses and countries can purchase credits for emissions reductions that occurred in climate mitigation projects realized in developing countries. These credits can be used to 'offset' emissions 'at home' and thus contribute to meeting national emission reduction commitments under the UNFCCC. Activities such as the recovery of CH_4 emissions from landfills or waste water treatment for energy generation have been accredited under the CDM (UNFCCC, 2019, 2006).

Methane has also been integrated into domestic emissions trading systems (ETS): 7 out of 21 existing domestic ETS cover CH_4 (as of January 1, 2021) (ICAP, 2021). The jurisdictions that include CH_4 in their ETS are California, Chongqing province (China), Québec, New Zealand, Nova Scotia, South Korea, and Switzerland. While most of these include CH_4 emissions from energy and/or industrial processes, New Zealand and South Korea's systems additionally tackle agriculture, and in the case of South Korea, waste. Although not governed under the UNFCCC per se, such domestic ETS have typically been designed so that they can contribute to meeting national emission reduction commitments and pledges under the Kyoto Protocol and/or Paris Agreement.

For existing carbon markets that include CH_4, the carbon price is assigned based on converting CH_4 emissions to CO_2e. That is, the price of one tonne of CH_4 emissions reflects its climate impact on a 100-year timescale. This approach is legally consistent as well practical, since a tonne of CO_2e can be assigned a monetary value relatively easily. Nonetheless, it should be recognized that the price of CH_4 within existing carbon markets reflects its long-term climate impacts only: additional negative externalities due to methane's impacts on near-term climate, ecosystems, and health are not represented.

4.2. Methane in national and international air quality governance

Unlike for climate change, there is no global framework that governs air pollution. Instead, air pollution is typically regulated at a national level, with transboundary pollution addressed by a patchwork of regional instruments and frameworks (Yamineva and Romppanen, 2017). One prominent example of a regional agreement on air pollution is the Convention on Long-Range Transboundary Air Pollution (CLRTAP), whose protocols include commitments by Parties to reduce emissions of air pollutants. To the authors' knowledge, however, no existing air quality frameworks – either national or international in character – regulate CH_4 as a pollutant, despite its important role as a precursor to O_3. Indeed, CH_4 itself is not generally categorized as an air pollutant since its harmful effects on human and ecosystem health are indirect in nature.

Many jurisdictions have standards for ambient O_3 concentrations, typically with the intent of protecting both human and ecosystem health. To ensure that these standards are met, regulatory frameworks limit the emissions of non-methane ozone precursors, primarily NOx and non-methane volatile organic compounds (NMVOCs), which themselves also have toxic health effects. However, it is increasingly recognized that meeting existing ambient air quality standards for O_3 will require reductions in CH_4 emissions as well, even more so under climate change (Turnock et al., 2018). With this as an important motivating factor, the EU considered regulating CH_4 emissions directly under the European air quality framework as part of a revision process of the National Emissions Ceiling Directive in 2015–2016 (Maione et al., 2016; European Parliament, 2015). Ultimately though, the CH_4-specific provisions of the proposal were not included in the final amendment (Directive 2016/2284/EU) amid concerns from the agricultural sector and regarding possible overlaps with commitments related to GHG reduction targets (Council of the European Union, 2015; European Commission, 2014).

In many ways, addressing CH_4 as a precursor to tropospheric O_3 is a better fit for international rather than national governance, since CH_4 abatement leads to global rather than local air quality benefits, as pointed out by Vandyck et al. (2020). The global rather than local impact of CH_4 emissions is a direct consequence of methane's atmospheric lifetime – despite being short-lived in comparison to CO_2, methane's ca. 12-year lifetime means that it gets transported far from its emission sources and becomes well-mixed within the atmosphere. Recognizing both the importance of CH_4 abatement for ozone air quality and the advantages for transboundary cooperation on this issue, the CLRTAP has identified CH_4 as an issue of importance, although until now it has stopped short of addressing CH_4 emissions directly in any of its eight protocols. The CLRTAP's current long-term strategy specifies that the ongoing review of the Gothenburg Protocol "should consider" appropriate steps towards reducing emissions of CH_4 as an O_3 precursor (CLRTAP, 2018).

