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Methane and Global Environmental Change

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Abstract

Global atmospheric methane concentrations have continued to rise in recent years, having already more than doubled since the Industrial Revolution. Further environmental change, especially climate change, in the twenty-first century has the potential to radically alter global methane fluxes. Importantly, changes in temperature, precipitation, and net primary production may induce positive climate feedback effects in dominant natural methane sources such as wetlands, soils, and aquatic ecosystems. Anthropogenic methane sources may also be impacted, with a risk of enhanced emissions from the energy, agriculture, and waste sectors. Here, we review the global sources of methane, the trends in fluxes by source and sector, and their possible evolution in response to future environmental change. We discuss ongoing uncertainties in flux estimation and projection, and highlight the great potential for multisector methane mitigation as part of wider global climate change policy.

Contents

1. INTRODUCTION

Methane (CH_4) is a powerful greenhouse gas, with human activities, such as livestock production and fossil fuel extraction, having become an increasingly important source of emissions since the Industrial Revolution (1). Since 1750, atmospheric concentrations have more than doubled compared to the preindustrial average and, up until the late twentieth century, there was deepening concern about their growing role in global climate forcing (2). However, around the turn of the new millennium, atmospheric CH_4 concentrations appeared to stabilize, raising hopes that their sustained growth in previous decades had come to an end (3). In fact, the period of stable concentrations was short-lived, with a resumption of increasing atmospheric CH_4 from 2007 onward (4, 5). The cause of these swings in net annual fluxes remains an area of intense debate and research (6, 7). More certain is that CH_4 has become a key agent of global climate forcing and that further increases in its atmospheric concentration in the twenty-first century risk undermining international climate change mitigation efforts.

Here we examine CH_4 and global environmental change, our primary focus being on responses to and interactions with climate change and elevated atmospheric CO_2 concentrations. We first review methane's direct and indirect role in climate forcing, its global sources and sinks, and past trends in fluxes and atmospheric concentrations. We then examine the ways in which natural and anthropogenic CH_4 fluxes are affected by environmental change and the potential feedback responses to future climate change. Finally, we reflect on the role of CH_4 in global climate change policy and the multisectoral potential for its mitigation.

1.1. Direct Radiative Forcing

Since the Industrial Revolution, the direct radiative forcing of increased CH_4 is estimated to have been 0.48 Wm^{-2} (compared to approximately 1.8 Wm^{-2} for carbon dioxide) (8). Atmospheric

Table 1   Evolving GWP estimates for CH$_4$ in the IPCC Assessment Reports FAR through AR5

Time horizon	FAR (1990)	SAR (1995)	TAR (2001)	AR4 (2007)	AR5 (2013)
20 years	63	56	62	72	84 (86)[a,b]
100 years	21	21	23	25	28 (34)[b]
500 years	9	6.5	7	7.6	NA

Abbreviations: AR4, Fourth Assessment Report; AR5, Fifth Assessment Report; FAR, First Assessment Report; GWP, global warming potential; IPCC, Intergovernmental Panel on Climate Change; NA, not applicable; SAR, Second Assessment Report; TAR, Third Assessment Report.
[a]Values in parentheses include climate–carbon cycle feedback effects.
[b]For fossil fuel CH$_4$, these GWP values are increased by 1 and 2 for time horizons of 20 and 100 years, respectively (177), to account for the CO$_2$ released during combustion. However, where the combusted CH$_4$ is biogenic, or where the CO$_2$ from fossil CH$_4$ combustion is already accounted for, no adjustment is required.

CH$_4$ concentrations increased from 722 ppb to more than 1,800 ppb by 2011, largely as a result of human activities (9). That CH$_4$ has such a powerful direct radiative forcing effect despite its relatively low concentrations is due to its very effective absorption of infrared radiation, particularly at wavelengths of 3.3 and 7.7 μm. Importantly, CH$_4$ emissions also have major indirect effects on net radiative forcing, with these complex impacts making methane's overall role in global climate change greater still (10).

Methane's global warming potential (GWP; a measure of the warming induced by emission of any greenhouse gas relative to that of CO$_2$ on a mass basis) has seen substantial revision over the past 20 years. In 1990, the GWP for CH$_4$ was estimated as being 21 over a 100-year time horizon (11) (i.e., that each metric ton of CH$_4$ emitted had a warming effect equivalent to 21 metric tons of CO$_2$). This estimate has both increased and become more nuanced in subsequent Intergovernmental Panel on Climate Change (IPCC) Assessment Reports (9), as understanding of the indirect climate forcing impacts of CH$_4$ has improved and background concentrations have continued to change (**Table 1**). Current national emissions reporting under the United Nations Framework Convention on Climate Change utilizes the 100-year time horizon value of 25 for CH$_4$ from the Fourth Assessment Report.

1.2. Indirect Forcing

The primary sink for CH$_4$ in the atmosphere is oxidation by hydroxyl (OH) radicals (12). As CH$_4$ concentrations increase, this atmospheric oxidizing capacity becomes more exhausted, meaning the effective lifetime and radiative forcing of CH$_4$ is enhanced. In addition to this positive feedback effect, CH$_4$ has further indirect impacts through its role as a precursor for ozone formation and through the additional climate forcing that results from the water vapor and carbon dioxide produced when it is destroyed (13). The atmospheric lifetime of CH$_4$ is approximately 9 years, but with an effective perturbation lifetime of 12 years (due to the feedback effect CH$_4$ has on its own lifetime) (8).

In the most recent IPCC Assessment Report two different estimates for the GWP of CH$_4$ over a 100-year time horizon are given, with a value of 28 when climate-carbon feedbacks (such as the enhancement of the atmospheric lifetime of CO$_2$ as a result of warming induced by CH$_4$) are excluded, and a value of 34 when such complex feedbacks are included (8). Methane can also play an indirect role in global radiative forcing through its interactions with sulfate aerosols and the lifetimes of powerful greenhouse gases such as hydrofluorocarbons and hydrochlorofluorocarbons (14). The intersecting domino effects that are the atmospheric interactions of CH$_4$ mean that current uncertainties in GWP remain large (∼40%).
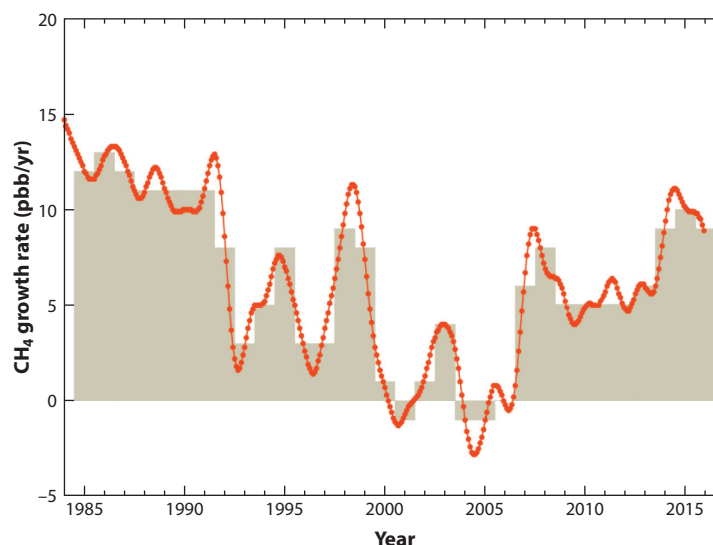
Figure 1

Globally averaged methane (CH_4) growth rate from 1984 to 2016. Shaded columns represent increases in successive annual means. Red dots represent monthly means (23). Figure reproduced with permission from the World Meteorological Office.

1.3. Past Trends and Current Concentrations

Through ice core records we are able to reconstruct global atmospheric CH_4 concentrations over the past 400,000 years and more (15). These indicate swings in concentration between approximately 350 and 750 ppb coinciding with glacial and interglacial periods, respectively. Over these long (20–100,000-year) time intervals, the cyclical changes in CH_4 concentrations can be broadly explained by Earth's orbit and consequent variations in solar input. However, within these orbital periods, shorter-term variations in CH_4 fluxes attributed to monsoon impacts on tropical wetlands can be observed (16). Recent analysis has also linked variations in tropical wetland CH_4 emissions with the El Niño–Southern Oscillation, with decreased CH_4 emissions associated with El Niño, and increased emissions with La Niña conditions (17). Such an interaction may help to explain lower growth rates in atmospheric CH_4 concentrations observed in the 1990s and early 2000s, as this period coincided with several El Niño events (18).

In addition to responses of wetland CH_4 fluxes to changes in temperature and precipitation, natural CH_4 sources such as permafrost soils, lakes, and coastal regions may have all played significant roles in determining the preindustrial CH_4 concentration (19). Indeed, loss of large amounts of CH_4 from marine clathrate deposits in response to warming (the clathrate gun hypothesis) has in the past been suggested as the primary cause of increases in atmospheric CH_4 concentrations during the Quaternary (20). Although the clathrate gun hypothesis remains controversial (21), a good understanding of how environmental change affects natural CH_4 sources is vital in terms of robustly projecting future fluxes under a changing climate.

In more recent history, and in particular since the nineteenth century, the atmospheric CH_4 concentration has risen far beyond the preindustrial average, with a growth rate reaching as high as 10–15 ppb year^{-1} in the late 1980s and early 1990s (22, 23) (**Figure 1**).

As mentioned above, a brief hiatus in atmospheric concentration increase around the turn of the millennium has since given way to renewed growth at 5–10 ppb year^{-1}. Although the
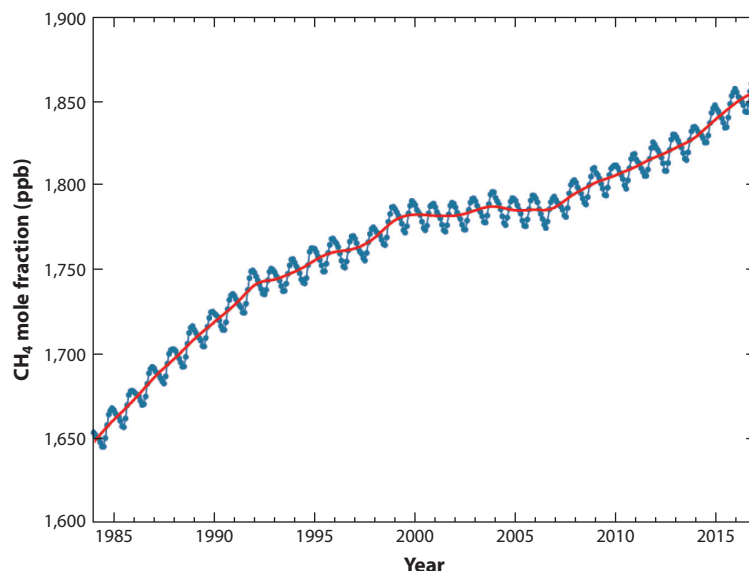
Figure 2

Globally averaged methane (CH$_4$) mole fraction in the atmosphere from 1984 to 2016. The red line is the monthly mean mole fraction with the seasonal variations removed; the blue dots and line depict the monthly averages. Observations from 125 stations have been used for this analysis (23). Figure reproduced with permission from the World Meteorological Office.

approximately 150% increase in CH$_4$ concentrations since 1750 is largely attributable to human-induced emissions, interannual variability in global fluxes and growth rates is also highly dependent on the balance of natural sources and sinks (4).

Recent measurements of atmospheric CH$_4$ show concentrations reached a new high of 1,853 ($\pm$2) ppb in 2016. This represents a 9-ppb annual rise and a 157% increase in abundance relative to 1750 (23) (**Figure 2**).

The continued increase in CH$_4$ concentrations has been linked to enhanced wetland emissions (24). However, more recent estimates indicate their role in this increase is a minor one and that elevated emissions from agriculture and fossil fuel extraction may be more important (6, 25, 26). A decrease in OH concentrations—the primary sink for CH$_4$—is also believed to have enhanced CH$_4$ in the atmosphere (7, 12). Importantly, several studies have highlighted the limitations of current surface observation networks (7, 27), inventory estimates (5), and models (28) in robustly attributing the sources of year-to-year variation in atmospheric CH$_4$ concentrations.

