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To cite this article: William J Collins et al 2018 Environ. Res. Lett. 13 054003

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Increased importance of methane reduction for a 1.5 degree target

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Keywords: carbon budgets, methane mitigation, non-CO2 greenhouse gases, climate targets

Supplementary material for this article is available online

Abstract

To understand the importance of methane on the levels of carbon emission reductions required to achieve temperature goals, a processed-based approach is necessary rather than reliance on the transient climate response to emissions. We show that plausible levels of methane (CH4) mitigation can make a substantial difference to the feasibility of achieving the Paris climate targets through increasing the allowable carbon emissions. This benefit is enhanced by the indirect effects of CH4 on ozone (O3). Here the differing effects of CH4 and CO2 on land carbon storage, including the effects of surface O3, lead to an additional increase in the allowable carbon emissions with CH4 mitigation. We find a simple robust relationship between the change in the 2100 CH4 concentration and the extra allowable cumulative carbon emissions between now and 2100 (0.27 ± 0.05 GtC per ppb CH4). This relationship is independent of modelled climate sensitivity and precise temperature target, although later mitigation of CH4 reduces its value and thus methane reduction effectiveness. Up to 12% of this increase in allowable emissions is due to the effect of surface ozone. We conclude early mitigation of CH4 emissions would significantly increase the feasibility of stabilising global warming below 1.5 °C, alongside having co-benefits for human and ecosystem health.

1. Introduction

Meeting the Paris temperature targets by reducing CO2 emissions alone represents a huge challenge, even for the more optimistic assessments of the allowable carbon budgets (Millar et al 2017). Most existing scenarios that avoid 2 °C of global warming, and almost all of those that avoid 1.5 °C, assume periods of negative global CO2 emissions in order to stay within the implied cumulative carbon budgets (Rogelj et al 2015a). This is via the widespread deployment of carbon dioxide removal (CDR) (Smith 2016) which might not be as effective as assumed (Harper et al 2018). Any additional options for mitigating greenhouse gases can therefore increase the feasibility of this challenge.

The transient climate response to emissions (TCRE) has proved useful in illustrating the dependence of temperature on the cumulative emissions of CO2. However care needs to be taken as the scenarios used in the IPCC 5th Assessment Report (AR5) (Pachauri et al 2014) assumed specific changes in non-CO2 agents such as aerosols and CH4. These calculations also did not include biogeochemical feedbacks that might affect the concentrations of the greenhouse gases such as changes in permafrost and wetlands (Comyn-Platt et al 2018). The relationship between cumulative carbon emissions and global temperature target will therefore depend crucially on the future mix of CO2 and non-CO2 agents which may differ significantly from that assumed in AR5. As a consequence cumulative carbon budgets are very
sensitive to assumptions in scenarios for non-CO₂ greenhouse gases (Rogelj et al 2015b).

Mitigation of anthropogenic CH₄ emissions leads to rapid decreases in its concentration, with an approximately 12 year response time. CH₄ mitigation therefore offers potential for rapidly reducing climate warming, either in the near-term to prevent a temporary exceedance of the 1.5 or 2.0 °C peak warming threshold, or later in the century to bring down temperatures after an overshoot of temperature to higher levels. A recent study (Stohl et al 2015) found that inexpensive or even cost negative CH₄ mitigation options could reduce 2050 temperatures by 0.25 °C.

Methane has a direct radiative forcing of climate. It is the second largest contributor to anthropogenic forcing over the historical period, and its atmospheric chemistry leads to O₃ and water vapour, themselves GHGs, adding to the forcing (Myhre et al 2013). Changes to atmospheric CH₄, O₃ and CO₂ will also affect the ocean and land carbon cycles, through direct warming effects (climate-carbon feedbacks), increasing the rates of plant respiration and decomposition of soil organic carbon. There are also indirect physiological effects of O₃, decreasing, and CO₂, increasing, plant productivity and hence carbon uptake (Sitch et al 2007, Collins et al 2010, Sitch et al 2008). These carbon-cycle effects are typically included in calculations of the effects of CO₂ emissions, but are currently ignored when calculating the CO₂-equivalence of non-CO₂ gases such as CH₄ (MacDougall et al 2013). Recent studies (Collins et al 2013, Gasser et al 2017) estimated that the climate-carbon cycle feedbacks increase the temperature impacts of CH₄ by around 20% on 100 year timescales.

