"Regional variation in the effectiveness of methane-based and land-based climate mitigation options"

Hayman et al. (ESD-2020-24)

Author Response

We thank the Editor for his interest in and for his comments on the paper. From some of the Editor's comments, it is clear that the Editor has not fully understood parts of the study design, assumptions and hence interpretation of our results. We acknowledge that these areas of the paper need attention.

Before proceeding to the specific comments, we make some general points (GP) about the study:

GP 1: **Previous work**: This paper brings together and builds on 3 separate papers that we have had published in the scientific literature (cited papers by Comyn-Platt et al., 2018; Collins et al., 2018 and Harper et al., 2018). We look to provide sufficient detail from those studies, while minimising any repetition.

GP 2: **Scenarios**: We will use the word "scenario" to define the control (or baseline) scenario and the 5 mitigation options that we investigated with the inverse version of IMOGEN-JULES. The 6 scenarios, which are listed in Table 1, are:

1. Control or baseline (denoted "CTL")
2. "CH_4" for the methane mitigation scenario
3. "BECCS" for the land-based mitigation using bioenergy crops with carbon capture & storage
4. "Natural" for the variant land-based mitigation scenario
5. Coupled ("BECCS+CH_4") for the combined land-based (BECCS) and methane mitigation scenario.
6. Coupled ("Natural+CH_4") for the combined land-based (Natural) and methane mitigation scenario.

As described in Section 2.4.2, we generate an additional 2 scenarios in the post-processing optimisation of the land-based mitigation scenarios: (1) land-based mitigation (optimised) and (2) coupled (optimised). These are the scenarios referred to in, for example, Figures 8 and 9. We concede that we did not explicitly define these scenarios as such in Section 2.4.2. We now include these scenarios in Table 1. See also Response 1.

GP 3: **Prescribed and input data:** We use prescribed temperature pathways for the 1.5°C warming and 2°C warming targets taken from our previous work (cited paper Huntingford et al., 2017). The scenarios described above use specific datasets developed for the IMAGE SSP2 baseline and SSP2 1.9 scenarios: (a) time series of annual atmospheric methane concentrations; (b) time series of the radiative forcing by non-CO_2 greenhouse gases and other climate forcers; and (c) time series of the gridded annual land area assigned to agriculture, and within that to bioenergy crops.

We use the time series of anthropogenic methane emissions in two of our post-processing scripts to attribute the global atmospheric carbon stores to the different IMAGE regions in those scenarios involving methane mitigation. We use the time series to generate Figures 11 and 12 (and Supplementary Information, Figures SI.3 and SI.4). See also Response 21.

GP 4: **Uncertainty**: For each of the 6 scenarios investigated using the inverse version of IMOGEN-JULES, we make 136 separate model runs for the 1.5°C warming target and a second set of 136 runs for the 2°C warming target. Within each ensemble of 136 runs, we emulate 34 of the CMIP5 climate and Earth system models. For each CMIP5 model, we make 4 runs (high & low Q_{10} and high & low vegetation O_3 sensitivity), which we now denote "factorial" runs. We use these ensembles to determine the range or "uncertainty" in the derived carbon budgets, specifically from climate change (as given by the 34 CMIP5 models) and from key land-surface processes.

For BECCS, there is an additional source of uncertainty from the productivity of the bioenergy crops and the assumptions about the losses from harvest to final long-term storage. We introduced a BECCS scale factor and investigated the effect of the scale factor on the derived carbon budgets in the post-processing step. We include this parameter uncertainty in the ranges given for the land-based mitigation scenarios involving BECCS.

GP 5: **1.5°C warming vs. 2°C warming targets:** We use the same input datasets for the scenario runs for the 1.5°C warming and 2°C warming targets, e.g., the gridded annual time series of areas assigned to agriculture, and within that the area assigned to bioenergy crops. This is in contrast to Integrated Assessment Model scenarios where, for example, a greater area of bioenergy crops would be needed to meet the 1.5°C warming compared to a 2°C warming target (Lines 56-61, version submitted in December 2020).

Figure 8 shows that the allowable fossil fuel carbon dioxide budget is, as expected, higher for the 2°C than the 1.5°C warming target. However, when we compare the mitigation potential of the mitigation scenarios, there is little difference between the two warming targets. If we were to make different assumptions about the deployment of BECCS in the two warming targets, this would affect the carbon budgets derived.

We give our Response and the Change(s) made to the paper and to the Supplementary Information, after each reviewer comment. The reviewer comments are in normal font, with our “Response” and “Change(s) to Paper” in ***bold italics and indented***. The line numbers for the Editor’s comments refer to the revised manuscript submitted in December 2020. The line numbers for the “Change(s) to Paper” refer to the track change versions of the paper and Supporting Information that are in the separate track change version of the paper.

Editor Decision:
Reconsider after major revisions (04 Jan 2021) by Steven Smith

Comments to the Author:
I've reviewed the revised paper and responses to referee comments. The paper is improved, however is still difficult to understand. The methodology is complex, combining forward modeling, inverse modeling, and scale factors, and needs to be more clearly explained.

The first major point of confusion regarding the methodology is the overall structure of the calculation with respect to how emissions, concentration, and forcing are calculated. This should be clarified in one place for the reader. This statement, Line 105, " Using a combination of calculated and prescribed time series of annual radiative forcings, we derive the atmospheric CO2 radiative forcing and hence its concentration, taking account of any land and ocean feedbacks." is unclear, but is central to the calculations done in the paper. I've searched through the paper but cannot find a succinct description of the methodology on this point. This should be added either in this section or soon after to clarify this for the reader (some specific comments below relate to this as well).

For example I infer from various parts of the paper that the following are exogenous: anthropogenic CH4 emissions and CH4 mitigation (from IMAGE), land-use patterns (except that later the paper discusses optimization of land-use between natural and biomass crops, which seems a bit in-consistent with this statement), and the assumed global mean temperature pathway. Land-use feedbacks on CO2 and CH4 emissions are endogenous to the models used in the paper. Its unclear how radiative forcing and concentrations of CO2 and CH4 are determined. It seems that some adjustment to the IMAGE CH4 concentrations is calculated, which leaves a residual CO2 forcing pathway that is inverted to obtain an anthropogenic fossil CO2 budget? These issues are central to the methodology of the paper and need to be better summarized for the reader. (see also comments below on Figure 3) Is total forcing also fixed to one time path, or is the inverse calcuation focused only on the temperature pathway?

Response 1: ***We note the Editor's comment on the improvements made to the paper but that the Editor still finds part of the paper unclear. In response, we have (1) re-written the section in the Introduction describing the study, (2) worked to make our "Approach and Methodology" clear and unambiguous; and (3) use Table 1 to list and provide details on our scenario simulations. In particular, Table 1 provides the notation used throughout the paper. All our text has been checked to ensure references to simulations are entirely consistent with the terminology of Table 1. See also Response 6 on nomenclature.***

Change(s) to the Paper: We amend the text (lines 94-160):

This paper models the potential for mitigation of greenhouse gases to contribute to meeting the Paris targets of limiting global warming to 1.5°C and 2°C respectively. Specifically, we investigate the effectiveness of mitigation of anthropogenic methane emissions and land-based mitigation (e.g., implementation of BECCS and AR), combining results from three recent papers (Collins et al., 2018; Comyn-Platt et al., 2018; Harper et al., 2018). We determine the effectiveness of these approaches in terms of their impact on the anthropogenic fossil fuel CO_2 emissions budget consistent with stabilising temperature at 1.5°C and 2° C of warming. The more effective the mitigation option, the larger the fossil fuel CO_2 emissions budget consistent with stabilisation at a given level. We estimate the impact of these mitigation scenarios relative to an existing scenario of greenhouse gas concentrations (based on the IMAGE SSP2 baseline), spanning uncertainties in both climate model projections (both global warming and regional climate change), process representation and the efficacy of BECCS. Sect. 2 provides a brief description of the models, the experimental set-up and the key datasets used in the model runs and subsequent analysis. Sect. 3 presents and discusses the results, starting with a global perspective before addressing the regional dimension. For BECCS, we additionally investigate the sensitivity to key assumptions and consider the implications for water security. Sect. 4 contains our conclusions.

2 Approach and Methodology

~~Figure 1 shows a schematic of our approach, the workflow and the prescribed data used. We use the Joint UK Land Environment Simulator (JULES, Sect. 2.1) (Best et al., 2011;Clark et al., 2011), coupled with an inverted form of the "Integrated Model Of Global Effects of climatic aNomalies" (IMOGEN, Sect. 2.2) (Huntingford et al., 2010;Comyn-Platt et al., 2018). IMOGEN is an intermediate complexity climate model, which uses "pattern scaling" to emulate 34 models in the CMIP5 ensemble. In the inverted form used here, IMOGEN follows a prescribed temperature pathway (Sect. 2.2.2). We derive the overall radiative forcing consistent with this temperature pathway using an energy balance model, including a simplified model of ocean uptake (of energy and CO_2). Using a combination of calculated and prescribed time series of annual radiative forcings, we derive the atmospheric CO_2 radiative forcing and hence its concentration, taking account of any land and ocean feedbacks. For the mitigation scenarios considered (Sect 2.3), we use consistent and compatible time series of (a) anthropogenic CH_4 emissions, (b) prescribed land areas for crops and BECCS (where relevant) and (c) radiative forcings for SLCFs and non-CO_2 GHGs (except CH_4), from the IMAGE integrated assessment model. In a post-processing step (Sect. 2.4.1), we take the modelled carbon stores for land (=vegetation and soil carbon), atmosphere and oceans from the IMOGEN-JULES output and calculate the anthropogenic fossil fuel emission budgets (AFFEB) compatible with the warming pathway. For the land-based scenarios involving BECCS, we optimise the AFFEB by selecting the greater land carbon uptake from the 'BECCS' or the variant 'natural' (i.e., no BECCS) scenario, for those grid cells where BECCS is deployed (Sect. 2.4.2). Further, we investigate the sensitivity of the optimisation to the assumption made about BECCS productivity and carbon uptake (Sect. 2.4.3). Section 2.3.3 lists the model runs undertaken and the key assumptions and datasets used.~~

Our overall modelling strategy is as follows. The starting point is the prescription of global temperature profiles that match the historical record, followed by a transition to a future stabilisation at either 1.5 or 2.0°C above pre-industrial levels. For these profiles, we then determine the related pathways in atmospheric radiative forcing by inversion of the global energy balance component of the IMOGEN impacts model. IMOGEN "Integrated Model Of Global Effects of climatic aNomalies" (Sect. 2.2) (Huntingford et al., 2010; Comyn-Platt et al., 2018) is an intermediate complexity climate model, which emulates 34 models in the CMIP5 climate model ensemble. Hence our Radiative Forcing (RF) trajectories have uncertainty bounds, reflecting the different thermal sensitivities of existing climate models.

For each radiative forcing pathway, we subtract the individual RF components for non-CO_2 and non-CH_4 radiatively-active gases that are perturbed by human activity, and for scenarios taken from the IMAGE integrated assessment model. Then, for CH_4, we use an understanding of its atmospheric lifetime to translate methane emissions into their atmospheric concentrations. The related RF for CH_4 is also subtracted from the overall value. Hence the remaining RF is that available for changes to atmospheric CO_2 concentration. The IMOGEN model uses pattern-scaling, again fitted to the same 34 climate models, to estimate local changes in near-surface meteorology. Combined with our global temperature pathways, these pattern-based changes (as well as atmospheric CO_2 concentration) drive the Joint UK Land-Environment Simulator land surface model (JULES, Sect. 2.1) (Best et al., 2011;Clark et al., 2011). JULES estimates atmosphere-land CO_2 exchange, and similarly, IMOGEN contains a single global description of oceanic CO_2 draw-down. These two estimates of carbon exchanges with the land and ocean respectively, in conjunction with atmospheric storage being linear in the CO_2 pathway, finally determine by simple summation compatible CO_2 emissions from fossil fuel burning. We call this the anthropogenic (CO_2) fossil fuel emission budgets (AFFEB) compatible with the warming pathway, subject to the assumptions made for non-CO_2 forcings.

