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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."

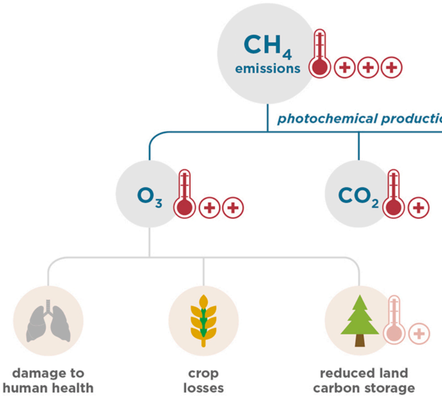

**Fig. 1.** Schematic overview of methane's primary impacts on climate, ecosystems, and health. Photochemical reactions of $CH_4$ in the atmosphere lead to the production of tropospheric ozone ($O_3$), $CO_2$, and stratospheric water vapor (Strat. $H_2O$), all of which are also GHGs and contribute directly 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

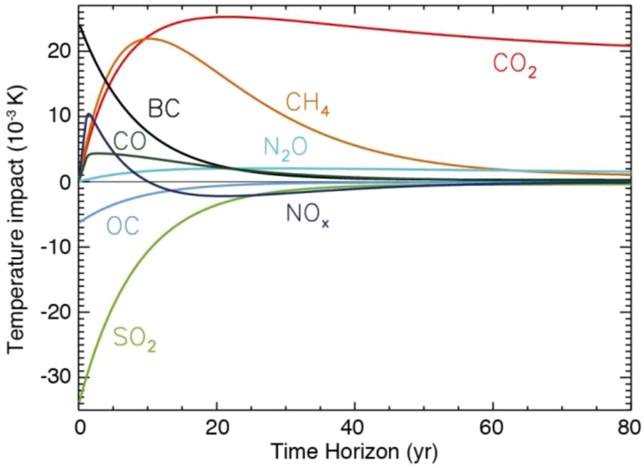

**Fig. 2.** Global temperature impact as a function of time for emissions of different anthropogenic climate forcers. The temperature impact is calculated based on the metric AGTP (Absolute Global Temperature change Potential) (Shine et al. 2005), defined as the change in global mean surface temperature 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)<br>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: $> 11$Gg $CH_4$. | 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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