As a result of these typically-neglected effects, it has been argued that the total carbon budget for stabilization of the climate at about 2 °C might be much more sensitive to the atmospheric concentration of CH₄ than heretofore expected (Cox and Jeffery 2010). This is likely to be even more so for a 1.5 °C target. This is because the impact on land carbon storage arising from a change in radiative forcing due to mitigation of CO₂ differs significantly from the impact of a similar non-CO₂ radiative forcing mitigation (Huntingford et al 2011). When including the damaging effects of surface O₃, reductions in the emissions of CH₄ have the potential to significantly increase land carbon storage.

2. Methods

2.1. IMOGEN-JULES

To understand the potential additional benefits of CH₄ reductions on allowable cumulative carbon emissions consistent with the Paris targets, we use the Joint UK Land-Environment Simulator (JULES) (Clark et al 2011) coupled with the intermediate complexity climate model IMOGEN ‘Integrated Model Of Global Effects of climatic aNomalies’ (Huntingford et al 2010). The combined IMOGEN-JULES framework thus provides an intermediate complexity climate-carbon modelling system. IMOGEN utilises ‘pattern-scaling’ to capture the main features of expected local and monthly meteorological changes interpolated to alternative future levels of global warming. This is connected to a gridded version of the land surface model JULES (version 4.8) (Clark et al 2011) to understand the impacts of any transition to different stable warming levels.

IMOGEN comprises a global energy balance model (EBM) whose global climate response characteristics (climate sensitivity for land and ocean, ocean diffusivity etc.) can be chosen to represent any global climate model (GCM). It is driven by time-series of CO₂ concentrations and non-CO₂ radiative forcing. IMOGEN generates gridded outputs of monthly anomaly fields of surface temperature, precipitation, humidity, wind-speed, surface shortwave and longwave radiation and pressure. These anomalies are derived by scaling the patterns from the output from each GCM, assuming these are linear in global surface temperature change. Here the data from the 34 CMIP5 GCMs running the RCP8.5 scenario (Taylor et al 2013) are used to derive both the global climate characteristics and climate patterns. Although the greenhouse gas forcings used in this study will be closer to the RCP2.6 scenario, the RCP8.5 scenario was used to get the clearest signal to determine the climate patterns.

The JULES configuration also includes modelled O₃ damage to photosynthesis, affecting land-atmosphere CO₂ exchange (Sitch et al 2007). This O₃ damage parameterisation can be set to ‘low’ or ‘high’ sensitivity to span the uncertainty in our knowledge of the sensitivity of plants globally. We also include a ‘no’ sensitivity to allow the separation of the ozone effect. In this study we use the low sensitivity parameterisation as the standard configuration, with separate tests of the effects of using the ‘no’ and ‘high’ sensitivities. Surface O₃ concentrations are parameterised as two-dimensional fields as a function of the global average CH₄ concentration. These are previously derived from global chemistry-climate simulations using the HadGEM3 model for global mean atmospheric CH₄ mixing ratios of 1285 ppb and 2062 ppb (Stohl et al 2015). Within IMOGEN-JULES, the O₃ concentration is calculated at each grid point as a function of CH₄ using a linear interpolation between O₃ concentrations at the above mixing ratios.