Our numerical simulation structure allows us to investigate the implications of three different key changes on AFFEB, for stabilisation at both 1.5 and 2.0°C, and in a structure that captures features of a full set of climate models. First and maybe most importantly, we work to understand how regional reductions in CH_4 emissions allow higher values of AFFEB. Second, we consider how alternative scenarios of BECCS implementation alter atmosphere-land CO_2 exchanges, and again presented as the resultant implications for AFFEB. Third, we determine how the newer understanding of warming impacts on wetland methane emissions also affects AFFEB. Figure 1 captures the modelling framework, derivation of AFFEB, and our numerical experiments in a single overall schematic diagram.

Each of the scenarios investigated using the IMOGEN-JULES framework comprises 2 ensembles of 136 members, one ensemble for each of the warming targets. We make use of these ensembles to derive an "uncertainty" in the derived carbon budgets, specifically from climate change (as given by the 34 CMIP5 models) and from key land-surface processes (methane emissions from wetlands and the ozone vegetation damage). The climate change uncertainty comprises both the range of climate sensitivities of the CMIP5 models and the different regional patterns in the models. We use the median of the 136-member ensemble as the central value to derive the carbon budgets and the interquartile range (25-75%) for the uncertainty.

We also modify Table 1 to:

Table 1 | The IMOGEN-JULES and post processing scenario runs, key features and the input and prescribed datasets used in the scenarios.

(a) IMOGEN-JULES modelling scenarios (Note 1)

	Scenario (Abbreviation) **Key features of the Scenario**	**Scenario-specific input and prescribed datasets (Notes 2, 3)**
1.	**Control ("CTL")** • Agricultural land accrued to feed growing populations associated with the SSP2 pathway • No deployment of BECCS • Anthropogenic CH_4 emissions rise from 318 Tg yr^{-1} in 2005 to 484 Tg yr^{-1} in 2100 • Effects of the methane and carbon-climate feedbacks from wetlands and permafrost thaw included	Scenario-specific input data • Time series of radiative forcing by non-CO_2 GHG and other non-CO_2 climate forcers, for the IMAGE SSP2 baseline scenario • Time series of annual global atmospheric concentrations of CH_4 and N_2O for the IMAGE SSP2 baseline scenario Scenario-specific prescribed data • Gridded annual time series of areas assigned to agriculture (crops & pasture), for the IMAGE SSP2 baseline scenario, converted into fractions of the IMOGEN-JULES grid cell
2.	**Methane mitigation ("CH_4")** • Agricultural land-use as in Control ("CTL") scenario • Anthropogenic CH_4 emissions decline from 318 Tg yr^{-1} in 2005 to 162 Tg yr^{-1} in 2100, from the IMAGE SSP2 RCP1.9 scenario • Effects of the methane and carbon-climate feedbacks from wetlands and permafrost thaw included	Scenario-specific input data • Time series of radiative forcing by non-CO_2 GHG and other non-CO_2 climate forcers, for the IMAGE SSP2 RCP1.9 scenario • Time series of annual global atmospheric concentrations of CH_4 and N_2O for the IMAGE SSP2 RCP1.9 scenario Scenario-specific prescribed data • As 1, gridded annual time series of area assigned to agriculture (crops & pasture). Converted into fractions of the IMOGEN-JULES grid cell
3.	**Land-based mitigation, including BECCS ("BECCS")** • Land use change based on the IMAGE SSP2 RCP1.9 scenario • High levels of REDD and full reforestation • Food-first policy so that bioenergy crops (BE) are only implemented on land not required for food production • Anthropogenic CH_4 emissions as in Control ("CTL") scenario • Effects of the methane and carbon-climate feedbacks from wetlands and permafrost thaw included	Scenario-specific input data • Time series of radiative forcing by non-CO_2 GHG and other non-CO_2 climate forcers, for the IMAGE SSP2 baseline scenario • Time series of annual global atmospheric concentrations of CH_4 and N_2O for the IMAGE SSP2 baseline scenario (as used in "CTL") Scenario-specific prescribed data • Gridded annual time series of areas assigned to agriculture (crops & pasture) and within that the area for bioenergy crops, for the IMAGE SSP2 RCP1.9 scenario. Converted into a fraction of the IMOGEN-JULES grid cell
4.	**Land-based mitigation with no BECCS ("Natural")** • Land use as 3, except any land area allocated to bioenergy crops is set to zero, allowing expansion of natural vegetation • Anthropogenic CH_4 emissions as in Control ("CTL") scenario • Effects of the methane and carbon-climate feedbacks from wetlands and permafrost thaw included	Scenario-specific input data • Time series of radiative forcing by non-CO_2 GHG and other non-CO_2 climate forcers, for the IMAGE SSP2 baseline scenario • Time series of annual global atmospheric concentrations of CH_4 and N_2O for the IMAGE SSP2 baseline scenario (as used in "CTL") Scenario-specific prescribed data • Gridded annual time series of areas assigned to agriculture (crops & pasture). As 3, except any land allocated to bioenergy crops is set to zero. Converted into a fraction of the IMOGEN-JULES grid cell

5.	**Combined methane & land-based mitigation** **“Coupled(CH$_4$+BECCS)**” - Combines CH$_4$ mitigation of 2 with land-based mitigation scenario of 3	Scenario-specific input data - As 2, time series of radiative forcing by non-CO$_2$ GHG and other non-CO$_2$ climate forcers, for the IMAGE SSP2 RCP1.9 scenario - As 2, time series of annual global atmospheric concentrations of CH$_4$ and N$_2$O for the IMAGE SSP2 RCP1.9 scenario Scenario-specific prescribed data - As 3, gridded annual time series of areas assigned to agriculture (crops & pasture) and within that the area for bioenergy crops, for the IMAGE SSP2 RCP1.9 scenario. Converted into prescribed fractions of the IMOGEN-JULES grid cell
6.	**Combined methane & land-based mitigation with no BECCS** **“Coupled (CH$_4$+Natural)”** - Combines CH$_4$ mitigation of 2 with land-based mitigation scenario of 4	Scenario-specific input data - As 2, time series of radiative forcing by non-CO$_2$ GHG and other non-CO$_2$ climate forcers, for the IMAGE SSP2 RCP1.9 scenario - As 2, time series of annual global atmospheric concentrations of CH$_4$ and N$_2$O for the IMAGE SSP2 RCP1.9 scenario Scenario-specific prescribed data - As 4, gridded annual time series of areas assigned to agriculture (crops & pasture). Converted into a fraction of the IMOGEN-JULES grid cell

(b) Post-processing scenarios (Note 1)

	Scenario **“Abbreviation”**	**Description of the Scenario**
7.	**Optimisation of land-based mitigation** **“Land-based mitigation: Optimised”**	- Optimisation of scenarios 3 and 4 by selecting the scenario which has the larger carbon uptake, on a grid cell by grid cell basis
8.	**Optimisation of the combined methane & land-based mitigation** **“Coupled Optimised”**	- Optimisation of scenarios 5 and 6 by selecting the scenario which has the larger carbon uptake, on a grid cell by grid cell basis

Notes

1. Each scenario comprises two 136-member ensembles (34 GCMs x 2 ozone damage sensitivities x 2 methanogenesis Q$_{10}$ temperature sensitivities), one for the 1.5°C warming target and the second for the 2°C warming target.
2. All of the above scenarios also use time series of (1) observed temperature changes between 1850 and 2015; (2) profiles of temperature change between 2015 and 2100 to achieve the 1.5°C and the 2°C warming targets; and (3) the radiative forcing changes of non-CO$_2$ radiative forcing between 1850 and 2015.
3. We define (a) a “prescribed” dataset as one that is used unchanged in the IMOGEN-JULES modelling; (b) an “input” dataset as one that provides the initial values that are subsequently changed.

A second point that is difficult to follow is the methodology for how uncertainty is treated in the paper. One issue is that the paper alternates between discussing uncertainty in some sections, and then discussing factorial runs in others. It might be useful to be more consistent in terminology. The overall approach to addressing uncertainty needs to be more clearly stated early on in the paper (e.g. first part of section 2). There is a clear statement at the beginning of the conclusion section, but this needs to be made much sooner.

Response 2: ***We refer to General Point 2. We now include a paragraph on our treatment of uncertainty at the end of the introduction to Section 2.***

Change(s) to the Paper: We add the following text, which is also included as the final paragraph of the "Change(s) to the Paper" for Response 1 above.

Each of the scenarios investigated using the IMOGEN-JULES framework comprises 2 ensembles of 136 members, one ensemble for each of the warming targets. We make use of these ensembles to derive an "uncertainty" in the derived carbon budgets, specifically from climate change (as given by the 34 CMIP5 models) and from key land-surface processes (methane emissions from wetlands and the ozone vegetation damage). The climate change uncertainty comprises both the range of climate sensitivities of the CMIP5 models and the different regional patterns in the models. We use the median of the 136-member ensemble as the central value to derive the carbon budgets and the interquartile range (25-75%) for the uncertainty.

On a specific point, the paper mentions two values of Q10 used as uncertainty bounds (~line 145). Are only the bounding cases used (the text implies this as currently written)? In that case, what do the central values presented in later figures (for example bars figure 9) represent?

Response 3: ***The IMOGEN-JULES runs only make use of the bounding values of Q_{10}. As indicated in Response 2, the central value in Figure 8-9, 11-14 is the median of the 136-member ensemble. In Figure 9 (and others), the points represent the results from individual ensemble members. We also refer the Editor to General Point 4 and Response 4 below.***

Change(s) to the Paper: The required changes are included in Response 2 above and Response 4 below.

The results of the factorial experiments do not really seem to be fully explored in the discussion of results overall. It would strengthen the paper substantially if these could be more fully examined. For example, what is the range in contributions of each specific component? For example the modeling of methane from wetlands is discussed, but what is the contribution of wetland methane to the allowed carbon budget? Same for ozone damage, etc. What uncertainty factors (and assumed BECCS efficiency) impact these the most? There are some aggregate results shown in Figure 8, but no detailed results are presented or discussed in the paper or the supplement.

Response 4: ***We have taken this request particular seriously and include additional analysis to derive the contribution from climate change and different spatial patterns in the 34 GCMs emulated and the 4 land process factorial runs..***

Change(s) to the Paper: We add the following text to the paper (lines 526-544):

For both temperature pathways (i.e., 1.5°C or 2°C of warming), we investigate the contribution to the uncertainty range from 'climate' as represented by the 34 GCMs emulated and from the land processes investigated (Sect. 2.1). A GCM with higher climate sensitivity will have a lower AFFEB for a specific warming target (and vice versa). In our post-processing steps, we derive a number of statistical parameters from the complete 136-member or the 34-member GCM ensemble for the individual factorial runs (low Q_{10}/low O_3, low Q_{10}/high O_3, high Q_{10}/low O_3 and high Q_{10}/high O_3), such as mean, standard deviation, median, and various percentiles. Our focus is on the contribution different factors make to the overall standard deviation of the 136-member ensemble (σ_{All}). By factoring out the climate variation (via their means), we calculate the standard deviation for the land processes investigated (σ_{land}). With a knowledge of the overall standard deviation and that for land-only processes, we derive the contribution from 'climate' ($\sigma_{climate}$) assuming that the variance are independent and can be summed (Eq. 17). The contributions of uncertainty are by comparing ratios of σ_{land} to $\sigma_{climate}$.

$$\sigma_{all}^2 = \sigma_{climate}^2 + \sigma_{land}^2 \qquad (17)$$

We present the results of this analysis in Table 3 for the Anthropogenic Fossil Field CO_2 Emission Budgets and the Mitigation Potential (= scenario – "CTL") for the 1.5°C temperature profile (Supplementary Information, Table SI.2 is equivalent table for the 2°C temperature profile). Our overall finding is that the climate uncertainty dominates the uncertainty of the AFFEBs. However, when considering different trade-offs between land uncertainty and mitigation options, the impact of climate uncertainty is much weaker. Within the land uncertainty, the O_3 vegetation damage appears to make the greater contribution (from the changes in the mean). Although there is some variation in the ratio ($\sigma_{climate}$:σ_{land}) between the scenarios (0.32±0.13, mean ± standard deviation), this gives us confidence in the robustness of the uncertainty estimates derived, across the scenarios and the 2 temperature profiles.