4.3. Gaps in the governance of methane impacts

Although legal frameworks for governance of global climate change and air pollution are relatively well-developed, CH_4 is only peripherally treated within these, despite its large impacts on both environmental areas. The UNFCCC climate regime is structured so that emissions of CH_4 (and other non-CO_2 GHGs) are treated as interchangeable with emissions of CO_2, with an equivalence determined by the value of GWP100. However, this practice of assigning "equivalence" belies the physical reality, namely that CH_4's impact on climate is distinct from CO_2's in several important ways, as described in Section 3. In effect, only the long-term climate impact of CH_4 (i.e., its radiative forcing over a 100-year time horizon) is robustly taken into account under the Kyoto Protocol and the Paris Agreement. Among other things, this means that CH_4's outsized contribution to near-term climate warming is overlooked. As pointed out by Shindell et al. (2017), there are multiple reasons that reducing near-term warming (in addition to limiting long-term warming) would be beneficial: importantly, it could slow the rate of climate change and consequently reduce the risk of triggering dangerous climate tipping points, as well as allow more time for climate adaptation. Besides neglecting near-term warming impacts, governing CH_4 based on its CO_2 equivalence fails to take into account other important differences in how CO_2 and CH_4 affect the climate, including the way they interact with land ecosystems. While increasing atmospheric CO_2 concentrations have a moderate fertilization effect on the biosphere (increasing the uptake of CO_2) CH_4 has the opposite effect, damaging ecosystems (via production of tropospheric O_3) and reducing their ability to absorb carbon.

The focus on CO_2 equivalence under the UNFCCC also leads to an information and transparency gap. The common practice of expressing mitigation targets in terms of aggregate CO_2e, without specifying which reductions come from which GHGs, compromises the ability of modelers to evaluate in detail how the climate will respond to pledged emission reductions; this is because the climate responds differently to the different climate forcers (Fig. 2). Among other things, this has practical implications for the Global Stocktake, the Paris Agreement's mechanism to periodically evaluate collective progress to achieving its long-term goals. It is worth noting that countries have the freedom to decide whether they indicate gas-specific targets in addition to CO_2e targets within their NDCs, so this gap could be filled by voluntary action on the part of national governments.

Within the landscape of air quality governance, tropospheric O_3 – a direct byproduct of atmospheric CH_4 oxidation – is widely regulated as an air pollutant. Thus, while the air quality impacts of CH_4 as a precursor to O_3 are largely targeted by existing air quality frameworks (most prevalently at the national level), CH_4 itself is not covered as a pollutant – i.e., no CH_4 emission controls are prescribed. We identify this as a clear gap. Despite the fact that CH_4 is currently left untreated within air quality governance, it is possible that challenges in meeting existing air quality standards for O_3 may lead to increased pressure to regulate CH_4 within air quality frameworks in the future.

Overall, we conclude that the complexity and multi-faceted nature of methane's impacts on climate, ecosystems, and health are not reflected by the regulatory structures in place to govern climate change and air pollution, at least at the international level. In the next section we further elaborate on some of the challenges of methane governance and then focus on opportunities for making progress.

5. Discussion and outlook

The complexity and multitude of methane's environmental impacts combined with the diversity of its sources make governance of CH_4 a complex and therefore challenging task. As we have described, CH_4 has never been the focus of policy approaches designed to address either climate change or air pollution, the two primary spheres of its negative impacts. Adding to the complexity of the governance challenge is the fact that some CH_4 emissions data is widely perceived to be insufficiently accurate. This is especially true for CH_4 leakages from oil and gas operations, where onsite measurements have repeatedly shown large deviations from reported emissions (e.g., Zavala-Araiza et al., 2021), and for agriculture, where reporting is still dominated by very basic estimation methods (Saunois et al., 2020). As a consequence, improved measurements and reporting would be desirable for informing mitigation measures (European Commission, 2020).

The gap between the urgency of mitigating CH_4 emissions and the political and policy response has been increasingly recognized among actors within the scientific and political spheres. As an example, the EU recently published a strategy to reduce CH_4 emissions (European Commission, 2020) as a priority initiative within the European Green Deal. Furthermore, COP26 saw the launch of the Global Methane Pledge, an US-EU led initiative wherein over 100 countries pledged to take voluntary actions to reduce CH_4 emissions by at least 30% by 2030, with a 2020 baseline. Against this backdrop, in this section we discuss approaches for driving increased CH_4 mitigation, both within and beyond existing governance frameworks for climate change and air pollution.

There are several opportunities to strengthen global action on CH_4 under the Paris Agreement. One is for countries to submit CH_4-specific targets within their NDCs, clearly delineating what part of their CO_2 equivalent emissions reductions will be achieved by reducing CH_4 (in addition to CO_2 and other climate forcers). Countries can also use supplementary metrics when reporting aggregated emissions, for instance, the GWP20/100 combination proposed by Ocko et al. (2017) and Fesenfeld et al. (2018). Such practices, if they gain support and acceptance from the countries, could be included in later UNFCCC guidance, e.g., under the Subsidiary Body for Scientific and Technological Advice (SBSTA) (Pekkarinen, 2020). Additionally, Pekkarinen (2020) has identified ways in which the Paris Agreement's transparency framework can be strengthened to better account for CH_4, for instance, by specifying that each GHG be addressed separately in the biennial transparency reports and national inventory reports that the secretariat is requested to produce under Article 13 of the Paris Agreement (UNFCCC, 2018).