To set the initial (2015) conditions for the land carbon stores, the IMOGEN-JULES model is spun up for 1000 years at 1850 conditions and then run to 2015 with prescribed historical CO₂ mixing ratios, land use, and global surface temperatures from Morice et al (2012) (reaching 0.89 °C by 2015). The spin up and historical simulation are carried out for each climate model realisation. For this study we invert the IMOGEN-JULES configuration, running forward from 2015 with specified global temperature profiles,
and specified non-CO$_2$ radiative forcing changes from 2015. IMOGEN-JULES derives the CO$_2$ concentrations in each year from the EBM calculations and hence the uptake by the land biosphere; the global carbon cycle is closed with a simple description of global oceanic draw-down of CO$_2$ (Joos et al 1996). A control simulation is also run maintaining 1850 forcings and temperatures until 2100. Further details of the IMOGEN-JULES setup and the inversion procedure can be found in Comyn-Platt et al (2018).

2.2. Temperature and methane scenarios

We determine the carbon budgets consistent with three specified temperature trajectories that stabilise at 1.5 °C (with and without overshoot) and 2.0 °C above pre-industrial levels as shown in figure 1(a). These profiles are generated according to the algorithm in Huntingford et al (2017) as in Comyn-Platt et al (2018). The results are found not to be sensitive to the exact form of the temperature trajectories.

The future non-CO$_2$, non-CH$_4$ radiative forcings are taken from one of the Shared Socio-economic Pathways (SSPs) SSP2–2.6 (O’Neill et al 2017, Riahi et al 2017) by subtracting the CO$_2$ and CH$_4$ (and associated O$_3$ and stratospheric water vapour) contributions from the total SSP2–2.6 radiative forcing. We follow the prescription of these terms in the MAGICC climate model (Meinshausen et al 2011). After 2015, land-use is fixed at 2015 levels. Here, the IMOGEN physical parameters are varied to represent the climate
characteristics, such as the different climate sensitivities, of 34 CMIP5 models.

There is a wide range in the CH$_4$ emissions in the SSPs that achieve a forcing of 2.6 W m$^{-2}$ in 2100, suggesting that the options for mitigation are not exhausted (Gernaat et al 2015). We construct four different anthropogenic CH$_4$ mitigation scenarios (figure 1 (b)). The first three are ‘High’ CH$_4$ and ‘Medium’ CH$_4$ which span the highest and lowest of the SSP2–2.6, and ‘Low’ CH$_4$ which we parameterise as following the Medium scenario to 2020 then decaying faster to 62 Tg CH$_4$ yr$^{-1}$ by 2100. For the High CH$_4$ scenario, CH$_4$ concentrations increase following the an upper bound of SSP4-2.6 and SSP5-2.6 CH$_4$ concentration projections from the GCAM integrated assessment model (IAM) (Calvin et al 2017). For the Medium CH$_4$ scenario, concentrations follow SSP2–2.6 as generated by the IMAGE 3.0 IAM (van Vuuren et al 2017). For the Low CH$_4$ scenario, we assume extra reductions are possible by removing the restriction on cost minimisation. To generate a smooth curve we parameterise emissions (in Tg CH$_4$) as $55 + \frac{337.25}{x}$, where $x$ is the number of years after 2020. This projects a lower CH$_4$ projection curve than the strongest mitigation SSP storyline (SSP1–2.6 variants). The High, Medium and Low scenarios lead to year 2100 atmospheric CH$_4$ concentrations of 1839, 1275 and 1008 ppb, respectively. We also consider a fourth scenario ‘Late’, to test whether the timing of the CH$_4$ mitigation matters, where emissions are maintained at current (2015) levels until 2050 and then apply the same rate of mitigation for the Low CH$_4$ profile post-2050, but extended to ensure that the 2100 concentration matches Low CH$_4$. Note that we are not assuming specific methane mitigation measures in these scenarios, or possible effects on co-emitted species such as N$_2$O.