We include a new Table as Table 3 (on next page)

Table 3 | For the 1.5°C temperature profile, the mean of the 34-GCM member ensembles for the "CTL" and mitigation scenarios for the different factorial runs (low Q_{10}/low O_3, low Q_{10}/high O_3, high Q_{10}/low O_3 and high Q_{10}/high O_3), the standard deviation of the full 136-member ensemble (GtC), the derived standard deviations for land processes (σ_{land}) and climate ($\sigma_{climate}$, as represented by the 34 GCMs) and the ratio of $\sigma_{climate}/\sigma_{land}$ for (a) the Anthropogenic Fossil Field CO_2 Emission Budgets and (b) the Mitigation Potential (= scenario – CTL).

(1) AFFEB

Scenario	Mean of 34-member Factorial Run (GtC)				Standard Deviation (GtC)			Ratio $\sigma_{climate}:\sigma_{land}$
	Low Q_{10} Low O_3	Low Q_{10} High O_3	High Q_{10} Low O_3	High Q_{10} High O_3	136-member Ensemble	Land σ_{land}	Climate $\sigma_{climate}$	
CTL	-9.66	-20.58	-18.91	-31.06	47.12	7.60	46.50	6.12
CH_4	179.44	186.79	168.73	174.90	47.54	6.59	47.08	7.14
BECCS	6.49	3.42	-2.09	-5.80	47.45	4.76	47.21	9.91
Natural	42.57	24.60	35.00	16.05	48.95	10.07	47.90	4.75
Optimised Land-based	46.42	29.18	37.89	20.00	48.85	9.84	47.85	4.86
Linear BECCS+CH_4	195.58	210.79	185.55	200.15	48.64	9.07	47.79	5.27
Linear_Natural+CH_4	231.67	231.97	222.64	222.00	48.70	4.76	48.47	10.19
Linear optimised	235.51	236.55	225.53	225.96	48.69	5.16	48.42	9.39
Coupled BECCS+CH_4	199.69	214.62	189.50	203.94	48.48	9.01	47.64	5.29
Coupled Natural+CH_4	237.83	238.95	228.72	228.91	48.60	4.80	48.36	10.07
Coupled optimised	241.50	243.29	231.35	232.60	48.60	5.27	48.31	9.17

(2) Mitigation Potential

Scenario	Mean of 34-member Factorial Run (GtC)				Standard Deviation (GtC)			Ratio $\sigma_{climate}:\sigma_{land}$
	Low Q_{10} Low O_3	Low Q_{10} High O_3	High Q_{10} Low O_3	High Q_{10} High O_3	136-member Ensemble	Land σ_{land}	Climate $\sigma_{climate}$	
CTL	-	-	-	-	-	-	-	-
CH_4	189.10	207.37	187.64	205.96	9.28	9.18	1.39	0.15
BECCS	16.14	24.01	16.82	25.26	4.24	4.11	1.05	0.26
Natural	52.23	45.18	53.91	47.11	3.93	3.58	1.62	0.45
Optimised Land-based	56.07	49.76	56.80	51.06	3.44	3.06	1.57	0.51
Linear BECCS+CH_4	205.24	231.38	204.46	231.21	13.39	13.23	2.09	0.16
Linear_Natural+CH_4	241.33	252.55	241.55	253.06	6.14	5.69	2.32	0.41
Linear optimised	245.17	257.13	244.44	257.02	6.55	6.14	2.28	0.37
Coupled BECCS+CH_4	209.34	235.20	208.41	235.00	13.27	13.12	2.01	0.15
Coupled Natural+CH_4	247.48	259.54	247.63	259.97	6.49	6.10	2.21	0.36
Coupled optimised	251.15	263.87	250.26	263.66	6.89	6.54	2.17	0.33

The way that uncertainty in BECCS is considered is difficult to understand since, by the way the calculations are structured, some uncertainties are addressed with a factorial design (natural or "BECCS" as an option), while uncertainty in BECCS potential is addressed by setting the value if "k" (Kapa). There are a few results presented with different values of "K", but most results seems to be based on one value of this scale factor.

> ***Response 5:*** ***We now define as scenarios the land-based mitigation options "BECCS" and "Natural" (i.e., no BECCS) (see General Point 2). We introduce the BECCS scale factor κ into the post-processing of the IMOGEN-JULES ensemble runs to provide a single parameter to assess the sensitivity to (a) bioenergy productivity and (b) losses from harvest to final storage. We make clear in Section 3.1 that we have used a value of κ = 1. We will however clarify how the selection of κ affects the uncertainty. See also General Point 2 and Reponses 1, 2, 27 and 29.***
>
> ***Change(s) to the Paper: We amend the text (lines 479-486):***
>
> **3.1 Global Perspective**
>
> We calculate the anthropogenic fossil fuel emission budget to limit global warming to a particular temperature target as the sum of the changes in the carbon stores of the atmosphere, land (vegetation and soil) and ocean between 2015 and 2100 (Sect. 2,4,1, Eq. 5 and 6). We use a BECCS scale factor (κ) of unity. We present in Fig. 8 the median and ~~ensemble member~~ spread of the AFFEB (as box and whiskers) from the 136-member ensemble, and the individual GCM/ESM contributions to the AFFEBs from the four carbon pools shown (points), for each of the ~~factorial experiments~~main scenarios modelled using the IMOGEN-JULES or derived in the post-processing optimisation step (see Table 1 for description of the scenarios).
>
> ***We include the following text (lines 700-703) with the Change(s) to the Paper for Response 27 (see later).***
>
> We investigate the efficacy of our "BECCS" scenario by increasing the productivity of BECCS (using a scale factor κ). From comparison with observed bioenergy crop yields, we argue that the scale factor could be between 1 and 3. We use this range of κ as an additional source of uncertainty on the land-based mitigation potential.

There is also some inconsistency in nomenclature:

Table 1 describes a scenario with "Land-based mitigation, including BECCS" and "Land-based mitigation with no BECCS". This is clear, although there is no mention of the assumed BECCS K value, which should be added.

However then in Figure 8, there are a number of other options presented. Such as "Land-based mitigation (Optimized)" and "Land-based mitigation (Natural)" - these should both be identified in Table 1. Then here are "Coupled" scenarios shown that don't correspond with any of the abbreviations given in Table 1.

Then, further, in Figure 9 there is no BECCs scenario presented, only "Land based mitigation", but evidently land-baed mitigation that also contains BECCS (with K =1 and K = 3), which also does not correspond to any label in Table 1. (It seems that these are two variants of "Land-based mitigation including BECCS"?)

The authors need to throughly go through the paper, tables, figures, and supplement and harmonize nomenclature to avoid confusing readers.

Response 6: ***We refer to General Point 2 where we describe the 6 scenarios investigated using the IMOGEN-JULES framework. With respect to the editor, Table 1 refers to a scenario "4. Land-based mitigation with no BECCS (Natural)", which we denoted "Natural" in that table. We accept that "Land-based mitigation (Optimized)" was not explicitly defined. As requested, we will ensure that a consistent set of terminology is used.***

In response to the Editor's comment, we add the 2 post-processing scenarios to Table 1 for completeness. As indicated in Response 1, we refer to Table 1 in relevant places to assist the reader.

Change(s) to the Paper: We list below the line numbers where we make changes to the manuscript, the line numbers refer to the track change version of paper included in this Author response.

- ***Lines 382, 391, 484, 593, 667, 734 and Table 1: "factorial" to "scenario"***
- ***Figure 11: "34 GCMs and 4 factorial runs" to "136-member ensemble"***
- ***We make additional reference to Table 1 at lines 325, 485, 684.***
- ***Equations renumbered following insertion of new equations 3 and 4***
- ***Equations 13-16: "IM1.9" replaced by "BECCS" and "IM1.9N" by "Natural"***
- ***Table 3 with CH_4 scale factors moved to Supplementary Information***
- ***New Table 3 on uncertainty analysis (see also Response 4)***

Further specific comments:

Abstract - I presume these results are specific for the IMAGE SSP2 scenario. This should be mentioned.

Response 7: **We add "for the SSP2 pathway" to the Abstract.**

Change(s) to the Paper: We amend lines 24-25:

~~using~~ We use consistent data and socio-economic assumptions from the IMAGE integrated assessment model for the second Shared Socioeconomic Pathway (SSP2)***"***

Line 90
"and methane climate feedbacks) in a climate/Earth System modelling framework to quantify the unrealised potential from the mitigation of land-based options and anthropogenic CH4 sources."

I don't see how the authors can claim here (and elsewhere) that methane mitigation has not been examined. There is substantial literature on methane migration in the context of temperature and forcing targets. Further, all the IAM scenarios such as the SSPs contain representations of anthropogenic methane mitigation, including the IMAGE scenarios from which this paper draws. Clarify this and make sure previous work is properly cited.

For example also the statement here "Although the primary challenge remains mitigation of fossil fuel emissions, these results highlight the unrealised potential of these mitigation options to make the

Paris climate targets more achievable" does not seem to be warranted. Most of the scenarios in the literature, and certainly the SSPs, all include methane mitigation.

Response 8: ***We agree that there is an extensive literature on methane mitigation and we discuss some of this in the Introduction (76-85). Both in the scientific literature and in the IAM scenarios, the multiple benefits of methane mitigation are clear.***

We are using "unrealised" in the sense that society has not yet acted on the potential of methane mitigation. We know that atmospheric methane concentrations are continuing to increase and are currently following a path consistent with the one of the high SSP5 emission scenarios. We will remove "unrealised" but we stand by our results in this and our previous paper (cited paper Collins et al., 2018) that methane mitigation makes the Paris climate targets more achievable (and is probably essential).

Change(s) to the Paper:

- ***Abstract (line 38-39):***

Although the primary requirement remains mitigation of fossil fuel emissions, our results highlight the ~~unrealised~~ potential for the mitigation of CH_4 emissions to make the Paris climate targets more achievable.

- ***Introduction (line 94-98). The sentence below has been replaced as part of the "Change(s) to Paper" for Response 1.***

~~For the first time, we combine these elements (land-based mitigation, anthropogenic CH4 mitigation, and natural carbon and methane climate feedbacks) in a climate/Earth System modelling framework to quantify the unrealised potential from the mitigation of land-based options and anthropogenic CH₄ sources. In contrast to previous studies, we use a process-based land surface model to assess these mitigation options by region, yielding policy-relevant information on the optimal mitigation strategy.~~ This paper models the potential for land-based mitigation of greenhouse gases to contribute to meeting the Paris targets of limiting global warming to 1.5°C and 2°C respectively. Specifically, we investigate the effectiveness of mitigation of anthropogenic methane emissions and land-based mitigation (e.g., implementation of BECCS and AR), combining results from three recent papers (Collins et al., 2018; Comyn-Platt et al., 2018; Harper et al., 2018).

- ***Section 3.1 (line 514-515)***

Although the primary challenge remains mitigation of fossil fuel emissions, these results highlight the ~~unrealised~~ potential of these mitigation options to make the Paris climate targets more achievable.

Line 141 not clear what "(the depth of zero annual amplitude)" means.

Response 9: ***This term is widely used in the permafrost community to refer to the depth below the surface, where seasonal changes in ground temperature are negligible (≤0.1 °C).***

Change(s) to the Paper: We add the following to line 186-187:

we diagnose permafrost wherever the deepest soil layer is below 0°C (assuming that this layer is below the depth of zero annual amplitude, i.e. where seasonal changes in ground temperature are negligible (≤0.1 °C)).