2. GLOBAL METHANE SOURCES AND SINKS

2.1. Methane Sinks

The atmosphere represents the dominant global sink for CH$_4$, being responsible for the destruction of approximately 600 Tg CH$_4$ year^{-1} (**Figure 3**). Of this, reaction with OH in the troposphere is the main (85–90%) mechanism of atmospheric loss, with stratospheric OH destruction and reaction with tropospheric chlorine (Cl) making up the rest (22). Soils are also a significant global CH$_4$ sink, estimated at approximately 30 Tg year^{-1}. This net exchange figure masks the much greater levels of coupled CH$_4$ production and consumption that can occur within soil profiles (29).
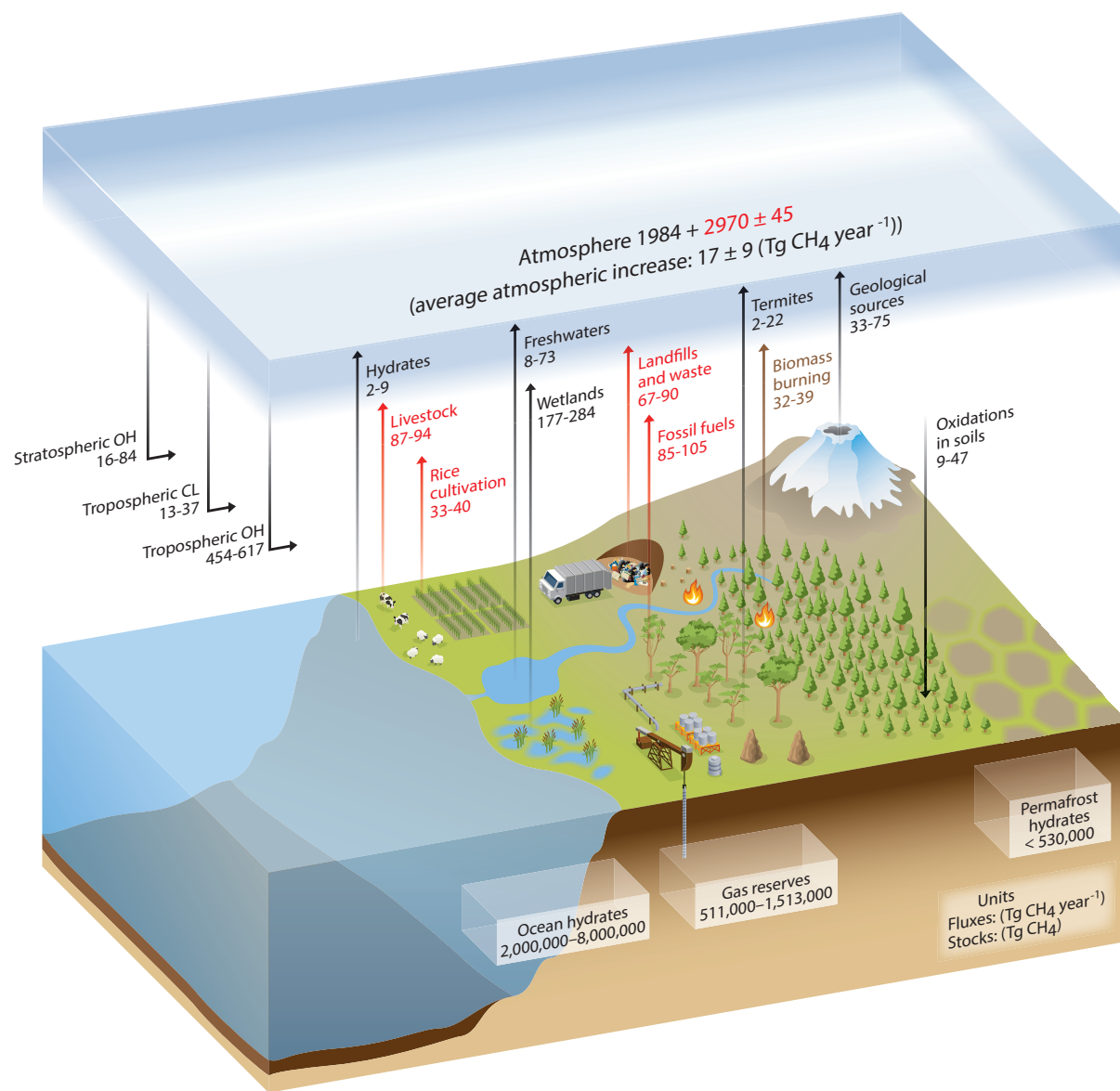
Figure 3

Global methane stocks and fluxes (22). Numbers represent annual fluxes in Tg CH_4 year^{-1} estimated for the 2000–2009 time period and CH_4 reservoirs in Tg CH_4. Black arrows denote "natural" fluxes, that is, fluxes that are not directly caused by human activities since 1750, red arrows anthropogenic fluxes, and the light brown arrow a combined natural plus anthropogenic flux. Figure reproduced with permission from the Intergovernmental Panel on Climate Change.

Environmental change has the potential to affect all CH_4 sinks (30). For the atmosphere, changes in OH radical availability in the troposphere would have the greatest impact. Increases in UV radiation (due to stratospheric ozone depletion), humidity and temperature (due to climate change), and ozone and NOx concentrations (due to both climate change and anthropogenic emissions) can all increase OH abundance (13). However, increasing CH_4 concentrations, together with

elevated carbon monoxide (CO) and volatile organic compound (VOC) emissions—themselves having significant anthropogenic sources (31, 32)—can decrease OH abundance. Since the Industrial Revolution, no clear trend in OH abundance at the global scale has emerged. However, for climate change impacts specifically, it is estimated that warming between 1850 and today has served to slightly increase OH abundance. This has effectively reduced the atmospheric lifetime of CH_4 by approximately four months and as such represents a weak negative feedback effect (33).

For the soil CH_4 sink, changes in land cover, temperature, precipitation, and deposition rates of nitrogen (N) and sulfur (S) may all alter local and regional sink strengths (34–36), with consequences for the magnitude of the global sink (see Section 3.2).

2.2. Methane Sources

Global sources of CH_4 are far more diverse than the sinks. Total emissions are currently of the order of 500–600 Tg year^{-1}, with anthropogenic sources now estimated to outweigh natural sources (**Figure 3**) (22).

2.2.1. Natural methane sources.
Natural CH_4 sources include wetlands, geological sources, lakes and rivers, termites, wildfires and wild animals. Wetlands dominate these natural emissions, at between 177 and 284 Tg year^{-1}. As the largest CH_4 source type, interannual changes in wetland CH_4 fluxes are the primary driver of variations in global CH_4 flux (37). Wetlands encompass a host of ecosystems ranging from flooded forest soils and swamps in the tropics to high latitude peatlands and bogs. Methane emissions from these seasonally or permanently flooded soils can be very sensitive to environmental change, with CO_2 enrichment, temperature, and precipitation change being especially important (38). For example, the pause in growth of atmospheric CH_4 concentrations observed around the start of the new millennium has been attributed to a predominance of drier conditions over some northern and tropical wetlands at that time (17, 39).

The relative magnitude of wetland CH_4 sources at a global scale makes understanding their interactions with environmental change a vital component of emissions projections (40). However, their spatial distribution and diversity represent major challenges. Uncertainties around responses to changing plant cover and nutrient deposition, along with those for temperature and precipitation, mean that confidence in projected CH_4 emissions in the twenty-first century remains low (22) (Section 3.1).

Of the other natural CH_4 sources, all have the potential to grow or diminish in response to environmental change. Freshwater systems may see alterations in key determinants of CH_4 production, such as temperature, carbon, and nutrient inputs (41) (Section 4.2). Similarly, large geological CH_4 stocks such as marine hydrates may experience increasing temperatures and as such greater instability (42) (Section 4.1). For terrestrial ecosystems, changes in precipitation, temperature, and vegetation could directly and indirectly affect CH_4 fluxes from wildfires (Section 3.3) and in soils (Section 3.2).

A novel natural source of CH_4 has been previously reported for vegetation under aerobic conditions (43), with a suggestion that exposure of plant material to UV radiation may be an important mechanism in such aerobic methanogenesis (44). Changes in UV exposure—such as those that may occur with stratospheric ozone depletion and recovery—may therefore alter the strength of such a CH_4 source. However, more recent estimates suggest its global magnitude is small (0.2–1.0 Tg year^{-1}) (45).

2.2.2. Anthropogenic methane sources.
Anthropogenic CH_4 sources are dominated by agriculture and energy-related emissions (approximately 130 and 100 Tg year^{-1}, respectively), with

waste responsible for a further 70–90 Tg year^{-1} and biomass burning approximately 35 Tg year^{-1} (**Figure 3**) (22). In the agriculture sector, ruminant livestock are the largest CH_4 source, with the potential for direct (e.g., animal welfare) and indirect (e.g., altered feed composition) impacts from future environmental change (Section 5.1). Rice agriculture—itself having global CH_4 emissions of approximately 36 Tg year^{-1}—may be especially sensitive to environmental change, with variations in temperature, water availability, and CO_2 concentrations all having the potential to alter fluxes (Section 5.2).

A potentially important indirect impact of climate change on CH_4 emissions from agriculture is through increased loss and waste along the food supply chain. Severe weather and pest damage can reduce productivity, and higher temperatures and humidity may accelerate postharvest food deterioration (46). For commodities with relatively high CH_4 emissions intensities, such as some rice, beef, and dairy products, any substantial enhancement in such loss and waste could decrease overall production efficiency and drive up CH_4 emissions intensity still further (47).

Energy-related CH_4 emissions largely result from fugitive emissions during fossil fuel extraction and supply (48). Warming in permafrost areas has the potential to directly increase gas pipeline leakage rates, and ice retreat in the Arctic may also result in greater fossil fuel exploitation (including that of CH_4 hydrates) and as such further increases in fugitive CH_4 emissions (Section 5.3). Hydroelectricity generation can also result in substantial CH_4 emissions via river damming and CH_4 production in the resulting reservoirs. Elevated temperatures and changing carbon and nutrient inputs may then further alter these emissions. As with wildfire CH_4 emissions, the amounts of CH_4 arising from human-induced biomass burning can be altered due to changes in precipitation, temperature, and the composition of the biomass itself.

Finally, waste-related CH_4 emissions may be affected by changes in climate, with higher temperatures tending to enhance CH_4 production from waste decomposition. Under controlled conditions (e.g., anaerobic digestion) this may enhance CH_4 yields for energy use (49), whereas in more open systems (e.g., constructed wetlands, waste treatments, and landfill sites) there is the potential for an increase in CH_4 emissions to the atmosphere. For livestock manure in particular, increased temperatures may enhance CH_4 production (50) and, in open storage systems, enhance emissions (51) (Section 5.1).

3. GLOBAL CHANGE AND TERRESTRIAL METHANE FLUXES

3.1. Wetland Methane and Global Change

Wetland ecosystems are an important component of the global carbon cycle, as Northern wetlands (those at >45°N) store more than 50% of global soil organic carbon, due to the slow organic carbon decomposition rates that result from wet surface conditions and low temperatures (52). Wetlands are also the largest single source of atmospheric CH_4, with current annual emissions estimated at 140–280 Tg CH_4 year^{-1} (53).

Key determinants of wetland CH_4 emissions include temperature, soil moisture, aerenchyma transport (the movement of CH_4 from soils to the atmosphere via the porous tissues in plant roots and stems), and substrate availability (28, 54). As such, any significant change in wetland CH_4 emissions in response to climatic change and CO_2 fertilization impacts would have major consequences for global emissions and atmospheric CH_4 concentrations.

For example, future climatic warming, particularly at high latitudes, could lead to a significant increase in net CH_4 emissions from wetlands, serving as a significant positive feedback to warming of the global climate system (55). Similarly, increased net primary production and soil water content could enhance methanogenesis (the microbial basis of wetland CH_4 production) and CH_4

emissions. However, more variable precipitation and drying of wetland soils—such as is likely to occur in the subtropics—could reduce wetland extent, limit methanogenesis, and as such reduce net emissions (56). One of the largest uncertainties in wetland CH_4 estimates is how wetland extent or inundated area will change over time (28, 53).

Estimating the magnitude of these responses at a global scale is extremely challenging given the limited spatial and temporal coverage of direct observations globally, the importance of local conditions and microbial communities in determining net fluxes, and the impacts of human activity of wetland extent and function (57). Land use activities such as grazing, drainage, and fertilization may all radically alter carbon cycling and net CH_4 fluxes. An assessment of wetland CH_4 emission in China over the past 30 years found that, whereas climate change enhanced wetland emissions (through increased temperature at high altitudes and increased precipitation in arid areas), human-induced reduction in wetland area led to an overall decrease in CH_4 emissions (58). Similarly, differences in land management history and internal characteristics of peatlands (such as open degraded peatlands compared to intact peatland forests) may alter the sensitivity of CH_4 emissions to temperature change (59).

To date, projections of wetland CH_4 flux at a global scale in the twenty-first century have tended to focus on potential climate change impacts (54), rather than attempting to integrate these with scenarios of land use change and human activities relevant to wetland CH_4 emissions at the local scale. The complexity involved in such an integrated assessment of wetland CH_4 at a global scale means that future human activity remains a large source of uncertainty (57).

