"**Regional variation in the effectiveness of methane-based and land-based climate mitigation options**"
Hayman et al. (ESD-2020-24)

Author Response

General

We are grateful to the two reviewers for their comments, which have helped us to improve the paper and make it clearer.

The reviewer comments about "reframing the study" and "reorganising" Section 2 suggest significant issues with the paper. Although we were advised that major revisions are needed, the changes made have nearly all been to improve the clarity of the paper or to provide further information. Our model results, analyses and interpretation remain unchanged.

- Reframing the study: It was certainly not our intention to suggest that methane mitigation is an alternative to mitigation of fossil fuel emissions. To avoid this impression, we make changes to the abstract, Section 3 and the conclusions (as given in Responses 1.1 and 1.16).
- Restructuring of Sections 2.3-2.5. We rework the original sections 2.3 and 2.5. Section 2.4 is unaffected by this. We move and integrate the first two paragraphs of the original Section 2.5 into Section 2.3. We integrate the third paragraph of the original Section 2.5 into Section 2.3.3 (Model Runs). We delete the fourth and final paragraph, as this repeats material in the original Section 2.3 and is therefore no longer required (see Responses 1.9 and 2.9).

We accept that there was some inconsistency in the abbreviations used for the land-based mitigation scenarios (bioenergy: CCS/IM-1.9; natural: Natural Land/IM-1.9N). We now define and use a consistent set of model scenario descriptors and abbreviations:

- Control ("CTL")
- "CH4" for the methane mitigation scenario
- "BECCS" for the land-based mitigation using bioenergy with carbon capture & storage
- "Natural" for the variant land-based mitigation scenario
- Coupled ("BECCS+CH_4") and coupled (Natural+CH_4") for the corresponding combined land-based and methane mitigation scenarios.

We make changes to the text, figures and tables to ensure a consistent use of these scenario descriptors and abbreviations.

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 reviewer comments refer to the originally submitted manuscript. The line numbers for the "Change(s) to Paper" refer to the track change versions of the paper and Supporting Information that are included in this document (after the Author Response).

"**Regional variation in the effectiveness of methane-based and land-based climate mitigation options**"
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Author Response to Reviewer 1 Comments

Reviewer 1

<u>Summary</u>

The authors present and apply a method for examining the contributions of methane and land-based mitigation to meeting 1.5 and 2 degree warming targets. They give a thorough description of their modeling framework and present the results of an ensemble analysis of individual and combined contributions of methane vs land mitigation to emissions reductions and how these reductions can allow for complementary fossil fuel emissions. They conclude that methane mitigation contributes 2-4 times more reduction potential than land-based mitigation, depending on the BECCS assumptions. They also show that there are regional differences in how effective BECCS is compared to afforestation/reforestation, and estimate that bioenergy crop productivity must be fairly high in some places (with low transport losses) for it to be an effective strategy. They also show that water usage for BECCS may impose limits to BECCS deployment in some regions.

<u>Overall Response</u>

This is an interesting and well-thought-out paper that examines key uncertainties in how to reach 1.5 and 2 degree targets. While I am not an expert in methane dynamics, the description of the framework is detailed enough to convey that the approach is reasonable for this analysis (assuming the methane references this is based on also have adequate methods). My main concern is the framing, and there is also some clarification of the experimental design that is needed. I elaborate on these two things here, with more detail below.

1) While I can appreciate the goal of presenting alternatives that allow for some fossil fuel emissions in these strict scenarios, this goal is not clearly articulated, and I am not sure that it is the most reasonable framing for this issue. Given that these are idealized scenarios and that there is considerable uncertainty on the adoption of mitigation policies, the actual extent of implementation of mitigation strategies, the assumptions and efficacy of mitigation strategies, and the modeling method, the estimated reduction levels here indicate that these approaches are more at the level of additional measures that would help ensure meeting particular targets under certain fossil fuel emission scenarios, rather than allow for more emissions to occur. Stating that doing these other mitigation actions allows for more fossil fuel emissions simply shifts responsibility away from the primary cause and increases the risk that these targets would not be met (the probability of exceedance is not particularly low to begin with). I suggest re-framing the study as additional mitigation potential or "insurance" mitigation potential. Barring a complete rework of the framing of the study away from allowing more fossil fuel emissions and toward additional mitigation potential, there at least needs to be more discussion regarding the magnitude of these results in relation to the large uncertainties inherent in mitigation approaches, idealized scenarios, and modeling.