Line 205 This " The increased/reduced atmospheric CH4 concentration will have a corresponding faster/slower atmospheric decay rate than the prescribed concentration pathway. We account for this following the approach of Cubasch et al. (2001). Related changes in atmospheric radiative forcing, in response to altered atmospheric 210 CH4 concentrations, are calculated using the formulation from Etminan et al. (2016). We also include the indirect effect of these CH4 emission changes on the forcing by tropospheric ozone and stratospheric water vapour by multiplying the CH4 forcing by 1.65, based on Myhre et al. (2013)."

is unclear and seems to involve quite a number of assumptions and simplifications that should be further detailed and tested (likely largely in the supplement). First, it is not clear what it means to say "following the approach of Cubasch et al." given that this is a reference to the entire WG I IPCC report. More details should be provided. Changes in wetland emissions are, according to the author's own equations, non-linearly related to temperature. It is not clear at all that this can be represented as a "faster/slower atmospheric decay rate", whatever that means.

It is not clear that "tropospheric ozone and stratospheric water vapour" can be accurately represented by a single multiplicative factor applied to CH4 forcing. Methane concentrations and tropospheric ozone are linked through a number of mechanisms, with tropospheric ozone forcing in Meinshausen etal 2011, for example, being tied more closely to methane emissions not forcing, and with methane and tropospheric ozone forcing linked through changes in atmospheric oxidation capacity. Given that methane is a central focus of the paper, the representation of methane in the atmosphere should be better described. Use of a constant multiplier might introduce some distortions in the results.

Response 10: ***We give more details of our treatment of methane and provide justification. We refer to the extensive uncertainty analysis that we undertook in our earlier study on the climate-methane feedback from wetlands (cited paper by Gedney et al. 2019). We provide a summary in the present paper. We do not think that further testing is therefore needed.***

The Editor is correct. Wetland emissions are expected to increase significantly with climate change, as discussed in the cited paper by co-author Gedney et al. (2019). This was a key reason for adjusting the IMAGE time series of atmospheric concentrations of methane and its radiative forcing. The IMAGE time series are based on constant natural emissions of 250 Tg per annum.

We follow the accepted practice for citing chapters in IPCC Assessment Reports. We now however give the specific page in the IPCC report. The Cubasch et al. reference is to Chapter 9 in the Third Assessment Report. In revising the manuscript, we no longer use this reference.

***Change(s) to the Paper**: We rewrite the paragraph (lines 252-292):*

~~Our simulations include a CH_4 feedback system that captures the climate impacts on CH_4 emissions from natural wetland sources. The approach used here follows Comyn-Platt et al. (2018) and Gedney et al. (2019), where the prescribed atmospheric CH_4 concentrations, which assume a constant annual wetland CH_4 emission (van Vuuren et al., 2017), are modified using the anomaly in the modelled annual wetland CH_4 emission. The increased/reduced atmospheric CH_4 concentration will have a corresponding faster/slower atmospheric decay rate than the prescribed concentration pathway. We account for this following the approach of Cubasch et al. (2001). Related changes in atmospheric radiative forcing, in response to altered atmospheric CH4 concentrations, are calculated using the formulation from Etminan et al. (2016). We also include the indirect effect of these CH_4 emission changes on the forcing by tropospheric ozone and stratospheric water vapour by multiplying the CH_4 forcing by 1.65, based on Myhre et al. (2013).~~ The atmospheric CH_4 concentrations available from the IMAGE database (see Sect. 2.3.1) assume a constant annual wetland CH_4 emission (van

Vuuren et al., 2017). However, these emissions have interannual variability and a positive climate feedback (e.g., Comyn-Platt et al., 2018; Gedney et al., 2019), and their correct representation is a central part of our study. We follow the same approach that we used in our previous studies (Collins et al., 2018; Comyn-Platt et al., 2018; Gedney et al., 2019). As the IMOGEN-JULES modelling framework does not have an explicit representation of the atmospheric chemistry of methane, we represent the oxidation and hence loss of CH_4 by a single lifetime (τ).

$$\frac{d([CH_4]-[CH_4]_{IMAGE})}{dt} = C\,\{\sum F\,[CH_4] - \sum F\,[CH_4]_{IMAGE}\} - \frac{[CH_4]-[CH_4]_{REF}}{\tau} \qquad (3)$$

where $[CH_4]$ and $[CH_4]_{IMAGE}$ are the atmospheric methane concentrations using our new wetland-based, time varying ($F[CH_4]$) and the constant IMAGE ($F[CH_4]_{IMAGE}$) wetland emissions, respectively. Here parameter C is a constant to convert from Tg CH_4 to a mixing ratio in parts per billion by volume (ppbv). Further, higher atmospheric concentrations of CH_4 and its oxidation product (carbon monoxide) lower the concentration of hydroxyl radicals, the major removal reaction for CH_4, thereby increasing the atmospheric lifetime of CH_4. Conversely, lower CH_4 concentrations will shorten its atmospheric lifetime. We take account of this feedback of CH_4 on its lifetime (τ), using Eq. 4 (Collins et al., 2018; Comyn-Platt et al., 2018; Gedney et al., 2019) as:.

$$\ln(\tau/\tau_o) = s.\ln([CH_4]/[CH_4]_o),\ \text{i.e.,}\ \tau = \tau_o \exp(s\,[CH_4]/[CH_4]_o) \qquad (4)$$

In Eq. 4, $[CH_4]_o$ and τ_o are the contemporary atmospheric CH_4 concentration and lifetime, and s is the CH_4-OH feedback factor, defined by $s = \partial \ln(\tau)/\partial \ln(CH_4)$. We take values of τ_o = 8.4 years, $[CH_4]_o$ = 1,745 ppbv and s = 0.28, from Prather et al. (2001) (pages 248 and 250). In our earlier study on the climate-wetland methane feedback (Gedney et al., 2019), we investigate the sensitivity to the methane lifetime and the feedback factor, in addition to an analysis of the main drivers on the wetland methane-climate feedback and the main sources of uncertainty. Gedney et al. (2019) conclude that the limited knowledge of contemporary global wetland emissions is a larger source of uncertainty than that from the projected climate spread of the 34 GCMs. We quantify this uncertainty in our experimental design by using two values of Q_{10} (see Sect. 2.1).

In response to our dynamic interactive calculations of atmospheric CH_4 concentrations, we derive the related change in methane radiative forcing (RF). We use the formulation from Etminan et al. (2016), which accounts for the short-wave absorption by CH_4 and the overlap with N_2O. The atmospheric oxidation of methane (by the hydroxyl radical) leads to the production of tropospheric ozone and stratospheric water vapour. We calculate these indirect contributions of methane to the overall radiative forcing, following the approach for methane adopted in our previous work (Collins et al., 2018; Comyn-Platt et al., 2018; Gedney et al., 2019). Collins et al. (2018) represent the forcing contributions from O_3 and stratospheric water vapour as linear functions of the CH_4 mixing ratio, based on the analysis presented in IPCC AR5 (Myhre et al 2013). The indirect methane forcings amount to $2.36\times10^{4} \pm 1.09\times 10^{-4}$ W m^{-2} per ppb CH_4 (i.e., 0.65±0.3 times the CH_4 radiative efficiency). Hence we incorporate the indirect effects of these CH_4 emission changes by an approximation, multiplying the CH_4 radiative forcing by 1.65.

The discussion above seems to contradict the statement in line 243 that "We use future projections of atmospheric CH4 concentrations and LULUC from the IMAGE SSP2 projections (Doelman et al.,

2018) for both the methane and land-based mitigation strategies. ". From what I'm understanding from the paper it appears that the CH4 concentration is later adjusted for feedback effects - that should be made clearer.

Response 11: **We make this clarification.**

Change(s) to the Paper: We amend lines 323-332.

We use future projections of atmospheric CH_4 concentrations and LULUC (specifically, the areas assigned to agriculture and within that to BECCS) from the IMAGE SSP2 projections (Doelman et al., 2018) as input or prescribed data for both the methane and land-based mitigation strategies (Table 1). This ensures that all projections are consistent and based on the same set of IAM model and socio-economic pathway assumptions. The SSP2 socio-economic pathway is described as "middle of the road" (O'Neill et al., 2017), with social, economic, and technological trends largely following historical patterns observed over the past century. Global population growth is moderate and levels off in the second half of the century. The intensity of resource and energy use declines. We define the upper and lower limits of anthropogenic mitigation as the lowest (RCP1.9, denoted "IM-1.9") and highest ("baseline", denoted "IM-BL") total radiative forcing pathways, respectively, within the IMAGE SSP2 ensemble (Riahi et al., 2017). As described in Section 2.2.1, we modify the atmospheric concentrations of CH_4 in the IMOGEN-JULES modelling as the IMAGE scenarios assume constant natural and hence wetland methane emissions.

Also, if CH4 mitigation is from IMAGE this statement in the abstract "Globally, mitigation of anthropogenic CH4 emissions has large impacts on the anthropogenic fossil fuel emission budgets, potentially offsetting (i.e. allowing extra) carbon dioxide emissions of 188-212 GtC" is, therefore, not a result of this work but a conclusion just taken from the IMAGE results. This needs to be made clearer if this is the case.

Response 12:* *We make clear that this is a result of this study. We are using the IMAGE SSP scenarios to provide realistic and consistent estimates of the methane changes in our CTL and CH_4 scenario. The mitigation of anthropogenic CH_4 emissions has a large impact on the anthropogenic fossil fuel CO_2 emission budgets for two reasons: (1) the reduction in the direct and indirect radiative forcing of methane in response to the lower emissions and hence atmospheric concentration of methane; and (2) the carbon-cycle changes through the increase in the uptake of CO_2 by the land and ocean from the higher atmospheric concentrations of CO_2 and a reduction in land vegetation ozone damage (lower atmospheric concentrations of methane lead to lower concentrations of tropospheric ozone).

Change(s) to the Paper: We amend the Abstract (lines 28-33):

Globally, mitigation of anthropogenic CH_4 emissions has large impacts on the anthropogenic fossil fuel emission budgets, potentially offsetting (i.e. allowing extra) carbon dioxide emissions of 188-212 GtC. This is because of (a) the reduction in the direct and indirect radiative forcing of methane in response to the lower emissions and hence atmospheric concentration of methane; and (b) carbon-cycle changes leading to increased uptake by the land and ocean by CO_2-based fertilisation. Methane mitigation is beneficial everywhere, particularly for the major CH_4-emitting regions of India, USA and China.

We also amend the Conclusions (lines 714-721): See also Response 26.

Stabilising the climate primarily requires urgent action to mitigate CO_2 emissions. However, CH_4 mitigation has the potential to make the Paris targets more achievable by offsetting up to 188-212 GtC of anthropogenic CO_2 emissions, while still meeting the same global-warming targets. This offset is a direct consequence of the reduced radiative forcing by methane and of carbon cycle gains. These balances and related flexibilities have the potential to make the Paris targets more achievable. Our range of additional CO_2 emissions broadly applies to both the 1.5° and 2°C warming targets, as the mitigation potential of the CH_4 scenario is similar for the two temperature pathways considered.

Line 310 - Is this "the temperature pathway (1.5° versus 2°C warming) having a minor effect." the case even for the high Q10 sensitivity? Presumably this also depends on the temperature pattern used as well?

__Response 13:__ We refer to General Points 2 and 5, where we explain why the mitigation potential of the different mitigation scenarios are similar for the 1.5°C warming vs. 2°C warming targets. The high Q_{10} methane runs are part of the 136-member ensembles and contribute to the uncertainty range. The solid line is the median of the ensemble and the width of the coloured band is the interquartile range of the ensemble. We will however amend the sentence to make this clear.

__Change(s) to the Paper__: We amend lines (395-397):

As we use the same input datasets for the two warming targets, ~~The~~ the major control on the modelled atmospheric CH_4 concentrations is the CH_4 emission pathway followed, with the temperature pathway (1.5° versus 2°C warming) having a minor effect.