Recent modeling has overtly included scenarios of climate change mitigation by examining the potential response of regional and global wetland CH_4 emissions under the four representative concentration pathways (RCPs) (60). Outputs indicate a substantial increase—from 172 ± 12 Tg CH_4 year^{-1} currently to 221.6 ± 15 by 2100—even for the lowest RCP (RCP 2.6). Under the business-as-usual (BAU) scenario (RCP 8.5), total wetland area increases by 13% and global CH_4 emissions almost double relative to current levels.

For high latitude (boreal) wetlands, higher temperatures, winter thawing, and a consequent increase in soil moisture content were found to be the primary drivers of elevated emissions. Whereas for tropical wetlands, higher temperatures and changing precipitation patterns result in higher and more annually variable emissions, despite a slight decrease in tropical wetland extent (60).

The high temporal variability common to wetland CH_4 fluxes—something likely to increase with climate change—poses a particular challenge for their robust quantification and projection. Assessment of surface warming and moisture availability impacts on northern latitude CH_4 emissions using satellite-derived fractional inundation (61) highlighted the importance of fine (submonthly) temporal resolution of fractional inundation on annual CH_4 emission estimation.

3.2. Soil Methane and Global Change

Section 3.1 deals with wetland/peatland soils (e.g., histosols), whereas this section deals with mineral soils (all those that are not wetlands/peatlands). In mineral soils, there are micro-organisms that produce CH_4 (methanogens) and micro-organisms that consume (and oxidize) CH_4 (methanotrophs; see 56). The balance between methanogenesis and methanotrophy determines the net flux of CH_4 from soils (30, 56).

Aerobic mineral soils act as a sink for CH_4, oxidizing 9–47 Tg CH_4 year^{-1} globally (22). Mineral soils under natural vegetation and forests tend to act as the strongest sink, followed by grasslands, with the sink strength weakest in cultivated soils and those receiving nitrogen fertilizer (62, 63); as such, as cropland has expanded, the CH_4 sink strength of soils globally will have declined (63). When mineral soils become anaerobic, the net flux to the atmosphere can be positive, with

waterlogged soils becoming a CH_4 source, often with large local emission rates (64). When soils are deliberately flooded, e.g., for rice cultivation, they can become very large global sources of CH_4 (see Section 5.2).

Permafrost soils contain large quantities of CH_4 in the form of hydrates, known as clathrates when trapped in permafrost, with a stock of the order of 500,000 Tg CH_4 (22), globally. Whereas permafrost soils are a relatively minor natural source of CH_4 emissions, estimated to contribute approximately 1 Tg CH_4 year^{-1} (22), permafrost thaw, driven by climate change, could release a portion of this vast CH_4 store to the atmosphere (65, 66).

In the tropics and subtropics, termites are a significant natural source of CH_4 emissions. Where termites occur, CH_4 oxidizing soil organisms are also present, meaning that a large proportion of the CH_4 produced by termites is oxidizing in mound material (67). Not all of the CH_4 is oxidized, however, meaning that globally termites are a net CH_4 source totaling 2–22 Tg CH_4 year^{-1} (22).

In terms of latitudinal differences in CH_4 fluxes, Arctic soils tend to act as a CH_4 source (65), as do termite-rich tropical/subtropical regions (22), whereas mineral soils in temperate regions tend to act as a CH_4 sink (unless waterlogged; see 63), with 30–50% of the global soil CH_4 sink located in the temperate zone (68). The positive north–south gradient in CH_4 concentrations, however, is mostly driven by the greater emissions of CH_4 from wetlands and anthropogenic emissions in the northern compared to the southern hemisphere (22).

Soil-mediated fluxes of CH_4 can be very sensitive to climate change and variability (22). Dlugokencky et al. (24), for example, showed that the high CH_4 growth rate during 2007 to 2008 was associated with positive precipitation and temperature anomalies. Warming would likely increase soil CH_4 fluxes in the Arctic through mobilization of CH_4 hydrates resulting from permafrost thawing (65), although, as with wetlands (Section 3.1), it might decrease emissions from otherwise waterlogged mineral soils in some regions if it dried the soils through increased evapotranspiration. Changing precipitation patterns will have mixed effects, with drying regions expected to emit less CH_4 and wetting regions (if already wet) expected to emit more CH_4 due to greater incidence of waterlogging. According to the IPCC (22), soil CH_4 oxidation is projected to increase overall (by up to 23% under a moderate climate forcing scenario), attributable to rising atmospheric CH_4 concentrations, increased soil temperature, and decreased soil moisture (69, 70).

Land management affects the sink strength in temperate mineral soils, with more intensive activity (i.e., cultivation for crops) decreasing the sink strength to the greatest degree (63; also see Section 5.2, where this is discussed further). Although wetland CH_4 emissions have been observed to increase in response to elevated atmospheric CO_2 concentrations, this has been attributed to increasing soil moisture due to the reduced plant demand for water under higher CO_2 (71), and emissions of CH_4 from permafrost are expected to increase due to CO_2 fertilization (72), the magnitude of any such effect on mineral soils is not clear. Nitrogen loading is known to decrease the CH_4 oxidation potential of soils (73), but the impacts of changes in nitrogen deposition, as with CO_2 fertilization, are complex and remain highly uncertain (63).

3.3. Wildfire Methane and Global Change

Wildfire CH_4 emissions show high interannual variability, with a global estimate of 3 Tg CH_4 year^{-1} and a range of 1–5 Tg year^{-1} (22). Climate change, land use, and fire management practices all have the potential to radically affect such emissions; CH_4 emissions arise from incomplete combustion of biomass and changes in vegetation, fire intensity, timing, and distribution, which are key determinants of this. Climate change projections suggest an increase in both wildfire frequency and intensity in regions such as North and South America, central Asia, and southern Africa (74). The projected increase is primarily driven by higher temperatures, with changing precipitation also being an important determinant in the subtropics (75).

Table 2   "Likely" response of CH_4 fluxes from major natural sources in response to global change in the twenty-first century[a,b]

Source	Temperature response	Precipitation response	CO_2 response	Overall
Soils and wetlands (low latitude)	↗	→	↗	↗
Soils and wetlands (high latitude; >45°)	↗	→	↗	↗
Wildfires	→	→	↗	→
Marine	↗	→	→	↗
Freshwater	↗	→	↗	↗

[a]These are "likely" responses in the view of the authors, assuming no confounding impacts from other human activities such as wetland drainage.
[b]Responses represent global averages unless otherwise specified.

A global increase in wildfire area, all else being equal, can be expected to increase CH_4 emissions from this source, although the emissions intensity of wildfires is highly dependent on factors such biomass type and moisture content (76). Given that climate, land use change, and CO_2 enrichment will also alter vegetation characteristics in many wildfire-prone regions, it is possible that the CH_4 emissions intensity of wildfires will increase in some areas (such as tropical peatlands and forests) (77), while decreasing in others (e.g., subtropical savannas). However, at a global scale recent estimates suggest wildfire emissions (in the form of CO_2) declined in the twentieth century and are unlikely to greatly increase in the twenty-first century due to climate change except under a high emissions scenario (i.e., RCP 8.5) (78) (**Table 2**). Finally, it has been suggested that wildfires can alter the magnitude of the soil CH_4 sink through driving vegetation change, reducing soil organic matter content, and altering gas diffusion rates (79, 80).

4. GLOBAL CHANGE AND AQUATIC METHANE FLUXES

4.1. Oceanic Methane Fluxes and Global Change

Compared to other natural and anthropogenic emissions, the oceans are a modest source of CH_4 to the atmosphere. Globally, they contribute approximately 30 Tg CH_4 year^{-1} (81); this estimate includes CH_4 emissions from the open ocean ($\sim$2 Tg CH_4 year^{-1}), shelf seas ($\sim$6 Tg CH_4 year^{-1}), and estuaries ($\sim$2 Tg CH_4 year^{-1}), as well as inputs from seafloor seeps (hydrocarbon seeps, mud volcanoes, hydrothermal vents) ($\sim$20 Tg CH_4 year^{-1}) (81). Although shallow marine sediments host vast quantities of CH_4 (>500 Pg C as CH_4; see 82) in the form of marine clathrate, these are not considered to be a significant source of atmospheric CH_4 at present (83). The uncertainty in all of these estimates is, however, high due to the limited number of measurements, the ephemeral nature of seafloor seeps, and difficulties in quantifying ebullition fluxes of CH_4.

Methane is produced in ocean sediments by thermal and anaerobic microbial degradation of organic carbon, as well as abiotically during high-temperature serpentinization of ultramafic rocks in the lower oceanic crust by circulating seawater. Methane is also produced within the ocean in oxygen and sulfate-replete surface waters. This so-called marine methane paradox has until recently been attributed to methanogenesis within anoxic microenvironments (such as digestive tracts and freshly released fecal pellets; see 84), but it is now clear that aerobic bacterial degradation of phosphonate constituents of dissolved organic matter can produce enough CH_4 to support the entire sea-air CH_4 flux at least at some locations (85). Aerobic production of CH_4 from CH_3SH by bacteria is also thermodynamically plausible (86).

Anthropogenic sources of CH_4 are growing in importance. Most of the CH_4 in the Yaquina estuary (USA) originates from the release of municipal wastewater (87), and CH_4 emissions from Guanabara Bay (Brazil) are dominated by sewage discharge (88). Fugitive emissions from oil and

gas extraction are also a concern: In the North Sea, CH_4 is still being released from an abandoned drill site more than 20 years after a major blowout (89), and the blowout of the Deepwater Horizon oil well in the Gulf of Mexico in April 2010 injected up to 500,000 metric tons of natural gas, mainly CH_4, into the deep sea (90).

Emissions of CH_4 from the oceans to the atmosphere are strongly moderated by aerobic and anaerobic microbial oxidation (91). Anaerobic oxidation of methane (AOM) occurs in anoxic seawater and sediment pore waters, and is believed to involve a consortia of archaea and sulfate-reducing bacteria:

$$CH_4 + SO_4^{2-} \rightarrow HCO_3^- + HS^- + H_2O.$$

After reduction by photochemical processes in the troposphere, AOM is the largest sink of CH_4 on our planet (92). However, if sedimentary CH_4 fluxes are high then the rate of sulfate diffusion into sediments limits the rate of AOM, and/or CH_4 solubility in the pore waters may be exceeded, such that free CH_4 gas is formed and CH_4 escapes into the overlying water column. Methane transported into oxic sediment pore waters and seawater, and CH_4 produced within the oxic water column, may be oxidized aerobically:

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O.$$
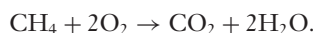
Methane oxidation rates are widely variable, with turnover times of the order of days to $>1,000$ years (93), depending on the availability of dissolved CH_4 and O_2, as well as temperature, salinity, and hydrographic dynamics. Most CH_4 bubbles emitted from sediments at depths >200 m do not reach the surface mixed layer of the ocean (where CH_4 can be exchanged with the atmosphere) because of bubble dissolution and CH_4 oxidation (94). However, CH_4 bubbles from hydrocarbon seeps can be coated with a thin layer of oil that inhibits dissolution and enables them to persist to much greater heights above the seafloor (550–600 m) (95).

The majority of the global CH_4 flux from the oceans comes from the continental shelf, coastal seas, and estuaries (96, 97) due to high rates of methanogenesis sustained by high biological productivity and organic matter sedimentation, as well as direct inputs of CH_4 from rivers. Projecting future emissions from these areas is difficult, given uncertainties in current estimates and the multiplicity of processes that moderate CH_4 emissions. Increased temperatures will stimulate microbial CH_4 production and decrease CH_4 solubility, increasing CH_4 emissions from the seabed. Higher seawater CH_4 concentrations, however, mean that CH_4 oxidation rates will also be higher (93). Nevertheless, it is likely that increased emissions from shallow gassy sediments beneath a well-mixed water column will increase CH_4 fluxes to the atmosphere and provide a positive feedback on climate (98). If mangroves are confirmed to be a significant source of atmospheric CH_4 (99), then their continued removal may, in part, mitigate increased coastal CH_4 emissions.

Although coastal eutrophication may both increase CH_4 and lower O_2 (100), oxygen-deficient zones (both in the coastal and open ocean) do not appear to be a significant source of atmospheric CH_4 at present, nor are they predicted to be in the future, even though these zones are expected to expand as climate warms (101).

The effects of global change on CH_4 production and consumption in the open ocean are essentially unknown. There is evidence that the Atlantic overturning circulation is slowing (102), and the upper ocean becomes more stratified, at most locations, in response to global warming (103), which may mean that a higher proportion of the flux from sediments is oxidized below the thermocline. Increased sea surface temperatures may enhance primary productivity and in turn CH_4 production in anoxic microenvironments, although stratification may reduce return of remineralized nutrients to surface waters (limiting primary production) and higher temperatures will increase the rate of aerobic CH_4 oxidation. Nevertheless, it is now clear that CH_4 production in aerobic surface

waters is directly linked to nitrogen, phosphorous, and carbon cycles (86), thus any change in the operation of these biogeochemical cycles will have a profound effect on CH_4 emissions.