Emissions are converted into concentrations using the formulation of the MAGICC model (which includes natural emissions of 250 Tg CH$_4$ yr$^{-1}$). Radiative forcings for the CH$_4$ scenarios are calculated using formulae including the short-wave absorption (Etminan et al 2016), and the overlap with N$_2$O using the N$_2$O concentrations in SSP2–2.6. The contributions from O$_3$ and stratospheric water vapour are added in as linear functions of CH$_4$ mixing ratio. From IPCC AR5 (Myhre et al 2013) these amount to $2.36 \times 10^{-4} + 1.09 \times 10^{-4}$ Wm$^{-2}$ per ppb CH$_4$ ($0.65 \pm 0.3$ times the CH$_4$ radiative efficiency).

This spread in possible CH$_4$ trajectories is wider than typically projected in integrated assessment models (IAMs) (Rogelj et al 2015a). However, the IAM outputs are unlikely to span the full range of CH$_4$ measures that are available. This is partly due to their cost minimisation approaches which exclude the more expensive measures and neglect the social costs of methane (Shindell et al 2017), and their lack of diversity in treatment of non-CO$_2$ mitigation measures. These IAMs also have limited representation of the specific processes responsible for methane production and of the technologies available for methane mitigation. It is therefore difficult to estimate how deep (or not) reductions can go. Achieving our most stringent scenario would be expected to draw on specific sectoral measures to address CH$_4$. These could include increasing agricultural efficiency, decreased food waste and decreased beef consumption (van Vuuren et al 2017). The Low and Late scenarios should therefore be seen as illustrative examples.

3. Results

3.1. Carbon budgets

For the High CH$_4$ scenario (no CH$_4$ mitigation) the allowable carbon emissions from 2015–2100 span from $149 \pm 51$ GtC for 1.5 °C (no overshoot), $143 \pm 56$ GtC for 1.5° with overshoot, to $403 \pm 94$ GtC for the 2° temperature pathway. The uncertainty is due to the range of climate sensitivities of the CMIP5 models emulated by the IMOGEN framework. Rather than these absolute budgets we focus on the differences in the cumulative carbon emissions from the inversions for the different CH$_4$ scenarios. These show almost no dependence on the climate model realisation and little dependence on the temperature profile. The benefit of the Medium vs the High CH$_4$ scenario is approximately 155 GtC over the period 2015–2100 (figure 2(a)). Stronger CH$_4$ mitigation down to the Low scenario gains another 80 GtC if it is done early. The loss in benefit from delaying CH$_4$ mitigation according to the Late CH$_4$ scenario is 40 GtC. These values are similar to a study comparing no mitigation with stringent mitigation (Rogelj et al 2015b) which calculated an increase of 130 GtC in the carbon budget, with a 30 GtC penalty for late mitigation.

The relationship between the allowable carbon emissions from 2015–2100 and CH$_4$ concentrations at 2100 is almost linear (excluding the Late CH$_4$ scenario) with very little difference between the climate model realisations (figure 2(b)). The slopes are $-0.269 \pm 0.001$ GtC ppb$^{-1}$ for the 1.5° and 1.5° overshoot profile and $-0.277 \pm 0.002$ GtC ppb$^{-1}$ for the 2° profile. Compared to the CH$_4$ forcing at 2100 (including the O$_3$ and stratospheric water vapour effects), this is equivalent to 350 or 360 GtC (Wm$^{-2}$)$^{-1}$. There are uncertainties in these relationships due to the uncertainty in the total radiative efficiency of methane. As these relationships are based on the methane concentrations, rather than emissions, uncertainties in the methane lifetime do not affect the result. The uncertainty in the direct methane radiative efficiency is taken to be 9% of the total (Etminan et al 2016). When combined with the 16% uncertainty from the ozone and water vapour contributions this leads to an overall uncertainty of 18%, (0.048 GtC ppb$^{-1}$). This uncertainty includes within its span the relationship ($-0.236$ GtC ppb$^{-1}$) expected using the Myhre et al (1998) forcing instead of Etminan et al (2016).
Figure 2. Impact of CH$_4$ mitigation on the carbon budget for the three temperature profiles. (a) Increase in allowable carbon emissions compared to the High CH$_4$ scenario. Data are shown for the three temperature profiles. The widths of the lines cover the range of the CMIP5 models. (b) Difference in allowable carbon emissions between pairs of CH$_4$ scenarios, as a function of difference in CH$_4$ concentration for each year 2015–2100. The widths of the lines cover the range of the CMIP5 models. The dashed lines connect the differences in 2100 carbon budget against 2100 CH$_4$ concentrations for the Low, Medium and High CH$_4$ scenarios. For the Late vs High CH$_4$ scenario only the 1.5°C temperature profile is shown.