Section "2.4.1 Anthropogenic Fossil Fuel Emission Budget and Mitigation Potential"
It would be useful here to clarify that this is only the CO2 emissions budget (not total GHG emissions).

__Response 14:__ We amend the text to indicate that it is only the CO_2 emission budget.

__Change(s) to the Paper__: We amend lines 401-402:

Following Comyn-Platt et al. (2018), we define the anthropogenic fossil fuel CO_2 emission budget (AFFEB) for scenario i as the change in carbon stores from present to the year 2100**.**

It would also be useful here to add some comment on what is driving each of the terms in the budget. (e.g., which models in Figure 1)

__Response 15:__ We add these comments. They are however generalisations as the changes are dependent on the scenario. We discuss the changes in the carbon stores in Section 3.1 (lines 487 and Figure 8).

__Change(s) to the Paper__: We amend the text (lines 405-411)

where $C^{land}(t)$, $C^{ocean}(t)$ and C^{atmos} (t) are the carbon stored in the land, ocean and atmosphere, respectively, in year t and $BECCS(t_1{:}t_2)$ is the carbon sequestered via BECCS between the years t_1 and t_2. The atmospheric carbon store does not include CH_4. This is a reasonable approximation, however, given the relative magnitudes of the atmospheric concentrations of CH_4 (~2 ppmv at the surface) and CO_2 (400 ppmv). where $C^{land}(t)$, $C^{ocean}(t)$ and $C^{atmos}(t)$ are the carbon stored in the land, ocean and atmosphere, respectively, in year t and $BECCS(t_1:t_2)$ is the carbon sequestered via BECCS between the years t_1 and t_2. The atmospheric carbon store does not include CH_4. This is a reasonable approximation, however, given the relative magnitudes of the atmospheric concentrations of CH_4 (~2 ppmv at the surface) and CO_2 (400 ppmv).

Within the IMOGEN-JULES modelling framework, we use (a) the IMOGEN climate emulator to derive the changes in the ocean and atmosphere carbon stores, and (b) JULES for the changes in the land carbon store and carbon sequestered through BECCS. We discuss the changes in the carbon stores for the baseline and different mitigation scenarios in Sect. 3.1.

Line 378 I assume that the calcuation of H* depends on the assumed loss from farm to final storage? If so the assumed for farm to final storage loss should be stated. (line 445 seems to imply that minimal losses are assumed? 13%).

***<u>Response 16:</u>* The Editor is correct; it does depend on assumed loss. It is implicit in the increase of ε from 0.6 (40% loss) to 0.87 (13% loss). We make this explicit by repeating the sentence at lines 438-440.**

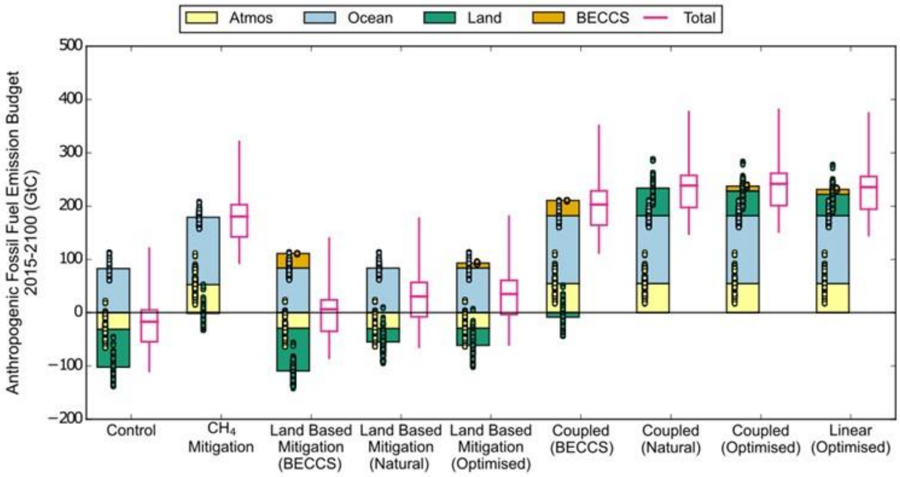
<u>Change(s) to the Paper</u>: We amend the text (lines 469-473):

In other words, $BECCS^*$ is equivalent to the carbon loss due to the land use change to grow the bioenergy crops. Our IMOGEN-JULES simulations assume a 40% carbon loss from farm to final storage, although other studies have assumed this to be as low as 13% (Harper et al., 2018). To assess the feasibility of meeting this break-even level of BECCS, we calculate the harvest (H^*) that would be needed if carbon losses are ~~to be~~ minimised, i.e. by increasing ε from 0.6 to 0.87, and assuming in Eq. 13 that:

Line 391 This line is confusing "We find that there is increased uptake of atmospheric CO2 in the land-based mitigation scenarios, although there is a reduction in land carbon from the land-use changes in these scenarios. " Aren't these just are two sides of the same effect? (and see next comment as well)

***<u>Response 17:</u>* This refers to Figure 8 (included for ease).**

In all the scenarios apart from the BECCS scenario, there is an increase in the land carbon store (shown as positive changes for Coupled (Natural) and Coupled (Optimised) but as smaller negative changes for "CH4", "Natural" and "Optimised" scenarios). In the "BECCS" scenario, the land carbon change becomes more negative than in the "CTL" scenario, as bioenergy crops replace ecosystems with higher carbon content. We now clarify that "the reduction in land carbon from the land-use changes in these scenarios" refers to the scenarios involving BECCS.



***Change(s) to the Paper*: We include the Changes to the Paper with those for the next response (Response 18).**

Line 395 "which is greater than the land carbon lost through land- use changes. " Not clear what this means. How do land-use changes factor into this, given that LULUC is exogenous from IMAGE and therefore constant?

***Response 18:* For LULUC, we use the time series of annual areas assigned to agriculture (crops and pasture) and within that the area allocated to BECCS in the "BECCS" land-based mitigation option. These areas are prescribed (i.e., exogenous). The distribution of the natural plant functional types (pfts) and the non-vegetated surface will evolve on the remaining land area in the grid cell. We use the dynamic vegetation model in JULES to calculate the evolution of this distribution. We amend Sections 3.1 and 2.3.2.**

***Change(s) to the Paper*: We amend lines 480-495. The changes shown below also include those for Responses 5 and 17.**

3.1 Global Perspective

We calculate the anthropogenic fossil fuel emission budget to limit global warming to a particular temperature target as the sum of the changes in the carbon stores of the atmosphere, land (vegetation and soil) and ocean between 2015 and 2100 (Sect. 2.4.1, Eq. 5 and 6). We use a BECCS scale factor (κ) of unity. We present in Fig. 8 the median and ~~ensemble member~~ spread of the AFFEB (as box and whiskers) from the 136-member ensemble, and the individual GCM/ESM contributions to the AFFEBs from the four carbon pools shown (points), for each of the ~~factorial experiments~~main scenarios modelled using the IMOGEN-JULES or derived in the post-processing optimisation step (see Table 1 for description of the scenarios~~.~~).

~~We find that there is increased uptake of atmospheric CO$_2$ in the land-based mitigation scenarios, although there is a reduction in land carbon from the land-use changes in these scenarios.~~ In all the scenarios apart from the BECCS scenario, there is an increase in the land carbon store (shown as positive changes for Coupled (Natural) and Coupled (Optimised) but as smaller negative changes for "CH$_4$", "Natural" and "Optimised" scenarios. In the "BECCS" scenario, the land carbon change becomes more negative than in the "CTL" scenario, as bioenergy crops replace ecosystems with higher carbon content. In the combined ('coupled') CH$_4$ and land-based mitigation scenarios, the reduction in the emissions and hence atmospheric concentrations of CH$_4$ allow increased atmospheric concentrations of CO$_2$ (Fig. 6). There is increased uptake of carbon by the land, directly because of the increased atmospheric CO_2 concentration and indirectly through the reduction in O_3 damage. In the coupled "BECCS" scenario, this increased uptake of atmospheric CO_2 is again offset by ~~which is greater than~~ the land carbon lost through ~~land-use changes~~conversion of the land to bioenergy crops.

We also amend Section 2.3.2 (lines 351-355)

2.3.2 **Land-based mitigation: baseline, BECCS and Natural scenarios**

For our land-based mitigation scenarios, we take time series of the annual areas assigned to agriculture (crops and pasture) and within that, the area allocated to bioenergy crops, from the IM-BL and IM-1.9 scenarios (defined at the start of Sect. 2.3). We use the dynamic vegetation module in JULES to calculate the evolution of the natural plant functional types and the non-vegetated surface on the remaining land area in the grid cell (see Land use in Sect. 2.1).

The IM-BL LULUC scenario assumes (a) moderate land-use change regulation; (b) moderately effective land-based mitigation; (c) the current preference for animal products; (d) moderate improvement in livestock efficiencies; and (e) moderate improvement in crop yields (Table 1 in (Doelman et al., 2018)).

Line 446 - "yields of > 30 ton DM ha-1 yr-1 would be more difficult to realise". Not clear what this refers to given that earlier in that sentence H* is estimated to be up to 10-20 tons DM/ha/year..

Response 19: ***Where BECCS is replacing ecosystems that have higher carbon content, the productivity required will be potentially unrealistic compared to bioenergy yields currently observed. We amend the text to make this clear***

Change(s) to the Paper: We amend the text (lines 563-568):

We calculate for each IMOGEN grid cell the increase in carbon removed via BECCS and the associated increase in bioenergy crop yields (H^* in Sect.2.4.3) required for BECCS to be the preferred mitigation option (Fig. 10(d)), rather than natural land carbon uptake, and assuming minimal amounts of carbon are lost during the BECCS lifecycle (13% carbon loss). In many places, we find that the required yield increases from <10 to 10-20 ton DM ha^{-1} yr^{-1} are achievable, but required yields of > 30 ton DM ha^{-1} yr^{-1} would be more difficult to realise given the range of yields observed (Li et al., 2018).

Line 462 and table 3. The meaning of Table 3 and the associated text is not clear given that cumulative CH4 emissions have no physical meaning since CH4 does not accumulative in the atmosphere on timescales considered here. What is the "regional scale factor" presented in the table (the one line description in the table is not sufficient to understand what this means)? That scale factor also doesn't appear to be used otherwise in this work.

Response 20: ***From an atmospheric chemistry perspective, the Editor is correct. Here, although we use the phrase "cumulative emissions", we sum the change in methane emissions between 2020 and 2100. We use these summed emissions to derive a scale factor for each IMAGE region to attribute a fraction of the global atmospheric carbon store to that region. This is equivalent to using the average change in the annual methane emissions between 2020 and 2100. We then***

use the scale factors in Table 3 to derive Figures 11 and 12 (and Supplementary Information, Figures SI.3 and SI.4).

***Change(s) to the Paper**: We amend the text (lines 587-594):*

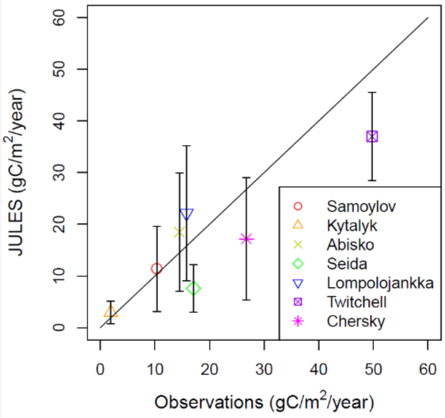
For CH_4, we ~~derive~~ use regional scale factors ~~the regional contribution~~ to allocate ~~the~~ changes in the global atmospheric CH_4 concentration, and therefore the CH_4 mitigation potential, to each region, as shown in Table 3. To derive the regional scale factors, we separately sum ~~using regional fractions of the global difference in~~ the projected anthropogenic CH_4 emissions between ~~(~~2020~~-~~ and 2100~~)~~ ,for~~between~~ the IMAGE SSP2-Baseline and SSP2-1.9 scenarios (van Vuuren et al., 2017). We calculate the scale factor as the regional fraction of the global difference in the summed emissions (Table 3). These two CH_4 scenarios are consistent with the CH_4 concentration pathways considered in the CH_4 ~~factorial~~ scenario simulations (Sect. 2.3). We use the scale factors to produce Fig. 11 and 12 (and Supplementary Information, Figures SI.3 and SI.4)”.