Sea ice acts as a physical barrier to CH_4 exchange with the atmosphere (104), and concentrations of atmospheric CH_4 have been shown to increase over open leads and regions with fractional sea ice cover (105). High latitudes of the northern hemisphere are expected to experience a larger temperature increase than other regions due to climate change (9), and sea ice coverage in the Arctic has decreased in recent decades, especially in the summer (106). The effect of this on sea-air CH_4 fluxes is manifold; the presence of sea ice reduces turbulence and wave generation in adjacent ice-free waters, restricting gas exchange (107). Melting may act to both increase gas exchange - as larger waves will be more likely and swells will be more common (108), and increase stratification between surface and deep waters. Such stratification would restrict the capacity of the deeper Arctic Ocean to act as a CH_4 sink (109). Although there appears to be a direct relationship between sea-ice decline and increasing CH_4 emissions in the Arctic, the contribution of oceanic CH_4 sources is still unclear (110).

Most modeling studies agree that warming of bottom waters on the continental shelf and slope will destabilize marine clathrate and consequently increase CH_4 fluxes across the seabed (111). In 2008, more than 250 plumes of CH_4 bubbles were discovered seeping from the seafloor offshore of western Svalbard, and these emissions have been attributed, at least in part, to clathrate dissociation as a result of warming of bottom waters in this area over the past ∼30 years (112). Partial thawing of submerged permafrost in Arctic shelf seas has also been observed and appears to be a significant source of CH_4 to the atmosphere (113), although this is likely related to warming initiated by permafrost submergence approximately 8,000 years ago rather than recent Arctic warming (114). Release of large quantities of CH_4 into marine sediments is of major concern because the efficacy of both AOM and aerobic CH_4 oxidation is reduced as CH_4 will be transported primarily in the gas phase, which is largely inaccessible to microbes (115). Nevertheless, it seems unlikely that catastrophic, widespread dissociation of marine clathrates will be triggered by continued climate warming at contemporary rates (0.2°C per decade; see 9) during the twenty-first century (116).

Although knowledge of the oceanic distribution, formation and consumption, and sea-air fluxes of CH_4 has improved considerably in recent decades, their response to environmental change remains uncertain. Coastal regions are especially heterogeneous both temporally and spatially, and changes to freshwater inputs to the coastal zone are highly uncertain. Moreover, there is a paucity of studies on CH_4 distributions in the southern hemisphere (117), and it is predicted that thousands of natural CH_4 seeps remain to be discovered on the continental margins (118) that are likely to be affected by warming of overlying waters. Improved knowledge of the response of microbial communities to increased temperature and changes in CH_4 fluxes is critical—AOM communities, especially, grow very slowly and may take decades to establish (119).

4.2. Freshwater Methane and Global Change

Globally, CH_4 emissions from freshwater systems have been estimated to be as much as 100 Tg year^{-1} (120). This estimate includes lakes, rivers, and reservoirs, with the latter representing an anthropogenic source of approximately 20 Tg year^{-1} (see also Section 5.3). Uncertainty in such global estimates remains high due to the limited number of direct measurements and the ephemeral nature of some freshwater systems, such as river flood plains.

Methane production in freshwater systems is predominantly via microbial methanogenesis in sediments, although in highly turbid, low-oxygen systems CH_4 may also be produced in the water column (121, 122). Methane is then primarily emitted to the atmosphere via diffusion, ebullition, and, where emergent vegetation is present, through plant aerenchyma. In most systems, microbially mediated CH_4 oxidation in surface waters plays a key role in buffering net emissions

to the atmosphere. However high rates of emission are possible in areas where bottom waters supersaturated with CH_4 are exposed directly to the atmosphere, such as in hydroelectric turbines and spillways (120, 123).

Environmental change may alter CH_4 emissions from freshwater systems in numerous ways. Temperature is a key determinant of methanogenesis and thus, all else being equal, climate change would be expected to enhance sediment CH_4 production and emission. This positive feedback effect is of particular importance in high latitude lakes, with warming of Arctic lakes under a high emissions scenario having the potential to more than double CH_4 emissions in the twenty-first century (from approximately 12 Tg year^{-1} today to more than 28 Tg year^{-1} in the 2090s) (124).

Much of this enhancement derives from the thawing of carbon-rich permafrost at the margins of Arctic lakes, and a consequent fueling of methanogenesis in the lake sediments (41). However, this same thawing of permafrost is expected to lead to drainage of some lake and pond areas (especially in the far north) and expansion of others. As such, an overall reduction in the area of Arctic lakes may serve to limit the extent of this positive climate change feedback. Increasing temperatures can also result in increased stratification of freshwater systems, reducing oxygen availability in sediments and bottom waters (125) and serving to enhance methanogenesis in some systems.

Changes in precipitation can have both direct and indirect effects on CH_4 emissions from freshwater systems. Reduced rain and meltwater inputs may extend water residence times, enhance eutrophication and anoxia, and as such increase methanogenesis. However, reduced precipitation due to climate change may also lead to area reduction or complete loss of some freshwater systems (41) (most notably in the subtropics), resulting in an overall decrease in CH_4 emissions. Increases in precipitation, however, can greatly increase the area of freshwater systems. Where these waters inundate areas with organic soils or above-ground biomass—such as occurs seasonally in the Amazon basin (126) or in the creation of large reservoirs (127)—significant enhancements in CH_4 production and emission may occur.

An increase in the intensity of precipitation events is also likely to increase the amounts of allochthonous organic matter and macronutrients that many freshwater systems receive via leaching and runoff (41). Such additional inputs may then serve to fuel eutrophication, methanogenesis, and net increases in CH_4 emissions. Similarly, CO_2 enrichment and changes in plant biomass across catchments may serve to enhance carbon inputs to drainage waters and the lakes and rivers they feed. A trend of increasing dissolved organic carbon (DOC) inputs to freshwater systems in North America and Northern Europe has already been reported, with a prediction that DOC production in some catchments could rise by 20% in response to doubling of CO_2 (128).

The sheer diversity of freshwater systems around the world inevitably makes any kind of robust estimation of CH_4 fluxes difficult. There remains a paucity of direct CH_4 measurements, especially those that encompass ebullition and plant-mediated fluxes alongside diffusion losses (120). As such, quantitative projections of future CH_4 emissions from this source are even more challenging. Uncertainties around the impacts of environmental change, and in particular climate change, on freshwater CH_4 fluxes in the twenty-first century, are compounded by changing land use and catchment management practices (129). The only certainty is that CH_4 emissions from some freshwater systems will increase, whereas in others they will decrease, with the overall climate change interaction likely to be a weak positive feedback effect at a global scale (**Table 2**).

5. GLOBAL CHANGE AND ANTHROPOGENIC METHANE

5.1. Livestock Methane Emissions and Drivers

Methane emissions arise from livestock in two principal ways; enteric CH_4 arising as a by-product of the breakdown of ingested feed and CH_4 from animal wastes arising from the anaerobic

fermentation of stored and pasture-deposited animal urine and feces. Enteric CH_4 arises mainly from ruminant livestock (cattle, buffalo, sheep, and goats), whereas CH_4 emissions from animal wastes arise from all types of livestock, although dairy cattle and pigs are the most important.

Enteric CH_4 is produced under anaerobic conditions by a diverse community of methanogenic archaea using mainly hydrogen and CO_2 as substrates, although smaller amounts are produced using formate and methyl compounds as alternatives to hydrogen (130). The biggest single determinant of how much CH_4 an individual ruminant animal produces is the quantity of feed it eats, although the type and chemical characteristics of ingested feed also have an influence (131, 132). The animal itself can also influence the quantity of CH_4 it produces via host effects on digestive physiology and the makeup of the resident microbial population (130, 132–135).

Methane production from animal wastes is also an anaerobic microbial process and occurs mostly when animal wastes are stored. Lesser amounts are produced from wastes deposited directly onto the ground. Manure type (e.g., wet versus dry), storage method, storage duration, manure chemical composition, and temperature all influence the quantity of manure produced per unit of substrate.

Estimates of the quantity of CH_4 currently produced globally by livestock vary with the method of estimation and are currently in the range 90–120 Tg CH_4 year^{-1} (22, 136–138). This is 6–7% of total global anthropogenic CO_2-e emissions and $\sim$35% of total anthropogenic CH_4 emissions. Enteric CH_4 emissions comprise approximately 90% of all livestock-derived CH_4 emissions, with cattle (77%) being the dominant source (136). Manure management emissions are dominated by pigs ($\sim$42%) and cattle ($\sim$41%) (136).

Livestock CH_4 emissions have risen by just over 50% in the past 50 years with the largest increase occurring in Africa, Asia, and the Americas. Europe is the only region where emissions have decreased. An analysis by latitude of changes between 2000 and 2013 (137) suggests that the largest increases have occurred between latitudes 30°N and 30°S driven by increases in Central America, East Africa, and Brazil.

Forecasting future livestock emissions is highly uncertain as they will be influenced by the demand for livestock products. This in turn is driven by population growth, dietary preferences, the successful implementation of mitigation practices, and to a minor extent climate change itself, although studies exploring climate change impacts on livestock and their emissions remain limited (139–141). There is currently a strong consensus that CH_4 emissions will continue to increase under BAU scenarios (136, 139, 142, 143). The United Nations Food and Agriculture Organization estimates are that, by 2030, global livestock CH_4 emissions will be 12% higher than current emissions with the largest increases occurring in the Asian region (138). Europe is the only region where emissions are not forecasted to rise.

Given that there is considerable variability in emissions per unit of product within and between systems of production, there remains considerable scope for reductions in emissions intensity into the future and for increased efficiency of production to be an economically viable method of constraining absolute emissions below BAU scenarios (136, 144).

The high-level ways in which climate change could have an impact on future livestock CH_4 emissions have been well described (145). However, few studies have attempted to quantify how the impacts of, and adaptation to, changes in temperature, rainfall, and CO_2 concentration could modify emissions projections that are based primarily on population growth and increased per capita consumption of milk and meat.

With respect to enteric fermentation, climate change will not impact the fermentation process itself, given that internal body temperatures are well regulated. Elevated temperatures will, however, influence CH_4 emissions from livestock wastes as ambient temperatures do affect the

quantity of CH_4 produced; the temperature effect changes little once annual average temperatures reach 20°C (146), meaning that the largest impacts will be at higher latitudes.

The principle effects of climate change on livestock CH_4 emissions will be mediated through changes in the quantity and quality of feed available, heat stress, and the incidence of pests and diseases (147). These effects will work at the individual and herd/flock level.

With regard to feed supply, the impact on both crops and grasslands needs to be considered. In aggregate, the impact of climate change on grassland and crop production is generally small once the CO_2 fertilization effect is considered, although this hides large regional and local variation and uncertainties (147, 148). Grassland productivity may in fact increase under climate change, particularly at higher latitudes (148, 149) and altitudes (147).

Close to 50% of the feed consumed by livestock is grass, and the nutritive value of grass is influenced by temperature (150). Lower nutritive value (e.g., high fiber content) tends to increase CH_4 production per unit of feed eaten (131, 151), and more feed needs to be consumed to reach a given level of production. Taken together, these effects will increase emissions from both enteric and waste sources. The combined effect has not been globally quantified, although the impact of a reduction in herbage quality at a constant intake has been estimated to be an increase in CH_4 emissions of 0.9% for every 1°C increase in temperature (150).

Livestock are widely distributed globally and are therefore well adapted climatically. However, they are directly influenced by temperature. Higher temperatures increase the quantity of energy required to meet a given level of production and simultaneously reduce feed intake (152). Reproductive performance is also adversely affected by heat stress (153). Increased mortality in livestock has also been linked to heat stress (154). Changes in temperature and rainfall may also influence the type and severity of pests and diseases that affect livestock. Collectively, these effects are likely to reduce the productivity of livestock systems and thus result in increasing emissions intensity. The potential net effect of temperature change on future CH_4 emissions has not so far been quantified in any systematic way. Reductions in forage quality, heat-induced increases in energy demand, impaired reproductive function, and increased fermentation rates in stored animal wastes all have the potential to increase emissions. However, given the adaptability of livestock production systems, these drivers of CH_4 emissions are likely to be small compared with demand-induced increases in animal numbers, individual animal productivity, and potential constraints due to competition for land.