<u>Response 1.1:</u> It was certainly not our intention to suggest that methane mitigation is an alternative to CO_2 mitigation. To avoid this impression, we will make the following changes:

<u>a)</u> We replace the last line of the abstract with: "Although the primary problem 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".

b) ***By rewriting the last three sentences of the paper as: "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. We conclude that CH_4 mitigation would be effective globally and especially so for the major CH_4-emitting regions of India, USA and China".***

Change(s) to Paper: For (a). We amend lines 32-36 (page 1), showing the added and ~~deleted~~ text:

"~~Our results highlight the extra potential CO_2 emissions that can occur, while still keeping global warming below key warming thresholds, by investment in regionally appropriate mitigation strategies~~ 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".

For (b): We amend lines 595-600 (page 19), showing the added and ~~deleted~~ text:

"~~Our overarching finding is however robust to these uncertainties. We conclude that CH4 mitigation can be a highly effective route to meeting the Paris Agreement targets, and could offset up to 188-212 GtC of anthropogenic CO_2 emissions. It is effective globally and especially so for the major CH_4-emitting regions of India, USA and China~~ 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. We conclude that CH_4 mitigation would be effective globally and especially so for the major CH_4-emitting regions of India, USA and China".

See also Response 1.16, where we add the following sentence (lines 450-451) "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".

2) The description and figures and tables associated with the experimental design and its corresponding conditions are inconsistent and confusing.

Response: We respond below to the specific reviewer comments on these points.

Specific comments and suggestions

Abstract

Lines 29-31: You should include that BECCS assumptions in general contribute to most of this range.

Response 1.2: We will amend the abstract to include this point about the BECCS assumptions.

Change(s) to Paper: At line 30, we add "the large range reflecting assumptions and uncertainties associated with BECCS".

Introduction

You should include a description and examples of the expected emissions for 1.5 and 2 degree targets, which generally indicate that total (and fossil fuel) emissions need to drop to zero or negative to reach these goals. This provides a better context for why you are looking at how methane and land mitigation can alleviate the pressure to eliminate fossil fuel emissions completely.

Response 1.3: ***The idealised temperature pathways used in this work imply the need to drop to zero emissions (lines 209-210). In our previous work (cited paper by Comyn-Platt et al., 2018), we derive the parameters for the temperature pathways from comparison with CMIP5 simulations for the RCP2.6 scenario (Supplementary Information, Figure 2 of Comyn-Platt et al., 2018).***

We add remaining carbon budget for the 1.5°C and 2°C warming targets, equivalent to the discussion we gave in our earlier paper (cited paper by Comyn-Platt et al., 2018) and also from the published literature and IPCC reports. As indicated above, we amend the text to make explicit the need for complete removal of fossil carbon emissions and the likely need for negative emission technologies.

Change(s) to Paper: At line 42, we add:

"The IPCC Special Report on Global Warming of 1.5°C (IPCC, 2018) gives the median remaining carbon budgets between 2018 and 2100 as 770 GtCO$_2$ (210 GtC) and 1690 GtCO$_2$ (~461 GtC) to limit global warming to 1.5°C and 2°C, respectively. These budgets represent ~20 and ~41 years at present-day emission rates. The actual budgets could however be smaller, as they exclude Earth system feedbacks such as CO$_2$ released by permafrost thaw or CH$_4$ released by wetlands".

We also include the underlined text in lines 46-49:

"Meeting the Paris Agreement goals will, therefore, require sustained reductions in sources of fossil carbon emissions, other long-lived anthropogenic greenhouse gases (GHGs) and some short-lived climate forcers (SLCFs) such as methane (CH$_4$), alongside increasingly extensive implementations of carbon dioxide removal (CDR) technologies (IPCC, 2018)".

Approach and Methodology

line 149: What is the first variable k?