We also amend the caption to Table 3, which is now Table SI.3 in the Supplementary Information:

Table 3 | IMAGE regions~~ and~~, the sum of the projected ~~accumulated~~ anthropogenic CH_4 emissions between ~~(~~2020~~-~~ and 2100~~)~~ for the SSP2-Baseline and SSP2-RCP1.9 scenarios and the differences between these summed emissions. The regional scale factor is calculated as the regional fraction of the global difference in the summed ~~anthropogenic CH_4~~ emissions~~ (2020-2100)~~.

Figure 2b - what do the error bars represent? In figure 2a, there is a high/low Q10 bound defined, but Figure 2b has a central point and an error bar for the simulation results. What do each of these represent? Clarify in caption and in paper text.

***Response 21:** The error bars denote the lower–upper estimates from the low and high Q_{10} simulations and the symbols represent the mean value between these estimates. We add this clarification.*



***Change(s) to the Paper**: We amend the text (lines 195-196):*

The range of uncertainty used in our study (JULES low Q_{10} - JULES high Q_{10}) captures the range of uncertainty in the observations (In Fig. 2b, the error bars denote the lower and upper estimates from the low and high Q_{10} simulations. The symbols represent the mean value between these estimates).

We add to the end of the caption for Figure 2:

The error bars denote the lower and upper estimates from the low and high Q_{10} simulations. The symbols represent the mean value between these estimates.

Figure 3. This figure is confusing. There are two temperature paths in 3a. But then there are two forcing paths in panel b that do not appear to be related to the temperature paths in panel a (what does CTRL and CH4 mitigation relate to the 1.5 and 2 degree pathways?). For a given set of climate parameters (climate sensitivity, etc.), wouldn't each forcing path uniquely relate to a temperature pathway?

Also, this seems to be a pivotal figure, but does not appear to be referenced in the text.

Response 22: ***Figure 3 shows key prescribed or input datasets for the IMOGEN-JULES modelling. We reference Figure 3a in Section 2.2.1 describing the IMOGEN modelling (line 293). Figure 3b is referenced in the same section (line 304). Except for the use of a common colour scheme, the panels are not related.***

Panel (a) shows the historic temperature change from 1850 to 2015 and the prescribed temperature pathways for 1.5° and 2°C of warming from 2015 to 2100.

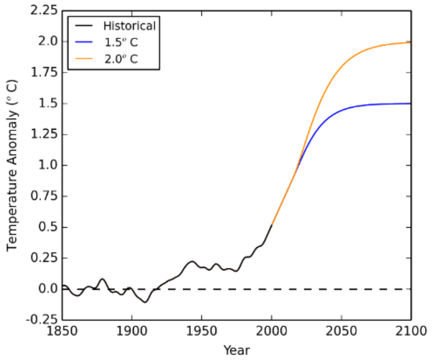
Panel (b) shows the input non-CO_2 GHG radiative forcing time series for the "CTL" and "CH4" mitigation scenario. These are adjusted during the IMOGEN-JULES modelling to take account of the natural methane feedback from wetlands and permafrost thaw.

Change(s) to the Paper: We amend the caption to Figure 3.

Figure 3 | Time series of key datasets used in the study: (a) the historic temperature record (black) and the prescribed temperature profiles used to represent warming of 1.5°C (blue) and 2°C (orange); (b) the historic (black) and the projected non-CO_2 greenhouse gas radiative forcing (W m^{-2}) for the control (orange) and methane mitigation (blue) scenarios.

We adjust the titles of the panels and use different colours in the plots.

(a) Time series of the prescribed temperature pathways



(b) Input time series of the input non-CO_2 radiative forcing

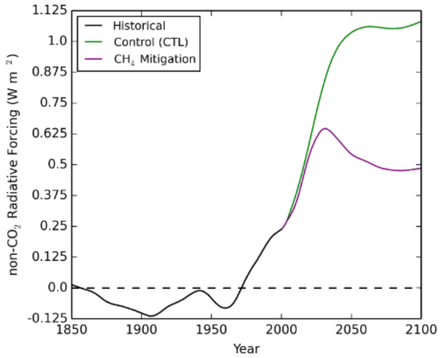


Figure 8 - This is a central figure, but is unclear. Describe in the legend the difference between the colored bars and the pink/red open bars? It is not clear what the text "Note that the gain in the land carbon store for the CH4 scenario is shown as a reduction from -70.8 GtC in the control run to -1.4 GtC in the “CH4” mitigation option (median of ensemble)." means, particularly given that there is no land (green) bar in the CH4 mitigation bar in this figure.

***Response 23:* We amend the legend to explain the coloured bars (the contribution of the different carbon stores to the AFFEB for each scenario) and the accompanying pink box and whiskers plot (AFFEB for the scenario, as the sum of the changes in the component carbon stores). The box and whiskers plot were placed to the right of the bars for greater clarity.**

In response to comments from the Reviewers, we added a note to explain the gain in the land carbon store for the coupled runs, whereas there appears to be no land carbon component for the CH_4 mitigation scenario. The median value of the change in the land carbon store for the CH_4 mitigation scenario is close to zero. The individual ensemble members are visible as the green points in the second bar.

***Change(s) to the Paper*: We amend the caption to Figure 8.**

Figure 8 | The contribution to the allowable anthropogenic fossil fuel emission budget (AFFEBs, GtC) from the changes in the different carbon stores (atmosphere, ocean, land and BECCS) for the various control and mitigation ~~runs~~scenarios, illustrated using the temperature pathway~~s reaching~~ for 1.5°C ~~without overshoot~~of warming. The bars are the median of the component 136-member ensembles, with the individual members shown as points. The accompanying pink box and whiskers plots to the right of each set of bars are for the AFFEBs (as the sum of the changes in the component carbon stores). The box and whisker plots show the median, interquartile range, minimum and maximum derived of the resulting AFFEB ensemble. The optimised land based and coupled mitigation options selects the land use option, which maximises the AFFEB for each model grid cell. Note that ~~the gain in~~ the land carbon store for the CH_4 scenario at -1.4 GtC (median of ensemble) is not visible, although the individual ensemble members can be seen as the green points.~~shown as a reduction from -70.8 GtC in the control run to -1.4 GtC in the “CH_4” mitigation option (median of ensemble)~~.

Similarly, we amend lines 501-505:

In both Figs. 8 and 9, it should be noted that ~~the gain in~~ the land carbon store for the “CH_4” mitigation option at -1.4 GtC (median of ensemble) is not visible in these figures. There has however been a net increase in the land carbon store in the “CH_4” scenario when compared to the land carbon store in the control scenario (~~shown~~

~~as a reduction from~~ -70.8 GtC ~~loss of land carbon in the control run to -1.4 GtC loss in the methane mitigation option (~~, median of ensemble).

And the caption to Figure 9:

Figure 9 | Panels (a & c): The allowable anthropogenic fossil fuel emission budgets (AFFEBs; GtC) for the control (grey), CH_4 mitigation (purple), land-based mitigation (green), coupled methane and land-based mitigation (orange) and the linearly summed methane and land-based mitigation (brown), for 2 temperature pathways asymptoting at 1.5°C (left) and 2.0°C (right). (b & d) The mitigation potential (GtC) as the increase in AFFEB from the corresponding control run. The breakdown of each AFFEB and mitigation potential by the changes in the carbon stores is also shown: atmosphere (pale yellow), ocean (light blue), land (dark green) and BECCS (gold) is included alongside each bar. Note that ~~the gain in~~ the land carbon store for the “~~CH_4~~ CH_4” scenario at -1.4 GtC (median of ensemble) is not visible. There has however been a net increase in the land carbon store in this scenario when compared to the land carbon store in the control run (~~shown as a reduction from~~ -70.8 GtC, ~~in the control run to -1.4 GtC in the “CH_4” mitigation option (~~median of ensemble).

Figure 10 - I assume this "The spread of the functions " should be "The width of the lines "?

Response 24: ***The Editor is correct. It is the width of the lines.***

Change(s) to the Paper: We amend the caption to Figure 10:

The ~~spread of the functions~~width of the lines represent the interquartile range of the ~~sensitivity~~ 136-member ensembles

One of the scientific contributions of this paper is the analysis of BECCS within this larger context, but there's not much detail in the results given. It would enhance the value of the paper to provide in the appendix some tables for the different scenarios of the regional land areas devoted to BECCS and the assumed biomass production rates. This would make the work more readily usable.

Response 25: ***We have undertaken further analysis and include in the Supplementary Information additional Tables (SI.3a-3d), which provide information on the areas, biomass production rates and carbon uptake by IMAGE region from the optimised land-based scenario for BECCS scale factors (κ) of 1, 2, 3 and 4.***

Change(s) to the Paper: We amend the text to refer to these Tables (lines 568-571):

We provide additional information in the Supplementary Information, Tables SI.3a-SI.3d on the modelled bioenergy yields and the yields required for bioenergy crops to be the preferred land-based mitigation option by IMAGE region. The tables also show that area of bioenergy crops and carbon sequestered by BECCS increases, as expected, with the BECCS scale factor (κ),

We also amend the text (lines 611-617)

The carbon uptake by BECCS increases as κ increases from 1 to 3 because there are more grid cells where ‘BECCS’ is the preferred mitigation option in the optimisation process, as evidenced by the increase in area of bioenergy crops (Supplementary Information, Tables SI.3a and SI.3c). As κ only affects the 'BECCS' term (Sect. 2.4.3, Eq. 13), the increased carbon removed by BECCS is often accompanied by a decrease in the carbon uptake from the "natural" vegetation that it replaces. This can be seen more clearly in Fig. 12 (and Supplementary Information, Figure SI.3 for 2°C warming) and the Supplementary Information, Tables SI.3b and SI.3d.

We include new Tables SI.4a-SI.4d in the Supplementary Information. Tables SI.4a and SI.4b for the 1.5°C temperature pathway are included here. Tables SI.4c and SI.4d are the equivalent tables for the 2°C temperature pathway.