5.2. Cropland Methane and Global Change

As described in Section 3.2, aerobic mineral cropland soils have a much lower CH_4 sink strength than undisturbed or forest soils (63). The lower measured oxidation rates are attributed to soil disturbance and nitrogen fertilizer use (155), which suppress the soil methanotroph community (56). Historical land use change and a move to more intensive cropping would therefore be expected to have decreased the CH_4 sink strength of soils.

When soils are deliberately flooded for rice cultivation, they can become very large global sources of CH_4, with rice paddy emissions accounting for 33–40 Tg CH_4 year^{-1} (22), a major anthropogenic emission source. The global cropland CH_4 emission profile of croplands is dominated by rice production, with 90% of emissions from tropical Asia, >50% from just China and India (156), and a small contribution to the global CH_4 soil sink from other croplands. Changes in rice management have the potential to significantly decrease paddy rice soil CH_4 emissions, with mid-season drainage now becoming prevalent in many rice-growing areas (144, 157). Other mitigation measures include changed fertilizer practices and tillage/residue management (144; see also Section 6).

As for mineral soils under natural vegetation, warming might decrease emissions from otherwise waterlogged mineral soils in temperate regions if it dried the soils through increased evapotranspiration, although croplands are less likely to become waterlogged than pastures. Given that global crop productivity is expected to be adversely affected by climate change at the global level (158), carbon returns to the soil could also decline thereby providing less substrate for methanogens, but the overall effect is not known. Ciais et al. (22) report that soil CH_4 oxidation is projected to increase under climate change due to rising atmospheric CH_4 concentrations, increased soil temperature and decreased soil moisture (69, 70).

Given that croplands are usually fertilized with nitrogen, one would expect changes in nitrogen deposition to have smaller effects on croplands compared to soils under natural vegetation, where N deposition will form the largest N input to the system. Although CO_2 fertilization might increase cropland productivity to some extent, at the global level, cropland productivity is projected to decline in the future under the combined impacts of climate change and increased atmospheric CO_2 concentration (i.e., climate change impacts will outweigh those of CO_2 fertilization). The impacts on future CH_4 fluxes arising from these complex interactions in croplands are not known.

5.3. Energy-Related Methane and Global Change

Energy-related CH_4 emissions are currently dominated by fugitive emissions during coal, oil, and gas extraction (159). The increase in shale gas exploitation over the past decade has added to such fugitive emissions, with high loss rates reported for some operations in the United States (160). Downstream CH_4 emissions can occur during processing (e.g., coal pulverization) and via leaks in the gas transmission network (161). The latter may be particularly sensitive to climate change due to thaw of permafrost soils and consequent fracturing of gas pipelines at high latitudes (162).

More widely, the retreat of sea and land ice in the Arctic as a result of warming is likely to result in increased exploitation of fossil fuel resources across the region (see, e.g., 163, 164). Such exploitation will inevitably lead to additional fugitive CH_4 emissions during extraction and transmission. A fast-emerging issue is the potential for large-scale exploitation of marine methane clathrates (CH_4 molecules enclosed in a frozen lattice of water molecules) found in continental shelf sediments. It is estimated that such clathrates constitute approximately 50% of all hydrocarbon resources, with an estimated 500–2,500 Pg C in the form of marine methane clathrates globally (82).

To date, extraction of these large CH_4 stocks has been uneconomic, but technological advances mean that commercial exploitation is now a real possibility (165–167). As discussed previously (Section 4.1), the stability of CH_4 clathrate deposits may already be at risk from climate change. Accidental or deliberate disturbance, due to fossil fuel extraction, has the potential for extremely high fugitive CH_4 losses to the atmosphere (168).

For hydroelectric power, reservoir creation and the inundation of organic soils and above-ground biomass is an established source of anthropogenic CH_4 emissions (41). The expansion of large-scale hydroelectric reservoirs may therefore increase such CH_4 emissions. Globally, hydroelectric reservoirs are estimated to emit approximately 3 Tg C as CH_4 each year, with the highest emissions occurring in tropical regions such as the Amazon basin (169).

As with natural freshwater systems, changes in precipitation, temperature, and plant growth (e.g., due to the CO_2 fertilization effect) can each affect CH_4 emissions from hydroelectric reservoirs (170). Projecting future emissions from these reservoirs is difficult, given uncertainties in current estimates and the impacts that catchment land use and climate change may have. Nevertheless, increasing temperatures are likely to enhance CH_4 production and emissions at many sites. More intense rainfall and accelerated primary production may also combine to increase allochthonous C and nutrient inputs, and thereby further fuel reservoir methanogenesis.

Table 3   "Likely" response of CH_4 fluxes from major anthropogenic sources in response to global change in the twenty-first century[a]

Source	Temperature response	Precipitation response	CO_2 response	Overall
Agriculture (direct)[b]	→	→	→	→
Agriculture (indirect)[c]	↗	↗	→	↗
Energy (fugitive)[d]	↗	→	→	↗
Energy (hydroelectric)	↗	→	↗	↗

[a]Responses represent global average response unless otherwise specified.

[b]Direct agriculture here refers to direct impacts of global change on CH_4 emissions from livestock, crop production, and agricultural wastes.

[c]Indirect agriculture here refers to global change impacts on loss and waste in the food supply chain that result in upstream changes in agricultural CH_4 emissions.

[d]Fugitive sources here include existing fossil fuel extraction and transport, as well as potential disturbance and exploitation of methane clathrate deposits.

Current estimates of anthropogenic CH_4 emissions from energy-related biomass (including some nonenergy biomass burning) are approximately 35 Tg CH_4 year^{-1} (22). The wide range of biomass types used for energy—from solid hardwoods and softwood pellets, to charcoal and peat, to rice straw and manure—together with a multitude of combustion methods, means such estimates are highly uncertain. As with wildfire CH_4 emissions, changes in biomass characteristics, such as moisture content, in response to environmental change may alter CH_4 emissions intensity. However, such changes in fuel quality are likely to be compensated for by improvements in combustion technology (e.g., clean cook stoves, cleaner-burn biomass-to-energy plants) (171). As such, this CH_4 source is likely to decrease in the twenty-first century even if total biomass volume burned increases (**Table 3**).

6. METHANE IN CLIMATE CHANGE MITIGATION

As underlying drivers of CH_4 emissions, such as energy and food demand, intensify in the twenty-first century, BAU anthropogenic CH_4 emissions are likely to rise further (48). Between 2010 and 2030, emissions from the energy sector are projected to increase by 25%, to approximately 130 Tg CH_4 year^{-1}. Similarly, a >15% increase in CH_4 emissions from the agriculture sector is expected under a BAU scenario by 2030, with expanding livestock production being the primary cause.

A sustained push toward low-CH_4 strategies in these key sectors is therefore vital if global CO_2 abatement policies aimed at avoiding dangerous climate change are not to be undermined. The role to arrest growth and then make deep cuts in global CH_4 emissions is substantial (**Figure 4**).

For the energy sector, there is significant potential for CH_4 abatement both in coal mining and in the oil and gas sector. For coal, strategies such as premine draining, postmine boreholes, and ventilation air methane (VAM) oxidation could more than halve CH_4 emissions relative to BAU in 2030 (reduction of 22 Tg CH_4 year^{-1}) at a cost of <\$100 per metric ton CO_2-e. In the oil and gas sector, reductions in approaching 50% compared to BAU in 2020 are also possible. Reduced emissions completions for shale gas, equipment maintenance and upgrading, and improved inspection regimes for leaks, could help to yield an overall cut in oil and gas sector emissions of approximately 50 Tg CH_4 year^{-1} by 2030.

For CH_4 arising from waste, the greatest potential for mitigation at a global scale is centered on landfill. Here, a combination of landfill gas collection for energy generation or flaring, and greater diversion of waste to recycling and reuse, could reduce CH_4 emissions by more than 40% (a reduction of 19 Tg CH_4 year^{-1} relative to BAU in 2030) at a cost of <\$100 per metric ton CO_2-e.
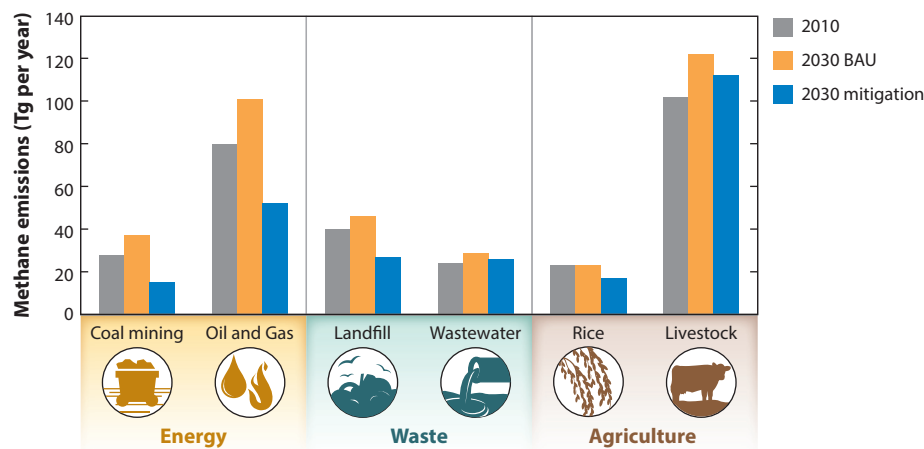
Figure 4

Global methane emissions and potential for mitigation across key sectors from 2010 to 2030. (48). Estimated emissions are in Tg CH_4 year^{-1}. Data are derived from estimates of CO_2-e by dividing by a GWP of 21. Red bars denote BAU emissions. Green bars denote emissions after all mitigation strategies with an abatement cost of <$100 per metric ton CO_2-e are implemented. These include drainage of coal mine CH_4, landfill CH_4 collection, improved livestock health and diet, and manure management. Projected CH_4 emissions for agriculture have been disaggregated from other non-CO_2 emissions based on an assumption that CH_4 comprises 60% of non-CO_2 emissions from manure management and 65% of non-CO_2 emissions from rice cultivation (48). Abbreviations: BAU, business-as-usual; GWP, global warming potential.

Finally, for the agriculture sector, strategies addressing enteric fermentation and manure management emissions in livestock production could deliver cuts of >10 Tg CH_4 year^{-1}, and improved water and harvest residue management also have the potential for significant reductions in global CH_4 emissions from rice cultivation. Food supply chain and demand-side interventions that induce production-phase CH_4 mitigation, such as reduced supply chain loss and waste, also have an important role to play in this sector (172).

Overall, emission of >100 Tg CH_4 year^{-1} could be avoided via such CH_4 abatement strategies—equivalent to a 30% cut by 2030 relative to a BAU (**Figure 4**). This is at an estimated cost of <$100 per metric ton of CO_2-e. If maximum technical abatement potential is included this figure rises to near 40% (48).

The greenhouse gas emission reductions proposed by all nations under the Paris Climate Change Agreement (termed Nationally Determined Contributions or NDCs) encompass both long-lived greenhouse gases, such as CO_2, and short-lived climate pollutants such as CH_4. However, identifying specific CH_4 mitigation strategies within such NDCs is difficult, as planned emission reductions are usually referred to in terms of CO_2 equivalents (173). For some strategies, such as drainage management in rice agriculture, CH_4 mitigation is the tacit focus, whereas for strategies such as more efficient biomass burning a mix of long- and short-lived climate pollutants is combined.

The importance of addressing CH_4 and other short-lived climate pollutants as part of wider climate change mitigation efforts has been debated for many years (174–176). Substantial cuts in CH_4 emissions can have a relatively quick impact on the extent of warming compared to CO_2 reductions. However, over longer timescales (i.e., the late twenty-first century and beyond) reductions in CO_2 have a much greater effect on global temperatures.

In fact, aggressive and sustained reductions in both long- and short-lived climate pollutants are now required. The goal of the Paris Agreement is to limit global temperature rise in the twenty-first century to well below 2°C, while simultaneously promoting sustainable development and poverty reduction (173). Regarding the former, sustained CH_4 mitigation would complement CO_2 reductions and help bring the "ambition target" of 1.5°C within reach. Regarding the latter, rapid, large-scale reductions in CH_4 emissions could help ensure that near-term climate change impacts are moderated and that positive feedback responses—including many of those we discussed in this article—are limited.

SUMMARY POINTS

1. Atmospheric methane concentrations continue to increase.

2. Limitations of surface observation networks and inventory estimates make robust attribution of interannual variations difficult.

3. Global change, especially climate change, is a key determinant of global methane fluxes.

4. Climate change and carbon dioxide enrichment in the twenty-first century are likely to enhance methane emissions from large natural sources, such as wetlands and aquatic systems.

5. Climate change and carbon dioxide enrichment in the twenty-first century are likely to enhance methane emissions from some anthropogenic sources, such as hydroelectric energy generation.