Within the landscape of air pollution governance, CH_4 will almost certainly remain a topic of interest in the context of the CLRTAP, and there is some discussion on regulating CH_4 directly within this forum (CLRTAP, 2018). Similarly, the EU methane strategy (European Commission, 2020) commits to exploring the possible inclusion of CH_4 as a regulated pollutant within European air quality legislation when the EU National Emission Reduction Commitments (NEC) Directive is next reviewed (by 2025). Whether or not it will be politically feasible to negotiate CH_4 emission limits into either of these frameworks remains an open question.

Another development that promises to strengthen action on CH_4 mitigation is the broadening of the actor landscape that has occurred during the past decade. In addition to national governments, a large variety of non-governmental organizations, transnational alliances as well as initiatives from the private sector have taken up the topic of CH_4 and proposed pathways for increased mitigation, often based on voluntary measures. For example, the Climate and Clean Air Coalition (CCAC) – itself a voluntary transnational partnership that brings together actors from governments, science, civil society, and the private sector (Unger et al., 2020) – created the Oil & Gas Methane Partnership (OGMP), a voluntary initiative with 62 partner companies representing 30% of the world's oil and gas production. With the recent launch of its measurement-based reporting framework "OGMP 2.0," the OGMP has set a target of reducing the oil and gas industry's CH_4 emissions by 45% (compared to 2015 levels) by 2025, with a 60–75% reduction by 2030 (UNEP, 2020). Notably, the EU methane strategy highlights European Commission support of this initiative and the intention to develop a legislative proposal for measurement, reporting, and verification of energy-related CH_4 emissions based upon the OGMP 2.0 framework (European Commission, 2020). Another example of a forum focused on CH_4 emissions is the Global Methane Initiative (GMI, 2021), an international public-private partnership that functions as a forum for technical support for countries that want to improve CH_4 recovery and use (from oil and gas, biogas, and coal mines). Further, the International Energy Agency (IEA) has developed a tool called the Methane Tracker, an online interactive database that allows users to explore country and regional estimates of CH_4 emissions from oil and gas in addition to abatement options (IEA, 2021).

The expansion of such alternative forms of governance has been the focus of research on international environmental policy and polycentric governance landscapes. Here, an argument raised often is that through offering concrete solutions that are easily accessible to many actors, such alliances may offer quicker and more feasible action, raise political awareness (e.g., on neglected topics such as methane) and enhance monitoring and learning (Bulkeley et al., 2014; Oberthür, 2016; Ostrom, 2010b; Victor et al., 2007; Bodansky, 2002; Unger and Thielges, 2021). Moreover, many of these alliances and programs may help action at the local level get better leverage and spread, and make them part of the global governance architecture (Betsill and Bulkeley, 2006; Corfee-Morlot et al., 2009; Ostrom, 2010a). While such initiatives and actors do not serve as a substitute for national and international regulations, they can support the implementation of existing agreements (including the Paris Agreement) and help create fertile ground for further policy making (Unger et al., 2020). Notably, voluntary initiatives around CH_4 have thus far have had a dominant focus on emissions from the energy industry, whereas attention to the agriculture and waste sectors has lagged behind.

Finally, while many studies have pointed out that CH_4 emissions reductions are already technically feasible and in many cases cost-effective (Höglund-Isaksson et al., 2020; Shindell et al., 2017; West et al., 2006; UNEP and WMO, 2011; UNEP., 2021), far less attention has been paid to the policies and governance arrangements that would support implementation of these solutions. We identify this as an area where more research efforts are needed. For instance, while there is a significant body of active research on climate change policy as a whole, we see the need for further studies that address the problem of CH_4 specifically, for instance, by analyzing specific CH_4 policy instruments. We also note that projections of future CH_4 emissions include a very limited set of control measures for the agricultural sector (e.g., Höglund-Isaksson et al., 2020); here more efforts are needed to identify mitigation options and represent them in emission scenarios for model studies. Progress on all of these fronts would support the accelerated mitigation of CH_4 emissions necessary to limit near- and long-term climate change as well as reduce methane's impacts on ecosystems and human health.

CRediT authorship contribution statement

Kathleen A. Mar was responsible for the conceptualization and took the lead in writing. She contributed expertise in the physical sciences and in the policy frameworks. Charlotte Unger contributed to the writing, taking the lead on the governance section and contributing expertise in the social and political sciences. Ludmila Walderdorff was responsible for the research on methane in the NDCs. Her Master's thesis was the basis for developing this article. Tim Butler contributed expertise in the physical sciences and on the CLRTAP. All authors contributed to reviewing and editing the manuscript.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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