Table SI.4a |

Region	Maximum area of BECCS (Mha)	BECCS Productivity		Required Scale Factor	Area of BECCS (Mha) in optimised land-based scenario			
		Modelled	Required to match Natural		BECCS scale factor $\kappa = 1$	BECCS scale factor $\kappa = 2$	BECCS scale factor $\kappa = 3$	BECCS scale factor $\kappa = 4$
Canada	65.9	2.99 (0.00-4.75)	6.39 (0.00-20.16)	2.93 (0.81-24.94)	1.02 (0.74-1.24)	6.69 (4.84-11.41)	23.49 (14.23-30.93)	31.93 (25.29-35.80)
USA	39.0	5.40 (0.00-6.86)	3.36 (0.00-10.88)	1.16 (0.42-3.68)	10.42 (5.06-15.73)	23.71 (19.65-32.99)	29.88 (25.55-37.69)	35.98 (34.87-38.93)
Mexico	7.1	6.86 (2.12-9.30)	3.09 (0.98-5.84)	0.73 (0.31-1.26)	5.25 (5.25-5.81)	7.28 (7.28-7.28)	7.28 (7.28-7.28)	7.28 (7.28-7.28)
Central America	0.5	7.61 (0.07-9.60)	2.64 (0.05-4.63)	0.59 (0.03-0.92)	0.56 (0.56-0.56)	0.56 (0.56-0.56)	0.56 (0.56-0.56)	0.56 (0.56-0.56)
Brazil	27.8	8.21 (0.00-10.89)	3.46 (0.00-8.45)	0.79 (0.34-2.32)	14.64 (13.72-16.06)	26.21 (26.21-31.42)	33.27 (29.36-33.27)	33.27 (31.89-33.27)
Rest of South America	20.3	5.88 (0.01-9.98)	3.53 (0.01-11.08)	0.82 (0.40-6.29)	12.14 (11.21-14.65)	16.05 (16.03-16.96)	18.54 (17.62-18.90)	18.55 (17.62-18.90)
Northern Africa	-	-	-	-	-	-	-	-
Western Africa	3.1	0.02 (0.00-4.72)	0.00 (0.00-16.62)	1.29 (0.33-8.01)	1.96 (1.89-1.96)	2.10 (2.10-2.10)	2.10 (2.10-2.10)	2.10 (2.10-2.10)
Eastern Africa	33.9	4.67 (0.00-7.84)	3.27 (0.00-35.69)	2.43 (0.43-53.31)	2.98 (2.58-3.41)	5.05 (4.72-5.74)	8.17 (7.78-8.37)	8.37 (8.16-11.37)
South Africa	1.0	0.00 (0.00-3.16)	0.00 (0.00-2.71)	1.03 (0.44-1.40)	0.72 (0.72-1.02)	1.02 (0.96-1.02)	1.02 (1.01-1.02)	1.02 (1.02-1.02)
Western Europe	23.6	4.79 (0.00-5.71)	3.80 (0.00-7.40)	1.17 (0.74-2.50)	4.84 (1.61-6.98)	19.47 (19.47-19.47)	22.52 (21.54-23.49)	23.49 (23.49-23.49)
Rest of Southern Africa	63.7	5.38 (0.00-8.83)	4.42 (0.00-13.68)	1.31 (0.57-10.90)	13.17 (8.29-14.28)	24.76 (24.76-25.25)	24.76 (24.76-27.22)	24.76 (24.76-27.59)
Central Europe	19.3	5.05 (4.07-6.10)	4.60 (1.96-11.93)	1.32 (0.69-3.27)	3.56 (1.21-6.49)	9.60 (7.50-11.71)	13.55 (13.55-13.55)	17.14 (13.55-19.62)
Turkey	-	-	-	-	-	-	-	-
Ukraine Region	11.4	4.78 (3.63-5.38)	4.73 (2.87-41.12)	1.35 (0.82-13.81)	2.46 (0.00-5.20)	5.20 (5.20-5.20)	5.20 (5.20-5.20)	8.06 (5.20-8.06)
Central Asia	0.5	2.14 (0.00-4.58)	0.00 (0.00-0.00)	-	0.47 (0.47-0.47)	0.47 (0.47-0.47)	0.47 (0.47-0.47)	0.47 (0.47-0.47)
Russia region	146.1	3.39 (0.03-4.50)	6.52 (0.02-44.97)	3.34 (1.14-33.58)	2.51 (0.48-4.59)	24.36 (13.68-36.87)	49.21 (36.39-69.33)	75.28 (68.13-81.69)
Middle East	-	-	-	-	-	-	-	-
India	6.0	6.92 (6.72-7.22)	2.50 (1.38-9.07)	0.53 (0.29-1.85)	0.14 (0.14-6.08)	6.08 (6.08-6.08)	6.08 (6.08-6.08)	6.08 (6.08-6.08)
Korea region	4.3	6.09 (5.86-6.29)	4.42 (3.41-5.54)	1.07 (0.84-1.30)	2.15 (0.00-4.30)	4.30 (4.30-4.30)	4.30 (4.30-4.30)	4.30 (4.30-4.30)
China region	58.1	5.08 (0.05-7.06)	3.00 (0.04-7.64)	0.89 (0.48-4.41)	18.13 (13.20-22.02)	35.11 (32.61-36.85)	38.84 (37.77-39.79)	46.08 (41.53-48.81)
Southeastern Asia	24.5	7.19 (0.03-9.65)	4.22 (0.02-16.68)	0.83 (0.48-11.75)	6.92 (6.92-6.92)	7.30 (7.30-7.30)	7.30 (7.30-7.30)	7.30 (7.30-7.30)
Indonesia region	-	-	-	-	-	-	-	-
Japan	2.7	5.59 (1.61-6.27)	6.38 (3.33-23.76)	1.56 (0.87-18.64)	1.08 (0.00-2.46)	2.46 (2.46-2.46)	2.46 (2.46-2.46)	2.46 (2.46-2.46)
Rest of South Asia	-	-	-	-	-	-	-	-
Oceania	78.7	2.66 (0.00-7.52)	3.26 (0.00-10.71)	1.88 (0.79-4.67)	18.36 (17.71-19.58)	33.78 (30.20-39.76)	64.41 (59.14-67.85)	77.58 (74.43-81.72)

Table SI.4b |

Region	Carbon Uptake (GtC)							
	BECCS	Land	BECCS	Land	BECCS	Land	BECCS	Land
	BECCS scale factor $\kappa = 1$	BECCS scale factor $\kappa = 1$	BECCS scale factor $\kappa = 2$	BECCS scale factor $\kappa = 2$	BECCS scale factor $\kappa = 3$	BECCS scale factor $\kappa = 3$	BECCS scale factor $\kappa = 4$	BECCS scale factor $\kappa = 4$
Canada	0.02 (0.01,0.02)	0.15 (0.12,0.21)	0.77 (0.59,1.41)	-0.49 (-0.87,-0.40)	3.88 (2.58,4.61)	-2.63 (-2.89,-1.83)	6.61 (5.88,6.95)	-3.91 (-4.00,-3.52)
USA	0.70 (0.36,1.07)	1.30 (0.58,1.88)	2.76 (2.67,3.22)	0.25 (-0.37,0.44)	4.72 (4.53,5.44)	-0.30 (-0.68,0.01)	7.39 (7.26,7.51)	-1.01 (-1.15,-0.86)
Mexico	0.44 (0.41,0.48)	1.00 (0.83,1.05)	1.25 (1.21,1.32)	0.76 (0.71,0.80)	1.88 (1.82,1.98)	0.76 (0.71,0.79)	2.50 (2.42,2.64)	0.76 (0.71,0.79)
Central America	0.06 (0.05,0.06)	0.24 (0.20,0.28)	0.11 (0.11,0.12)	0.24 (0.20,0.28)	0.17 (0.16,0.18)	0.24 (0.20,0.28)	0.23 (0.22,0.24)	0.24 (0.20,0.28)
Brazil	1.72 (1.63,2.03)	5.84 (5.28,6.58)	5.21 (5.02,5.35)	4.84 (4.51,5.33)	8.05 (7.68,8.21)	4.66 (4.28,5.13)	10.80 (10.44,10.96)	4.63 (4.28,5.06)
Rest of South America	1.32 (1.20,1.47)	4.20 (3.73,4.56)	3.41 (3.29,3.55)	3.69 (3.41,3.94)	5.28 (5.10,5.48)	3.57 (3.28,3.84)	7.05 (6.81,7.32)	3.57 (3.27,3.83)
Northern Africa	-	-	-	-	-	-	-	-
Western Africa	0.02 (0.01,0.02)	17.63 (16.30,19.04)	0.06 (0.06,0.06)	17.62 (16.28,19.02)	0.09 (0.09,0.09)	17.62 (16.28,19.02)	0.12 (0.12,0.12)	17.62 (16.28,19.02)
Eastern Africa	0.12 (0.09,0.15)	1.97 (1.88,2.14)	0.50 (0.41,0.58)	1.76 (1.61,1.97)	1.11 (1.05,1.22)	1.44 (1.38,1.63)	1.48 (1.39,2.04)	1.40 (1.19,1.63)
South Africa	0.00 (0.00,0.01)	-0.13 (-0.14,-0.13)	0.03 (0.02,0.03)	-0.15 (-0.15,-0.13)	0.04 (0.04,0.04)	-0.15 (-0.15,-0.13)	0.05 (0.05,0.06)	-0.15 (-0.15,-0.13)
Western Europe	0.39 (0.10,0.59)	-0.27 (-0.43,-0.04)	3.13 (3.08,3.19)	-1.83 (-2.25,-1.61)	4.97 (4.90,5.05)	-2.15 (-2.46,-1.84)	6.69 (6.57,6.80)	-2.16 (-2.57,-1.84)
Rest of Southern Africa	1.49 (0.96,1.59)	4.87 (4.68,5.60)	4.84 (4.74,4.93)	3.57 (3.47,3.71)	7.27 (7.11,7.44)	3.57 (3.46,3.70)	9.70 (9.48,9.92)	3.56 (3.43,3.70)
Central Europe	0.24 (0.07,0.46)	-0.33 (-0.44,-0.22)	1.33 (1.09,1.61)	-0.90 (-0.96,-0.88)	2.62 (2.58,2.66)	-1.66 (-1.76,-1.07)	3.87 (3.52,4.16)	-1.71 (-1.76,-1.62)
Turkey	-	-	-	-	-	-	-	-
Ukraine Region	0.14 (0.00,0.31)	-0.13 (-0.25,-0.03)	0.64 (0.63,0.66)	-0.36 (-0.47,-0.25)	0.96 (0.95,0.99)	-0.44 (-0.47,-0.25)	1.57 (1.32,1.64)	-0.54 (-0.57,-0.47)
Central Asia	0.00 (0.00,0.00)	0.02 (0.01,0.03)	0.00 (0.00,0.00)	0.02 (0.01,0.03)	0.01 (0.01,0.01)	0.02 (0.01,0.03)	0.01 (0.01,0.01)	0.02 (0.01,0.03)
Russia region	0.15 (0.03,0.28)	0.84 (0.64,1.02)	3.15 (1.95,4.32)	-1.43 (-2.08,-0.52)	7.85 (6.43,9.22)	-3.81 (-4.38,-3.36)	13.05 (12.41,13.60)	-5.84 (-6.55,-5.49)
Middle East	-	-	-	-	-	-	-	-
India	0.00 (0.00,0.12)	0.18 (0.15,0.20)	0.25 (0.24,0.26)	0.02 (-0.01,0.12)	0.38 (0.37,0.39)	0.01 (-0.02,0.08)	0.51 (0.49,0.52)	0.01 (-0.02,0.08)
Korea region	0.13 (0.00,0.26)	-0.11 (-0.23,-0.01)	0.54 (0.53,0.55)	-0.29 (-0.36,-0.23)	0.81 (0.79,0.83)	-0.29 (-0.36,-0.23)	1.09 (1.05,1.11)	-0.29 (-0.36,-0.23)
China region	1.36 (1.03,1.61)	-0.23 (-0.43,-0.01)	5.42 (5.27,5.56)	-2.16 (-2.47,-2.07)	8.54 (8.42,8.65)	-2.63 (-3.06,-2.19)	12.10(11.61,12.49)	-3.18 (-3.23,-3.12)
Southeastern Asia	0.88 (0.86,0.90)	1.52 (1.33,1.65)	1.82 (1.77,1.85)	1.49 (1.31,1.61)	2.72 (2.66,2.78)	1.49 (1.31,1.61)	3.63 (3.55,3.71)	1.49 (1.31,1.61)
Indonesia region	-	-	-	-	-	-	-	-
Japan	0.10 (0.00,0.23)	-0.04 (-0.16,0.05)	0.47 (0.45,0.48)	-0.24 (-0.32,-0.16)	0.70 (0.68,0.72)	-0.24 (-0.32,-0.16)	0.93 (0.91,0.96)	-0.24 (-0.32,-0.16)
Rest of South Asia	-	-	-	-	-	-	-	-
Oceania	0.20 (0.19,0.27)	1.71 (1.60,1.88)	2.37 (1.62,2.94)	0.47 (-0.14,1.15)	6.17 (5.72,6.90)	-1.54 (-1.88,-1.38)	9.18 (8.51,10.26)	-2.52 (-2.81,-2.17)
Global	9.31 (7.19,11.93)	41.82 (36.12,46.59)	37.83 (35.74,41.73)	27.50 (23.51,31.04)	67.96 (65.96,71.25)	18.82 (16.30,21.23)	98.62(95.98,100.77)	12.61 (11.16,13.67)

The title and abstract of the paper focus on the combination of CH4 and land-based mitigation, but the conclusion section doesn't integrate these nor give context from the literature. The abstract indicates that methane mitigation offsets 88-212 GtC, while land-based mitigation offsets 51-100 GtC, which is much smaller. The methane mitigation analysis is exogenous to this paper, but is this range robust across models that do include this? Does the methane range include the offsetting effects from wetland emissions?