6. Commercial exploitation of methane clathrate deposits has the potential to induce very large fugitive emissions.

7. There exists great potential for further, cost-effective (<$100 per metric ton CO_2-e) climate change mitigation through reduced methane emissions in the energy, agriculture, and waste sectors.

FUTURE ISSUES

1. Enhanced surface observation networks, emissions inventories, and remote sensing products can improve methane source attribution and emissions management at national and subnational scales.

2. Integrating the response of global wetland methane fluxes to future climate change with that of local-scale human activities, such as wetland drainage and land use change, poses a significant modeling challenge.

3. Warming of the Arctic, coupled with technological developments in methane extraction, risks large-scale exploitation of methane clathrates and associated fugitive emissions to the atmosphere.

4. As methane emissions from the agriculture sector are dominated by ruminant livestock, future changes in population and dietary preference may radically alter national and global emissions from this source.

5. More assessment is required on the indirect impacts of global change on methane emissions via food loss and waste (e.g., increased food spoilage), ice retreat (e.g., increased accessibility to fossil methane deposits), and vegetation change (e.g., altered emergent vegetation in wetlands).

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LITERATURE CITED

1. Reay DS, Smith KA, Hewitt CN. 2007. Methane: importance, sources and sinks. In *Greenhouse Gas Sinks*, ed. DS Reay, CN Hewitt, KA Grace, pp. 143–51. Oxfordshire, UK: CABI Publ.

2. Wuebbles DJ, Hayhoe K. 2002. Atmospheric methane and global change. *Earth-Sci. Rev.* 57:177–210

3. Dlugokencky E, Houweling S, Bruhwiler L, Masarie K, Lang P, et al. 2003. Atmospheric methane levels off: Temporary pause or a new steady-state? *Geophys. Res. Lett.* 30:19. **https://doi.org/10.1029/2003GL018126**

4. Kirschke S, Bousquet P, Ciais P, Saunois M, Canadell JG, et al. 2013. Three decades of global methane sources and sinks. *Nat. Geosci.* 6:813–23

5. Nisbet EG, Dlugokencky EJ, Bousquet P. 2014. Methane on the rise—again. *Science* 343:493–95

6. Saunois M, Jackson RB, Bousquet P, Poulter B, Canadell JG. 2016. The growing role of methane in anthropogenic climate change. *Environ. Res. Lett.* 11:120207

7. Turner AJ, Frankenberg C, Wennberg PO, Jacob DJ. 2017. Ambiguity in the causes for decadal trends in atmospheric methane and hydroxyl. *PNAS* 114:5367–72

8. Myhre G, Shindell D, Bréon F, Collins W, Fuglestvedt J, et al. 2013. Anthropogenic and natural radiative forcing. See Ref. 9, pp. 659–740

9. Intergov. Panel Clim. Change. 2013. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, UK: Cambridge Univ. Press

10. Lelieveld J, Crutzen PJ, Dentener FJ. 1998. Changing concentration, lifetime and climate forcing of atmospheric methane. *Tellus B* 50:128–50

11. Intergov. Panel Clim. Change. 1990. *Climate Change 1990: The Scientific Basis. Contribution of WGI to the Second Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, UK: Cambridge Univ. Press

12. Rigby M, Montzka SA, Prinn RG, White JW, Young D, et al. 2017. Role of atmospheric oxidation in recent methane growth. *PNAS* 114:5373–77

13. Holmes CD, Prather MJ, Søvde O, Myhre G. 2013. Future methane, hydroxyl, and their uncertainties: key climate and emission parameters for future predictions. *Atmos. Chem. Phys.* 13:285–302

14. Shindell DT, Faluvegi G, Koch DM, Schmidt GA, Unger N, Bauer SE. 2009. Improved attribution of climate forcing to emissions. *Science* 326:716–18

15. Spahni R, Chappellaz J, Stocker TF, Loulergue L, Hausammann G, et al. 2005. Atmospheric methane and nitrous oxide of the late Pleistocene from Antarctic ice cores. *Science* 310:1317–21

16. Loulergue L, Schilt A, Spahni R, Masson-Delmotte V, Blunier T, et al. 2008. Orbital and millennial-scale features of atmospheric CH_4 over the past 800,000 years. *Nature* 453:383–86

17. Zhu Q, Peng C, Ciais P, Jiang H, Liu J, et al. 2017. Inter-annual variation in methane emissions from tropical wetlands triggered by repeated El Niño southern oscillation. *Glob. Change Biol.* 23:4706–16

18. NOAA. 2017. *Multivariate ENSO Index (MEI)*. Earth Syst. Res. Lab., NOAA. **https://www.esrl.noaa.gov/psd/enso/mei/**

19. Singarayer JS, Valdes PJ, Friedlingstein P, Nelson S, Beerling DJ. 2011. Late Holocene methane rise caused by orbitally controlled increase in tropical sources. *Nature* 470:82–85

20. Kennett JP, Cannariato KG, Hendy IL, Behl RJ. 2003. *Methane Hydrates in Quaternary Climate Change: The Clathrate Gun Hypothesis*. Washington, DC: Am. Geophys. Union

21. Maslin M, Owen M, Day S, Long D. 2004. Linking continental-slope failures and climate change: testing the clathrate gun hypothesis. *Geology* 32:53–56

22. Ciais P, Sabine C, Bala G, Bopp L, Brovkin V, et al. 2013. Carbon and other biogeochemical cycles. See Ref. 9, pp. 465–570

23. World Meteorol. Organ. (WMO). 2017. *The state of greenhouse gases in the atmosphere based on global observations through 2016*. WMO Greenhouse Gas Bull. 13, WMO, Geneva

24. Dlugokencky E, Bruhwiler L, White J, Emmons L, Novelli PC, et al. 2009. Observational constraints on recent increases in the atmospheric CH_4 burden. *Geophys. Res. Lett.* 36. **https://doi.org/10.1029/2009GL039780**

25. Poulter B, Bousquet P, Canadell JG, Ciais P, Peregon A, et al. 2017. Global wetland contribution to 2000–2012 atmospheric methane growth rate dynamics. *Environ. Res. Lett.* 12:094013

26. Worden JR, Bloom AA, Pandey S, Jiang Z, Worden HM, et al. 2017. Reduced biomass burning emissions reconcile conflicting estimates of the post-2006 atmospheric methane budget. *Nat. Commun.* 8:2227

27. Dlugokencky EJ, Nisbet EG, Fisher R, Lowry D. 2011. Global atmospheric methane: budget, changes and dangers. *Philos. Trans. R. Soc. Lond. A* 369:2058–72

28. Riley WJ, Subin ZM, Lawrence DM, Swenson SC, Torn MS, et al. 2011. Barriers to predicting changes in global terrestrial methane fluxes: analysis using CLM4ME, a methane biogeochemistry model integrated in CESM. *Biogeosciences* 8:1925–53

29. Dunfield PF. 2007. The soil methane sink. In *Greenhouse Gas Sinks*, ed. D Reay, CN Hewitt, KA Smith, J Grace, pp. 152–70. Oxfordshire, UK: CABI Publ.

30. Reay D, Smith P, Van Amstel A, eds. 2010. *Methane and Climate Change*. London: Routledge

31. Worden H, Deeter M, Frankenberg C, George M, Nichitiu F, et al. 2013. Decadal record of satellite carbon monoxide observations. *Atmos. Chem. Phys.* 13:837–50

32. Fry M, Schwarzkopf M, Adelman Z, West J. 2014. Air quality and radiative forcing impacts of anthropogenic volatile organic compound emissions from ten world regions. *Atmos. Chem. Phys.* 14:523–35

33. Naik V, Voulgarakis A, Fiore AM, Horowitz L, Lamarque J-F, et al. 2013. Preindustrial to present-day changes in tropospheric hydroxyl radical and methane lifetime from the Atmospheric Chemistry and Climate Model Intercomparison Project (ACCMIP). *Atmos. Chem. Phys.* 13:5277–98

34. Bodelier PL, Laanbroek HJ. 2004. Nitrogen as a regulatory factor of methane oxidation in soils and sediments. *FEMS Microbiol. Ecol.* 47:265–77

35. Hütsch BW, Webster CP, Powlson DS. 1994. Methane oxidation in soil as affected by land use, soil pH and N fertilization. *Soil Biol. Biochem.* 26:1613–22

36. Whalen S, Reeburgh W. 1990. Consumption of atmospheric methane by tundra soils. *Nature* 346:160–62

37. Saunois M, Bousquet P, Poulter B, Peregon A, Ciais P, et al. 2016. The global methane budget 2000–2012. *Earth Syst. Sci. Data* 8:697–751

38. Melton J, Wania R, Hodson E, Poulter B, Ringeval B, et al. 2013. Present state of global wetland extent and wetland methane modelling: conclusions from a model inter-comparison project (WETCHIMP). *Biogeosciences* 10:753–88

39. Bousquet P, Ciais P, Miller J, Dlugokencky E, Hauglustaine D, et al. 2006. Contribution of anthropogenic and natural sources to atmospheric methane variability. *Nature* 443:439–43

40. Bloom AA, Palmer PI, Fraser A, Reay DS, Frankenberg C. 2010. Large-scale controls of methanogenesis inferred from methane and gravity spaceborne data. *Science* 327:322–25

41. Tranvik LJ, Downing JA, Cotner JB, Loiselle SA, Striegl RG, et al. 2009. Lakes and reservoirs as regulators of carbon cycling and climate. *Limnol. Oceanogr.* 54:2298–314

42. Archer D, Buffett B, Brovkin V. 2009. Ocean methane hydrates as a slow tipping point in the global carbon cycle. *PNAS* 106:20596–601

43. Keppler F, Hamilton JT, Braß M, Röckmann T. 2006. Methane emissions from terrestrial plants under aerobic conditions. *Nature* 439:187–91

44. McLeod AR, Fry SC, Loake GJ, Messenger DJ, Reay DS, et al. 2008. Ultraviolet radiation drives methane emissions from terrestrial plant pectins. *New Phytol.* 180:124–32

45. Bloom AA, Lee-Taylor J, Madronich S, Messenger DJ, Palmer PI, et al. 2010. Global methane emission estimates from ultraviolet irradiation of terrestrial plant foliage. *New Phytol.* 187:417–25

46. James S, James C. 2010. The food cold-chain and climate change. *Food Res. Int.* 43:1944–56

47. Porter S, Reay D. 2015. Addressing food supply chain and consumption inefficiencies: potential for climate change mitigation. *Reg. Environ. Change* 16:2279–90

48. U.S. Environmental Protection Agency (EPA). 2017. *Global mitigation of non-CO$_2$ greenhouse gases: 2010– 2030*. Rep. EPA-430-S-14–001, Off. Atmos. Progr., EPA, Washington, DC

49. Chae K, Jang A, Yim S, Kim IS. 2008. The effects of digestion temperature and temperature shock on the biogas yields from the mesophilic anaerobic digestion of swine manure. *Bioresour. Technol.* 99:1–6

50. Elsgaard L, Olsen AB, Petersen SO. 2016. Temperature response of methane production in liquid manures and co-digestates. *Sci. Total Environ.* 539:78–84

51. Husted S. 1994. Seasonal variation in methane emission from stored slurry and solid manures. *J. Environ. Q.* 23:585–92

52. Hugelius G, Tarnocai C, Broll G, Canadell JG, Kuhry P, Swanson DK. 2013. The Northern Circumpolar Soil Carbon Database: spatially distributed datasets of soil coverage and soil carbon storage in the northern permafrost regions. *Earth Syst. Sci. Data* 5:3–13

53. Meng L, Hess PG, Mahowald NM, Yavitt JB, Riley WJ, et al. 2012. Sensitivity of wetland methane emissions to model assumptions: application and model testing against site observations. *Biogeosciences* 9:2793–819

54. Gedney N, Cox P, Huntingford C. 2004. Climate feedback from wetland methane emissions. *Geophys. Res. Lett.* 31:L20503

55. Intergov. Panel Clim. Change. 2001. *Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, UK: Cambridge Univ. Press

56. Singh BK, Bardgett RD, Smith P, Reay DS. 2010. Microorganisms and climate change: terrestrial feedbacks and mitigation options. *Nat. Rev. Microbiol.* 8:779–90

57. Paudel R, Mahowald NM, Hess PG, Meng L, Riley WJ. 2016. Attribution of changes in global wetland methane emissions from pre-industrial to present using CLM4.5-BGC. *Environ. Res. Lett.* 11:034020

58. Zhu QA, Peng CH, Liu JX, Jiang H, Fang XQ, et al. 2016. Climate-driven increase of natural wetland methane emissions offset by human-induced wetland reduction in China over the past three decades. *Sci. Rep.* 6:38020