The change in carbon budgets (high methane vs low methane) can be broken down into the different carbon stores: atmosphere, land (soil and vegetation) and ocean (figure 3(a)). We define the airborne fraction $\alpha_F = \Delta CO_2 / \Delta ECO_2$, where $\Delta CO_2$ is the change in the atmospheric CO$_2$ burden and $\Delta ECO_2$ is the change in cumulative CO$_2$ emissions, both in GtC. We find that the $\alpha_F$ of the extra carbon allowed through CH$_4$ mitigation is independent of the climate sensitivity of each climate model. $\alpha_F$ is also the same when comparing Low-High and Medium-High CH$_4$ mitigation (not shown). There is a slight dependence of $\alpha_F$ on temperature profile with the 1.5°C profiles having an $\alpha_F$ of 0.44 vs 0.49 for the 2°C profile. The Late CH$_4$ mitigation does not follow the same linear relationship as the Low or Medium scenarios, falling well below the line of proportionality in figure 2(b). With late CH$_4$ mitigation, the comparative increase in allowable atmospheric CO$_2$ concentrations (compared to High CH$_4$) does not occur until late in the century. The increase in the atmospheric carbon is the same as for the early mitigation, but the ocean and the land have not had time to take up this extra carbon and the $\alpha_F$ of the extra CO$_2$ is thus higher (0.53).

Since surface O$_3$ decreases vegetation productivity, mitigation of CH$_4$ leads to additional climate benefits than might be expected simply through the radiative forcing. Decreasing atmospheric CH$_4$ concentrations...
reduces O$_3$ levels and increases the uptake of carbon into vegetation and soils. In terms of equation (1), reducing O$_3$ reduces $\alpha_F$. We test this through further inversions assuming no and high sensitivity of vegetation to O$_3$, compared with the baseline parameterisation in the previous results of lower plant-O$_3$ sensitivity. We find that by increasing the impacts on the land carbon uptake, O$_3$ damage adds 9–28 GtC (4%–12%) to the benefit of the Low vs High CH$_4$ land carbon uptake, O$_3$ sensitivity. We find that by increasing the impacts on the land carbon uptake, O$_3$ damage adds 9–28 GtC (4%–12%) to the benefit of the Low vs High CH$_4$ scenarios depending on the assumed sensitivity of vegetation to O$_3$ (figure 3(b)).

3.2. Linearity of carbon budgets
To maintain the radiative balance in the inverse model the change in atmospheric CO$_2$ is entirely determined by the change in the non-CO$_2$ forcing. Since we invert IMOGEN to derive the radiation balance consistent with the specified temperature profiles, the greenhouse gas forcing must be the same at any given time, such as at 2100, (assuming the climate sensitivities to radiative forcing from CH$_4$ and CO$_2$ are equal). So

$$\Delta F_{CO_2} + \Delta F_{CH_4} = 0, \quad \Delta CO_2 \times \bar{A}_{CO_2} + \Delta CH_4 \times \bar{A}_{CH_4} = 0;$$