Response 26: ***We refer to Responses 1 and 13, where we explain why the methane mitigation analysis is not exogenous. We add further text to the Conclusions to address the integration of the mitigation scenarios and comparison with relevant literature.***

The analysis does include the offsetting effect of wetland methane emissions. We state in the Abstract (lines 25-26) "The analysis includes the effects of the methane and carbon-climate feedbacks from wetlands and permafrost thaw, which we have shown previously to be significant constraints on the AFFEBs". We also state in the Conclusion (line 533-534) "We utilise the detailed JULES land-surface model, which includes the temperature sensitivity of methanogenesis (Comyn-Platt et al., 2018) and the effect of CH_4 emissions on land carbon storage via ozone impacts on vegetation …".

Change(s) to the Paper: We amend the sentence in the Conclusion (line 663-665) to make explicit that we are referring to wetlands (and permafrost thaw).

We utilise the detailed JULES land-surface model, which includes the temperature sensitivity of ~~methanogenesis~~ methane production from wetlands and permafrost thaw (Comyn-Platt et al., 2018) and the effect of CH_4 emissions on land carbon storage via ozone impacts on vegetation …

We amend the text to address the integration (lines 669-683):

This analysis quantifies the regional differences in potential CH_4 and/or land-based strategies to aid mitigation of climate change. ~~Our~~ We present our findings ~~are presented~~ within a full probabilistic framework, capturing uncertainty in climate projections across the CMIP5 ensemble, as well as process uncertainties associated with the strength of natural CH_4 climate feedbacks from wetlands and ozone-induced vegetation damage. Globally, mitigation of anthropogenic CH_4 emissions and the optimised land-based mitigation can potentially offset (i.e. allow extra) fossil fuel carbon dioxide emissions of 188-212 GtC and 51-100 GtC, respectively. These bounds are almost independent of the eventual global-warming target, or the climate sensitivity of the climate models emulated. As shown in Sect.3.1, the CH_4 and land-based mitigation strategies show little interaction and their potential can be summed to give a comparable result to the corresponding coupled simulation. This decoupling is despite the CH_4 emissions from the agricultural sector being influenced by land use choices. We can therefore treat the two mitigation strategies as independent, and sum their individual potentials. Such linearity enables simpler and more direct comparisons between the carbon budgets of methane and land-based mitigation strategies. Some caveats remain however. ~~We acknowledge that l~~Land surface models still require refinement, alongside improved characterisation of the assumptions inherent in the socio-economic pathways and IAM modelling. Further, we do not allow for the reduced emissions from fossil fuel combustion due to the bioenergy crop being grown (or the converse when bioenergy crops are replaced in the Natural model run), as this would require energy sector modelling that is beyond the scope of this study.

We also amend the text (lines 716-730):

Stabilising the climate primarily requires urgent action to mitigate CO_2 emissions. However, CH_4 mitigation ~~has the potential to make the Paris targets more achievable by~~may offset~~ting~~ up to 188-212 GtC of anthropogenic CO_2 emissions, while still meeting the same global-warming targets. This offset is a direct consequence of the reduced radiative forcing by methane and of carbon cycle gains. These balances and related flexibilities have the potential to make the Paris targets more achievable. Our range of additional CO_2 emissions broadly~~This~~ applies to both the 1.5° and 2°C warming targets as the mitigation potential of the CH_4 scenario is similar for the two temperature pathways considered. Although there are differences in the precise methane emission scenarios used, our mitigation potential is similar to that given in Collins et al. (2018). That paper presents values of 155 or 235 GtC for offsetting CH_4 mitigation from a high to a medium or from a high to a low emission scenario, respectively. Our value, and those of Collins et al. (2018), can be compared to the increase of 130 GtC in the carbon budget between a no and a stringent CH_4 emission mitigation scenario estimated by Rogelj et al. (2015). More recently, Harmsen et al. (2020) have also investigated the mitigation potential of methane, although their results are expressed in terms of changes in radiative forcing and temperature, rather than carbon budgets. An advantage of our analysis remains the inclusion of climate response to altered radiative forcing, enabling understanding in terms of actual CO_2 emissions. We conclude that CH_4 mitigation would be effective globally as a contribution to constraining global warming, and especially so for the major CH_4-emitting regions of India, USA and China.

For the land-based mitigation, it would be useful if the conclusion section could provide some context for these results. What factors impact this range (e.g., under what conditions is this low, and under what conditions is this high?). How does this compare with what is assumed in the literature from IAM scenarios? Seems this might be much smaller than commonly assumed, why is that?

Response 27: ***We provide text comparing our results to those from IAM and identify possible reasons why our results might be lower, drawing on our previous work (cited paper by Harper et al, 2018).***

***Change(s) to the Paper**: We amend the text (lines 684-710):*

For the "Natural" land-based scenario (see Table 1), we find a mitigation potential of 50-55 GtC (183-201 $GtCO_2$). The land-based mitigation estimates vary over wide ranges, partly related to different assumptions on land use and carbon pools. Our results are within the wide range of the overall deployment of CO_2 removal by Agriculture, Forestry and Other Land Use (including afforestation and reforestation) to 2100 of 200 [0-550] $GtCO_2$ (Page 2.40 in IPCC, 2018) and of estimates of the cumulative potential to 2100 from 80 to 260 $GtCO_2$ (Table 2) in Minx et al. (2018). In the "BECCS" scenario, we obtain a geological carbon storage via BECCS (27±1 GtC median, interquartile range) similar to that (30±1 GtC) derived by Harper et al. (2018), for the same land use scenario (IM-1.9). Our result is lower as we include the natural methane feedbacks from wetlands and permafrost thaw. Inclusion of this better process description leads to ~10% reduction in carbon budgets (Comyn-Platt et al., 2018). These estimates for the geological carbon storage via BECCS are much lower than the corresponding value derived by the IMAGE IAM (130 GtC). Harper et al. discuss this difference, identifying a number of reasons for the lower value: the use of initial above ground biomass harvested in boreal forests for BECCS, the replacement of fossil-fuel based emissions in the energy system, as well as specific assumptions about crop yields, conversion efficiency, use of residues, the proportion of bioenergy crops used with CCS. Estimates of the BECCS contribution in the literature vary over a wide range (from 178 to >1000 $GtCO_2$, according to Minx et al., 2018), but in recent studies these result are typically revised downwards taking into account among others sustainability constraints (e.g. Fuss et al. 2018 suggests a potential of 0.5-5 $GtCO_2$ per year in 2050).

We investigate the efficacy of our "BECCS" scenario by increasing the productivity of BECCS (using a scale factor κ). From comparison with observed bioenergy crop yields, we argue that the scale factor could be between 1 and 3. We highlight how using this range of κ provides characterisation of an additional source of uncertainty on the land-based mitigation potential, and is therefore a key feature of our manuscript. In our optimised land-based mitigation scenario, which maximises the land carbon uptake (Sect 2.4.2, Eq. 10), the increased carbon removed by BECCS is often accompanied by a decrease in the carbon uptake from the "natural" vegetation that it replaces (as discussed in Sect. 3.3 and shown in Figure 12). This concern is equivalent to the statement in Harper et al. that the "use of BECCS in regions where bioenergy crops replace ecosystems with high carbon contents could easily result in negative carbon balance". Hence the particularly novel feature of our paper is that our optimal approach accounts explicitly for that trade-off, only suggesting BECCS where there is a net gain. ~~We quantify the sensitivity to the assumed productivity of bioenergy crops and the efficiency of the BECCS process. In consequence, our results for land-based mitigation strategies are nuanced, with considerable regional variations~~

Are both of these ranges across 1.5 and 2.0 targets? Does a 1.5 or 2.0 degree target shift either of these ranges significantly?

***Response 28:* We refer to General Point 5 (1.5°C warming vs. 2°C warming targets). The ranges are similar for the two warming targets. For that reason, we presented a single range across the two warming targets.**

***Change(s) to the Paper*: We amend the Abstract (28-36):**

Globally, mitigation of anthropogenic CH_4 emissions has large impacts on the anthropogenic fossil fuel emission budgets, potentially offsetting (i.e. allowing extra) carbon dioxide emissions of 188-212 GtC. Methane mitigation is beneficial everywhere, particularly for the major CH_4-emitting regions of India, USA and China. Land-based mitigation has the potential to offset 51-100 GtC globally, the large range reflecting assumptions and uncertainties associated with BECCS. The ranges for CH_4 reduction and BECCS implementation are valid for both the 1.5° and 2°C warming targets. That is the mitigation potential of the CH_4 and of the land-based scenarios is similar whether society aims for one or other of the final stabilised warming levels. Further, both the effectiveness and the preferred land-management strategy (i.e., AR or BECCS) have strong regional dependencies.

We amend the Conclusions (720-721):

Our range of additional CO_2 emissions broadly applies to both the 1.5° and 2°C warming targets, as the mitigation potential of the CH_4 scenario is similar for the two temperature pathways considered.

I noticed that the upper end of land mitigation given in the abstract is lower than the high end of the line provided in Figure 10. (Presumably you haven't allowed the BECCS scale factor to be as high as 6 in the main results?).

***Response 29:* The Editor is correct. This also links to the earlier comment about bioenergy productivity (Response 27). The lower end of the range is based on results using a BECCS scale factor of 1 and the upper end of the range is based on a BECCS scale factor of 3. We make this clear in the Conclusions. We already state in the Abstract that the large range of the land-based mitigation reflects "assumptions and uncertainties associated with BECCS" (line 30).**

***Change(s) to the Paper*: We include the following text with those to Response 27 (see above).**

We investigate the efficacy of our "BECCS" scenario by increasing the productivity of BECCS (using a scale factor κ). From comparison with observed bioenergy crop yields, we argue that the scale factor could be between 1 and 3. We use this range of κ as an additional source of uncertainty on the land-based mitigation potential.

Note that the journal's data policy requests that data and code associated with articles to be deposited in public data repositories. See: https://www.earth-system-dynamics.net/policies/data_policy.html. The paper does not currently follow best practices here. Please consider depositing key input and output data in a public data repository.

***Response 30:* We have created a github project, where we make available (a) the IMOGEN-JULES source code (as a zipped tarball); and (b) the post-processing scripts, which we use in the analysis and with which we generate the Figures. We will lodge key model outputs in a publically accessible repository.**

***Change(s) to the Paper*: We amend the Code and Data Availability section (lines 559-565):**

Code and Data Availability

The IMOGEN-JULES source code used in this work is available from the JULES code repository (https://code.metoffice.gov.uk/trac/jules/browser/main/branches/dev/annaharper/r7971_vn4.8_1P5_DEGREES_CCS, at JULES revision 14477, user account required). The rose suites used for the specific scenario and factorial runs are: u-as624, u-at010, u-at011, u-at013, u-av005, u-av007, u-av008, u-av009, u-ax327, u-ax332, u-ax455, u-ax456, u-ax521, u-ax523, u-ax524, u-ax525, u-bh009, u-bh023, u-bh046, u-bh081, u-bh084, u-bh098, u-bh103 and u-bh105. These can be found at https://code.metoffice.gov.uk/trac/roses-u/ (user account required).

The IMOGEN-JULES source code is also available as a zipped tarball from https://github.com/GarryHayman/Regional_Mitigation_Paper, as are the python scripts used for post-processing. Relevant outputs from the IMOGEN-JULES runs will be made available through a publically accessible data repository (tbc) .

Requests for information about the ~~All~~ code, data ~~and~~ or parameterisations ~~are available on request~~can be made to the corresponding author.