59. Jauhiainen J, Kerojoki O, Silvennoinen H, Limin S, Vasander H. 2014. Heterotrophic respiration in drained tropical peat is greatly affected by temperature—a passive ecosystem cooling experiment. *Environ. Res. Lett.* 9:105013

60. Zhang Z, Zimmermann NE, Stenke A, Li X, Hodson EL, et al. 2017. Emerging role of wetland methane emissions in driving 21st century climate change. *PNAS* 114:9647–52

61. Watts JD, Kimball JS, Bartsch A, McDonald KC. 2014. Surface water inundation in the boreal-Arctic: potential impacts on regional methane emissions. *Environ. Res. Lett.* 9:075001

62. Dutaur L, Verchot LV. 2007. A global inventory of the soil CH$_4$ sink. *Glob. Biogeochem. Cycles* 21:GB4013

63. Tate KR. 2015. Soil methane oxidation and land-use change—from process to mitigation. *Soil Biol. Biochem.* 80:260–72

64. Le Mer J, Roger P. 2001. Production, oxidation, emission and consumption of methane by soils: a review. *Eur. J. Soil Biol.* 37:25–50

65. Zona D, Gioli B, Commane R, Lindaas J, Wofsy SC, et al. 2016. Cold season emissions dominate the Arctic tundra methane budget. *PNAS* 113:40–45

66. Tarnocai C, Canadell J, Schuur E, Kuhry P, Mazhitova G, Zimov S. 2009. Soil organic carbon pools in the northern circumpolar permafrost region. *Glob. Biogeochem. Cycles* 23:GB2023

67. Ho A, Erens H, Mujinya BB, Boeckx P, Baert G, et al. 2013. Termites facilitate methane oxidation and shape the methanotrophic community. *Appl. Environ. Microbiol.* 79:7234–40

68. Ojima D, Valentine D, Mosier A, Parton W, Schimel D. 1993. Effect of land use change on methane oxidation in temperate forest and grassland soils. *Chemosphere* 26:675–85

69. Curry CL. 2007. Modeling the soil consumption of atmospheric methane at the global scale. *Glob. Biogeochem. Cycles* 21:GB4012

70. Curry C. 2009. The consumption of atmospheric methane by soil in a simulated future climate. *Biogeosciences* 6:2355–67

71. Van Groenigen KJ, Osenberg CW, Hungate BA. 2011. Increased soil emissions of potent greenhouse gases under increased atmospheric CO_2. *Nature* 475:214–16

72. Koven CD, Ringeval B, Friedlingstein P, Ciais P, Cadule P, et al. 2011. Permafrost carbon-climate feedbacks accelerate global warming. *PNAS* 108:14769–74

73. Reay DS, Nedwell DB. 2004. Methane oxidation in temperate soils: effects of inorganic N. *Soil Biol. Biochem.* 36:2059–65

74. Liu Y, Stanturf J, Goodrick S. 2010. Trends in global wildfire potential in a changing climate. *Forest Ecol. Manag.* 259:685–97

75. Flannigan M, Cantin AS, De Groot WJ, Wotton M, Newbery A, Gowman LM. 2013. Global wildland fire season severity in the 21st century. *Forest Ecol. Manag.* 294:54–61

76. Andreae MO, Merlet P. 2001. Emission of trace gases and aerosols from biomass burning. *Glob. Biogeochem. Cycles* 15:955–66

77. Turetsky MR, Benscoter B, Page S, Rein G, Van Der Werf GR, Watts A. 2015. Global vulnerability of peatlands to fire and carbon loss. *Nat. Geosci.* 8:11–14

78. Knorr W, Jiang L, Arneth A. 2016. Climate, CO_2 and human population impacts on global wildfire emissions. *Biogeosciences* 13:267–82

79. McNamara NP, Gregg R, Oakley S, Stott A, Rahman MT, et al. 2015. Soil methane sink capacity response to a long-term wildfire chronosequence in northern Sweden. *PLOS ONE* 10:e0129892

80. Sullivan BW, Kolb TE, Hart SC, Kaye JP, Hungate BA, et al. 2011. Wildfire reduces carbon dioxide efflux and increases methane uptake in ponderosa pine forest soils of the southwestern USA. *Biogeochemistry* 104:251–65

81. EPA. 2010. *Methane and nitrous oxide emissions from natural sources*. Rep. EPA 430-R-10-001, Off. Atmos. Progr., US Environ. Protect. Agency

82. Milkov AV. 2004. Global estimates of hydrate-bound gas in marine sediments: How much is really out there? *Earth-Sci. Rev.* 66:183–97

83. Myhre CL, Ferré B, Platt SM, Silyakova A, Hermansen O, et al. 2016. Extensive release of methane from Arctic seabed west of Svalbard during summer 2014 does not influence the atmosphere. *Geophys. Res. Lett.* 43:4624–31

84. de Angelis MA, Lee C. 1994. Methane production during zooplankton grazing on marine phytoplankton. *Limnol. Oceanogr.* 39:1298–308

85. Repeta DJ, Ferrón S, Sosa OA, Johnson CG, Repeta LD, et al. 2016. Marine methane paradox explained by bacterial degradation of dissolved organic matter. *Nat. Geosci.* 9:884–87

86. Damm E, Helmke E, Thoms S, Schauer U, Nöthig E, et al. 2010. Methane production in aerobic oligotrophic surface water in the central Arctic Ocean. *Biogeosciences* 7:1099–108

87. Butler JH, Jones RD, Garber JH, Gordon LI. 1987. Seasonal distributions and turnover of reduced trace gases and hydroxylamine in Yaquina Bay, Oregon. *Geochim. Cosmochim. Acta* 51:697–706

88. Cotovicz LC, Knoppers BA, Brandini N, Poirier D, Costa Santos SJ, Abril G. 2016. Spatio-temporal variability of methane (CH_4) concentrations and diffusive fluxes from a tropical coastal embayment surrounded by a large urban area (Guanabara Bay, Rio de Janeiro, Brazil). *Limnol. Oceanogr.* 61:S235–52

89. Leifer I, Judd A. 2015. The UK22/4b blowout 20 years on: investigations of continuing methane emissions from sub-seabed to the atmosphere in a North Sea context. *Mar. Petroleum Geol.* 68:706–17

90. Kessler JD, Valentine DL, Redmond MC, Du M, Chan EW, et al. 2011. A persistent oxygen anomaly reveals the fate of spilled methane in the deep Gulf of Mexico. *Science* 331:312–15

91. Boetius A, Ravenschlag K, Schubert CJ, Rickert D, Widdel F, et al. 2000. A marine microbial consortium apparently mediating anaerobic oxidation of methane. *Nature* 407:623–26

92. Reeburgh WS. 2007. Oceanic methane biogeochemistry. *Chem. Rev.* 107:486–513

93. Nauw J, de Haas H, Rehder G. 2015. A review of oceanographic and meteorological controls on the North Sea circulation and hydrodynamics with a view to the fate of North Sea methane from well site 22/4b and other seabed sources. *Mar. Petroleum Geol.* 68:861–82

94. McGinnis DF, Greinert J, Artemov Y, Beaubien S, Wüest A. 2006. Fate of rising methane bubbles in stratified waters: How much methane reaches the atmosphere? *J. Geophys. Res. Oceans* 111:C09007

95. Solomon EA, Kastner M, MacDonald IR, Leifer I. 2009. Considerable methane fluxes to the atmosphere from hydrocarbon seeps in the Gulf of Mexico. *Nat. Geosci.* 2:561–65

96. Bange HW, Bartell U, Rapsomanikis S, Andreae MO. 1994. Methane in the Baltic and North Seas and a reassessment of the marine emissions of methane. *Glob. Biogeochem. Cycles* 8:465–80

97. Bakker DC, Bange HW, Gruber N, Johannessen T, Upstill-Goddard RC, et al. 2014. Air-sea interactions of natural long-lived greenhouse gases (CO_2, N_2O, CH_4) in a changing climate. In *Ocean-Atmosphere Interactions of Gases and Particles*, ed. PS Liss, MT Johnson, pp. 113–69. London: Springer

98. Borges AV, Champenois W, Gypens N, Delille B, Harlay J. 2016. Massive marine methane emissions from near-shore shallow coastal areas. *Sci. Rep.* 6:27908

99. Barnes J, Ramesh R, Purvaja R, Nirmal Rajkumar A, Senthil Kumar B, et al. 2006. Tidal dynamics and rainfall control N_2O and CH_4 emissions from a pristine mangrove creek. *Geophys. Res. Lett.* 33:L15405

100. Gelesh L, Marshall K, Boicourt W, Lapham L. 2016. Methane concentrations increase in bottom waters during summertime anoxia in the highly eutrophic estuary, Chesapeake Bay, USA. *Limnol. Oceanogr.* 61:S253–66

101. Naqvi S, Bange HW, Farías L, Monteiro P, Scranton M, Zhang J. 2010. Marine hypoxia/anoxia as a source of CH_4 and N_2O. *Biogeosciences* 7:2159–90

102. Rahmstorf S, Feulner G, Mann ME, Robinson A, Rutherford S, Schaffernicht EJ. 2015. Exceptional twentieth-century slowdown in Atlantic Ocean overturning circulation. *Nat. Clim. Change* 5:475–80

103. Capotondi A, Alexander MA, Bond NA, Curchitser EN, Scott JD. 2012. Enhanced upper ocean stratification with climate change in the CMIP3 models. *J. Geophys. Res. Oceans* 117:C04031

104. Kitidis V, Upstill-Goddard RC, Anderson LG. 2010. Methane and nitrous oxide in surface water along the North-West Passage, Arctic Ocean. *Mar. Chem.* 121:80–86

105. Kort E, Wofsy S, Daube B, Diao M, Elkins J, et al. 2012. Atmospheric observations of Arctic Ocean methane emissions up to 82° north. *Nat. Geosci.* 5:318–21

106. Maslanik J, Fowler C, Stroeve J, Drobot S, Zwally J, et al. 2007. A younger, thinner Arctic ice cover: increased potential for rapid, extensive sea-ice loss. *Geophys. Res. Lett.* 34:L24501

107. Loose B, McGillis WR, Perovich D, Zappa CJ, Schlosser P. 2014. A parameter model of gas exchange for the seasonal sea ice zone. *Ocean Sci.* 10:17–28

108. Thomson J, Rogers WE. 2014. Swell and sea in the emerging Arctic Ocean. *Geophys. Res. Lett.* 41:3136–40

109. Damm E, Rudels B, Schauer U, Mau S, Dieckmann G. 2015. Methane excess in Arctic surface water-triggered by sea ice formation and melting. *Sci. Rep.* 5:16179

110. Parmentier F-JW, Christensen TR, Sørensen LL, Rysgaard S, McGuire AD, et al. 2013. The impact of lower sea-ice extent on Arctic greenhouse-gas exchange. *Nat. Clim. Change* 3:195–202

111. Marín-Moreno H, Minshull TA, Westbrook GK, Sinha B, Sarkar S. 2013. The response of methane hydrate beneath the seabed offshore Svalbard to ocean warming during the next three centuries. *Geophys. Res. Lett.* 40:5159–63

112. Westbrook GK, Thatcher KE, Rohling EJ, Piotrowski AM, Pälike H, et al. 2009. Escape of methane gas from the seabed along the West Spitsbergen continental margin. *Geophys. Res. Lett.* 36:L15608

113. Shakhova N, Semiletov I, Salyuk A, Yusupov V, Kosmach D, Gustafsson Ö. 2010. Extensive methane venting to the atmosphere from sediments of the East Siberian Arctic Shelf. *Science* 327:1246–50

114. Dmitrenko IA, Kirillov SA, Tremblay LB, Kassens H, Anisimov OA, et al. 2011. Recent changes in shelf hydrography in the Siberian Arctic: potential for subsea permafrost instability. *J. Geophys. Res. Oceans* 116:C10027

115. Treude T, Boetius A, Knittel K, Wallmann K, Jørgensen BB. 2003. Anaerobic oxidation of methane above gas hydrates at Hydrate Ridge, NE Pacific Ocean. *Mar. Ecol. Prog. Ser.* 264:1–14

116. Ruppel C. 2011. Methane hydrates and contemporary climate change. *Nat. Educ. Knowl.* 3:29

117. Bange HW. 2006. Nitrous oxide and methane in European coastal waters. *Estuar. Coast. Shelf Sci.* 70:361–74

118. Skarke A, Ruppel C, Kodis M, Brothers D, Lobecker E. 2014. Widespread methane leakage from the sea floor on the northern US Atlantic margin. *Nat. Geosci.* 7:657–61

119. Knittel K, Boetius A. 2009. Anaerobic oxidation of methane: progress with an unknown process. *Annu. Rev. Microbiol.* 63:311–34