where $\Delta CO_2$ and $\Delta CH_4$ are the CO$_2$ and CH$_4$ burdens in GtC and GtCH$_4$, and $\bar{A}_{CH_4}$ and $\bar{A}_{CO_2}$ are the average radiative efficiencies for increases in CH$_4$ (including its indirect effects) and CO$_2$ in Wm$^{-2}$ GtCH$_4^{-1}$ or Wm$^{-2}$GtC$^{-1}$. So combining these with the airborne fraction $\alpha_F$ defined previously gives the ratio of extra cumulative carbon emissions ($\Delta E_{CO_2}$) to change in CH$_4$ abundance:

$$\frac{\Delta E_{CO_2}}{\Delta CH_4} = \frac{\bar{A}_{CH_4}}{\bar{A}_{CO_2}} \frac{1}{\alpha_F};$$

This equation is exact and simply follows from the way we have defined $\bar{A}_{CH_4}$, $\bar{A}_{CO_2}$ and $\alpha_F$. The linear relationship between the change in the allowable emissions and the change in 2100 forcing therefore implies a constant ratio between the cumulative emissions to 2100 and the 2100 atmospheric CO$_2$ burden, i.e. a constant airborne fraction for the extra allowable emissions as found in figure 3(a). Although $\bar{A}_{CH_4}$ and $\bar{A}_{CO_2}$ are not constant, but functions of the atmospheric CO$_2$ levels and the magnitudes of the changes $\Delta CO_2$ and $\Delta CH_4$, the deviations from linearity are small for the methane mitigation scenarios used here. The slightly higher $\alpha_F$ for the 2.0$^\circ$C temperature profile is due to the lower radiative efficiency ($\bar{A}_{CO_2}$) at higher absolute CO$_2$ levels.

The equation also holds in the more realistic case where the extra allowed CO$_2$ is not emitted with the time profile required to precisely follow the prescribed temperature curve, although in this case the $\alpha_F$ may be slightly different from found in this study. The energy balance has little dependence on the shape of the temperature curve before 2100 (or any specific time), and is dominated by the absolute temperature and its time derivative at 2100. This relationship has no dependence on climate sensitivity. However the $\alpha_F$ will be affected by the sensitivity of the carbon cycle to changes in atmospheric CO$_2$, surface temperature and precipitation (Arora et al. 2013).

Allen et al. (2016) have derived a variant of the Global Warming Potential metric (GWP*) that relates the change in cumulative emissions of CO$_2$ to the change in instantaneous emissions of a short-lived species (here CH$_4$).

$$GWP^* = \frac{\Delta E_{CO_2}}{\Delta E_{CH_4}} = \frac{\text{AGWPH}}{\text{AGWPH}_{CO_2/H}}.$$
where $\Delta e_{\text{CH}_4}$ is the change in the instantaneous CH$_4$ emission rate (in GtCH$_4$ yr$^{-1}$), $H$ is a chosen time-frame, and AGWP$^H_X$ are the absolute GWP for CH$_4$ and CO$_2$. The absolute GWP can be expanded to give:

$$\frac{\Delta E_{\text{CO}_2}}{\Delta e_{\text{CH}_4}} = \frac{\lambda_{\text{CH}_4}}{A_{\text{CO}_2} \times \alpha_F(H)}$$

Figure 4. (a) Effect of CH$_4$ mitigation (Low-High) on surface ozone levels. (b) Effect of CH$_4$ mitigation (Low-High) on global NPP where vegetation has no sensitivity to O$_3$, low sensitivity (as standard setup) and high sensitivity to ozone. The widths of the lines cover the range of the CMIP5 models. (c) Map of the regions of increased NPP attributable to reducing surface O$_3$ (Low CH$_4$ vs High CH$_4$ scenarios) using the high sensitivity to O$_3$, as a percentage of the total NPP.
where $\alpha_F (H)$ is the airborne fraction of a pulse of CO$_2$ averaged over $H$ years. This is similar to equation (1), but only equal to it if the CH$_4$ has reached equilibrium (i.e. $\Delta$CH$_4$ can be replaced by $\Delta$eCH$_4 \times \tau_{CH4}$) and the airborne fraction of CO$_2$ in the AGWP$^H_{CO2} (\alpha_F (H))$ is equal to the $\alpha_F$ of the extra allowed CO$_2$.