120. Bastviken D, Tranvik LJ, Downing JA, Crill PM, Enrich-Prast A. 2011. Freshwater methane emissions offset the continental carbon sink. *Science* 331:50

121. Upstill-Goddard RC, Barnes J. 2016. Methane emissions from UK estuaries: re-evaluating the estuarine source of tropospheric methane from Europe. *Mar. Chem.* 180:14–23

122. Tang KW, McGinnis DF, Frindte K, Brüchert V, Grossart H-P. 2014. Paradox reconsidered: methane oversaturation in well-oxygenated lake waters. *Limnol. Oceanogr*. 59:275–84

123. Bastviken D, Cole J, Pace M, Tranvik L. 2004. Methane emissions from lakes: dependence of lake characteristics, two regional assessments, and a global estimate. *Glob. Biogeochem. Cycles* 18:GB4009

124. Tan Z, Zhuang Q. 2015. Arctic lakes are continuous methane sources to the atmosphere under warming conditions. *Environ. Res. Lett.* 10:054016

125. Jankowski T, Livingstone DM, Bührer H, Forster R, Niederhauser P. 2006. Consequences of the 2003 European heat wave for lake temperature profiles, thermal stability, and hypolimnetic oxygen depletion: implications for a warmer world. *Limnol. Oceanogr.* 51:815–19

126. Sawakuchi HO, Bastviken D, Sawakuchi AO, Krusche AV, Ballester MV, Richey JE. 2014. Methane emissions from Amazonian rivers and their contribution to the global methane budget. *Glob. Change Biol.* 20:2829–40

127. Fearnside PM. 2016. Greenhouse gas emissions from Brazil's Amazonian hydroelectric dams. *Environ. Res. Lett.* 11:011002

128. Pagano T, Bida M, Kenny JE. 2014. Trends in levels of allochthonous dissolved organic carbon in natural water: a review of potential mechanisms under a changing climate. *Water* 6:2862–97

129. Anderson NJ, Bennion H, Lotter AF. 2014. Lake eutrophication and its implications for organic carbon sequestration in Europe. *Glob. Change Biol.* 20:2741–51

130. Tapio I, Snelling TJ, Strozzi F, Wallace RJ. 2017. The ruminal microbiome associated with methane emissions from ruminant livestock. *J. Anim. Sci. Biotechnol.* 8:7

131. Hristov AN, Oh J, Lee C, Meinen R, Montes F, et al. 2013. *Mitigation of greenhouse gas emissions in livestock production: a review of technical options for non-CO$_2$ emissions*, ed. PJ Gerber, B Henderson, HPS Makkar. FAO Animal Prod. Health Pap. 177, Rome

132. Negussie E, de Haas Y, Dehareng F, Dewhurst R, Dijkstra J, et al. 2017. Large-scale indirect measurements for enteric methane emissions in dairy cattle: a review of proxies and their potential for use in management and breeding decisions. *J. Dairy Sci.* 100:2433–53

133. Goopy JP, Donaldson A, Hegarty R, Vercoe PE, Haynes F, et al. 2014. Low-methane yield sheep have smaller rumens and shorter rumen retention time. *Br. J. Nutr.* 111:578–85

134. Pinares-Patiño C, Ebrahimi SH, McEwan J, Dodds K, Clark H, Luo D. 2011. Is rumen retention time implicated in sheep differences in methane emission. *Proc. N. Z. Soc. Anim. Prod.* 71:219–22

135. Shi W, Moon CD, Leahy SC, Kang D, Froula J, et al. 2014. Methane yield phenotypes linked to differential gene expression in the sheep rumen microbiome. *Genome Res*. 24:1517–25

136. Gerber PJ, Steinfeld H, Henderson B, Mottet A, Opio C, et al. 2013. *Tackling Climate Change Through Livestock: A Global Assessment of Emissions and Mitigation Opportunities*. Rome: Food Agric. Org. U.N.

137. Wolf J, Asrar GR, West TO. 2017. Revised methane emissions factors and spatially distributed annual carbon fluxes for global livestock. *Carbon Balance Manag*. 12:16

138. Food Agric. Org. U.N. 2016. FAOSTAT: food and agriculture data. *Food Agric. Org. Stat. Div. U.N.*, Rome. **http://www.fao.org/faostat/en/#home**

139. Steinfeld H, Gerber P, Wassenaar T, Castel V, Rosales M, de Haan C. 2006. *Livestock's Long Shadow: Environmental Issues and Options*. Rome: Food Agric. Org. U.N.

140. Thornton PK. 2010. Livestock production: recent trends, future prospects. *Philos. Trans. R. Soc. Lond. B* 365:2853–67

141. Clark M, Tilman D. 2017. Comparative analysis of environmental impacts of agricultural production systems, agricultural input efficiency, and food choice. *Environ. Res. Lett.* 12:111002

142. Havlík P, Valin H, Herrero M, Obersteiner M, Schmid E, et al. 2014. Climate change mitigation through livestock system transitions. *PNAS* 111:3709–14

143. Popp A, Calvin K, Fujimori S, Havlik P, Humpenöder F, et al. 2017. Land-use futures in the shared socio-economic pathways. *Glob. Environ. Change* 42:331–45

144. Smith P, Bustamante M, Ahammad H, Clark H, Dong H, et al. 2014. Agriculture, forestry and other land use (AFOLU). In *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, ed. O Edenhofer, R Pichs-Madruga, Y Sokona, E Farahani, S Kadner, et al. pp. 811–922. Cambridge, UK: Cambridge Univ.

145. Porter JR, Xie L, Challinor A, Cochrane K, Howden S, et al. 2014. Food security and food production systems. In *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, ed. CB Field, VR Barros, DJ Dokken, KJ Mach, MD Mastrandrea et al. pp. 1–82. Cambridge, UK: Cambridge Univ. Press

146. Intergov. Panel Clim. Change. 2006. *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. Prepared by the National Greenhouse Gas Inventories Programme, ed. S Eggleston, L Buendia, K Miwa, T Ngara, K Tanabe. Hayama, Jpn: IGES/IPCC

147. Thornton PK, Boone RB, Ramirez-Villegas J. 2015. *Climate change impacts on livestock*. CCAFS Work. Pap. 120. CGIAR Res. Program Clim. Change, Agric. Food Secur. (CCAFS). Copenhagen, Den.

148. Weindl I, Lotze-Campen H, Popp A, Müller C, Havlík P, et al. 2015. Livestock in a changing climate: production system transitions as an adaptation strategy for agriculture. *Environ. Res. Lett.* 10:094021

149. Chang J, Ciais P, Viovy N, Soussana J-F, Klumpp K, Sultan B. 2017. Future productivity and phenology changes in European grasslands for different warming levels: implications for grassland management and carbon balance. *Carbon Balance Manag.* 12:11

150. Lee MA, Davis AP, Chagunda MG, Manning P. 2017. Forage quality declines with rising temperatures, with implications for livestock production and methane emissions. *Biogeosciences* 14:1403–17

151. Knapp J, Laur G, Vadas P, Weiss W, Tricarico J. 2014. Enteric methane in dairy cattle production: quantifying the opportunities and impact of reducing emissions. *J. Dairy Sci.* 97:3231–61

152. Nardone A, Ronchi B, Lacetera N, Ranieri MS, Bernabucci U. 2010. Effects of climate changes on animal production and sustainability of livestock systems. *Livestock Sci.* 130:57–69

153. Rojas-Downing MM, Nejadhashemi AP, Harrigan T, Woznicki SA. 2017. Climate change and livestock: impacts, adaptation, and mitigation. *Climate Risk Manag.* 16:145–63

154. Sirohi S, Michaelowa A. 2007. Sufferer and cause: Indian livestock and climate change. *Clim. Change* 85:285–98

155. Saggar S, Tate K, Giltrap D, Singh J. 2008. Soil-atmosphere exchange of nitrous oxide and methane in New Zealand terrestrial ecosystems and their mitigation options: a review. *Plant Soil* 309:25–42

156. Yan X, Akiyama H, Yagi K, Akimoto H. 2009. Global estimations of the inventory and mitigation potential of methane emissions from rice cultivation conducted using the 2006 Intergovernmental Panel on Climate Change Guidelines. *Glob. Biogeochem. Cycles* 23:GB2002

157. Smith P, Martino D, Cai Z, Gwary D, Janzen H, et al. 2008. Greenhouse gas mitigation in agriculture. *Philos. Trans. R. Soc. Lond. B* 363:789–813

158. Zhao C, Liu B, Piao S, Wang X, Lobell DB, et al. 2017. Temperature increase reduces global yields of major crops in four independent estimates. *PNAS* 114:9326–31

159. Schwietzke S, Sherwood OA, Bruhwiler LM, Miller JB, Etiope G, et al. 2016. Upward revision of global fossil fuel methane emissions based on isotope database. *Nature* 538:88–91

160. Howarth RW, Santoro R, Ingraffea A. 2011. Methane and the greenhouse-gas footprint of natural gas from shale formations. *Clim. Change* 106:679

161. Patterson J. 2012. Exploitation of unconventional fossil fuels: enhanced greenhouse gas emissions. In *Greenhouse Gases-Emission, Measurement and Management*, ed. G Lui, pp. 147–70. London: InTech

162. Zhou J, Horsley D, Rothwell B. 2006. Application of strain-based design for pipelines in permafrost areas. In *ASME. International Pipeline Conference*, Vol. 1, IPC2006-10054, pp. 899–907. **http://proceedings.asmedigitalcollection.asme.org/proceeding.aspx?articleid=1596744**

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163. Pizzolato L, Stephen E, Howell L, Derksen C, Dawson J, Copland L. 2014. Changing sea ice conditions and marine transportation activity in Canadian Arctic waters between 1990 and 2012. *Clim. Change* 123:161–73

164. Gautier DL, Bird KJ, Charpentier RR, Grantz A, Houseknecht DW, et al. 2009. Assessment of undiscovered oil and gas in the Arctic. *Science* 324:1175–79

165. Martín M 2016. Nonconventional fossil energy sources: shale gas and methane hydrates. In *Alternative Energy Sources and Technologies*, ed. M Martín, pp. 3–16. Cham, Switz.: Springer

166. Chen L, Yamada H, Kanda Y, Sasaki H, Okajima J, et al. 2016. Study of methane hydrate as a future energy resource: low emission extraction and power generation. *Proc. IOP Conf. Ser.* 40:012074

167. Zhao J, Song Y, Lim X-L, Lam W-H. 2016. Opportunities and challenges of gas hydrate policies with consideration of environmental impacts. *Renew. Sustain. Energy Rev.* 70:875–85

168. Zhang Y, Zhai W-D. 2015. Shallow-ocean methane leakage and degassing to the atmosphere: triggered by offshore oil-gas and methane hydrate explorations. *Front. Mar. Sci.* 2:34

169. Barros N, Cole JJ, Tranvik LJ, Prairie YT, Bastviken D, et al. 2011. Carbon emission from hydroelectric reservoirs linked to reservoir age and latitude. *Nat. Geosci.* 4:593–96

170. DelSontro T, McGinnis DF, Sobek S, Ostrovsky I, Wehrli B. 2010. Extreme methane emissions from a Swiss hydropower reservoir: contribution from bubbling sediments. *Environ. Sci. Technol.* 44:2419–25

171. Jetter J, Zhao Y, Smith KR, Khan B, Yelverton T, et al. 2012. Pollutant emissions and energy efficiency under controlled conditions for household biomass cookstoves and implications for metrics useful in setting international test standards. *Environ. Sci. Technol.* 46:10827–34

172. Porter SD, Reay DS, Higgins P, Bomberg E. 2016. A half-century of production-phase greenhouse gas emissions from food loss & waste in the global food supply chain. *Sci. Total Environ.* 571:721–29

173. U.N. Environ. Programme (UNEP). 2017. *The Emissions Gap Report 2017*. Nairobi, Kenya: UNEP

174. Reilly J, Prinn R, Harnisch J, Fitzmaurice J, Jacoby H, et al. 1999. Multi-gas assessment of the Kyoto Protocol. *Nature* 401:549–55

175. Smith SJ, Mizrahi A. 2013. Near-term climate mitigation by short-lived forcers. *PNAS* 110:14202–6

176. Rogelj J, Schaeffer M, Meinshausen M, Shindell DT, Hare W, et al. 2014. Disentangling the effects of CO_2 and short-lived climate forcer mitigation. *PNAS* 111:16325–30

177. Boucher O, Friedlingstein P, Collins B, Shine KP. 2009. The indirect global warming potential and global temperature change potential due to methane oxidation. *Environ. Res. Lett.* 4:044007

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Our World in Data (2018) provides visualizations of global and national trends in key areas relevant to methane fluxes, including population, food, energy, and environment: **https://ourworldindata.org.**