In terms of GWP*, the results from our experiments give a ratio $\frac{\Delta eCO2}{\Delta eCH4}$ at the end of the century of 2900 (low-medium mitigation) to 3300 (low-high mitigation) in GtCO$_2$ yr$^{-1}$, which compares well with a GWP* (100 years) of 2800 yr$^{-1}$, given that implicit in the GWP* approximation are the assumptions that the CH$_4$ concentrations have equilibrated and that the CO$_2$ airborne fraction is constant.

### 3.3. Air quality and productivity benefits

We find that CH$_4$ mitigation has non-climate benefits in terms of air quality and vegetation productivity (by allowing greater atmospheric CO$_2$ levels, and by reducing the damage from O$_3$). West et al (2012) found that a strong methane mitigation scenario (emission decrease of 180 Tg CH$_4$ yr$^{-1}$) resulted in a decrease in global ozone concentrations of around 2 ppb and avoided mortalities of around 90 000 per year. In this study, mitigation by 260 Tg CH$_4$ yr$^{-1}$ (Low vs High scenario) achieves a decrease in surface O$_3$ concentration of 3 ppb as a global average, with the largest impact in the tropics (see figure 4(a)). Therefore a rough scaling of West et al (2012) would suggest a benefit of around 130 000 avoided mortalities per year.

The increased allowable CO$_2$ levels lead to increased net primary plant productivity (NPP) in JULES by 4% as a global average (figure 4(b)). If we assume the high sensitivity of plants to ozone the effects of O$_3$ reduction add up to another 2% increase in NPP globally. In places where the changes in ozone overlap with areas of high productivity (Eastern US, northern Europe) the reductions in ozone could increase total NPP by 4%–6% in the high sensitivity case (figure 4(c)).

### 4. Conclusions

We conclude that mitigating CH$_4$ can lead to substantial benefits in the allowable carbon emissions consistent with either a 1.5°C or 2.0°C temperature target. We find a robust relationship between decreased CH$_4$ concentrations at the end of the century and increased budget of allowable carbon emissions to 2100. This relationship is independent of climate sensitivity or temperature pathway. These changes come from the direct radiative effects of CH$_4$ and its atmospheric oxidation products, from the carbon uptake by the land and ocean, and from the effects of O$_3$ on plant productivity. Budget calculations based simply on TCRE will therefore underestimate allowed emissions. As well as making carbon targets more feasible, CH$_4$ mitigation leads to substantial land ecosystem benefits through increased productivity, and to improved air quality. The variation in CH$_4$ emissions between the IAMs in the SSP scenarios shows that there is substantial opportunity for CH$_4$ mitigation even using the cost optimisation assumptions in these models. Very large cuts in CO$_2$ emissions will certainly be needed to achieve the climate goals, but our study shows that the benefits of CH$_4$ mitigation could be substantially larger than the IAMs assume, making the exploration and costing of more ambitious reduction potentials and their co-benefits a priority.

### Acknowledgments

The work was undertaken as part of the UK Natural Environment Research Council’s programme ‘Understanding the Pathways to and Impacts of a 1.5°C Rise in Global Temperature’ through grants NE/P014909/1, MOC1.5 (WC, CW, CH, PC, SS, JL), NE/P015050/1 CLIFFTOP (EC-P, GH, SC), and NE/P014941/1 CLUES (PC, TP). AH acknowledges support from the EPSRC Fellowship ‘Negative Emissions and the Food-Energy-Water Nexus’ (EP/N030141/1). WC also acknowledges support under Research Council of Norway, project no. 235548.

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