Response 1.4: ***k is a dimensionless scaling constant such that the global annual wetland methane emissions are 180 Tg CH$_4$ in 2000. We will add this sentence.***

Change(s) to Paper: At line 160, we add: "k is a dimensionless scaling constant such that the global annual wetland methane emissions are 180 Tg CH$_4$ in 2000 (as described in Comyn-Platt et al. (2018))"

line 172: It isn't clear how the global annual CH4 concentration is used to linearly interpolate monthly ozone values.

Response 1.5: ***We do not model tropospheric ozone production from methane explicitly in IMOGEN. Instead, we use two sets of monthly near-surface O$_3$ concentration fields (January-December) from HADGEM3-A GA4.0 model runs, the sets corresponding to low (1285 ppbv) and high (2062 ppbv) global mean atmospheric CH$_4$ concentrations. We assume that the atmospheric O$_3$ concentration responds linearly to the atmospheric CH$_4$ concentration in each grid cell. We derive separate linear relationships for each month and grid cell, and use these to calculate the surface O$_3$ concentration from the corresponding atmospheric CH$_4$ concentration as it evolves during the IMOGEN run.***

We will amend the text using the above.

Change(s) to Paper: We amend the text from line 179, including ~~the deleted text~~, to:

"…, we do not model tropospheric ozone production from CH_4 explicitly in IMOGEN. Instead, we use two sets of monthly near-surface O_3 concentration fields (January-December) from HADGEM3-A GA4.0 model runs, with the sets corresponding to~~we take two sets of monthly near-surface O3 concentration fields calculated using the HADGEM3-A GA4.0 model for~~ low (1285 ppbv) and high (2062 ppbv) global mean atmospheric CH_4 concentrations (Stohl et al., 2015). We assume that the atmospheric O_3 concentration in each grid cell responds linearly to the atmospheric CH_4 concentration. We derive separate linear relationships for each month and grid cell, and use these to calculate the surface O_3 concentration from the corresponding global atmospheric CH_4 concentration as it evolves during the IMOGEN run.~~We regrid these fields (1.875°x1.25° horizontal grid) to the spatial grid of IMOGEN-JULES (3.75°x2.5° horizontal grid). We then linearly interpolate between the respective months in the regridded O3 fields using the global annual atmospheric CH4 concentration~~".

lines 203-204? Why only the non-CO_2 components? If the models use different radiation schemes the CO2 component could also contribute to this uncertainty. Unless the CO_2 radiative forcing is calculated the same way across the GCMs and in IMOGEN?

<u>Response 1.6:</u> From the cited paper by Huntingford et al. (2010), IMOGEN uses four parameters for the energy balance model: these are climate feedback parameters over land and ocean, λ_l and λ_o (W m^{-2} K^{-1}) respectively, oceanic "effective thermal diffusivity", κ (W m^{-1} K^{-1}) representing the ocean thermal inertia and a land-sea temperature contrast parameter, ν, linearly relating warming over land, ΔT_l (K) to warming over ocean, ΔT_o (K), as $\Delta T_l = \nu \Delta T_o$. The climate feedback parameters (λ_l and λ_o) are calibrated using GCM data for top of the atmosphere radiative fluxes, mean land and ocean surface temperatures, along with an estimate of the radiative forcing modelled by the GCM for the CO_2 changes. Thus, IMOGEN emulates the radiative forcing of CO_2 within the individual GCMs.

For a given prescribed trajectory in temperature, and pathway in atmospheric non-CO_2 greenhouse gas emissions, we calculate compatible CO_2 emissions. These emissions trajectories are different, dependent on which climate or Earth system (ES) model is emulated (via IMOGEN).

<u>Change(s) to Paper</u>: We add the following paragraph (lines 204-210)

"The EBM includes a simple representation of the ocean uptake of heat and CO_2 and uses a separate set of four parameters for each climate and Earth system model emulated (Huntingford et al., 2010): the climate feedback parameters over land and ocean, λ_l and λ_o (W m^{-2} K^{-1}) respectively, the oceanic "effective thermal diffusivity", κ (W m^{-1} K^{-1}) representing the ocean thermal inertia and a land-sea temperature contrast parameter, ν, linearly relating warming over land, ΔT_l (K) to warming over ocean, ΔT_o (K), as $\Delta T_l = \nu \Delta T_o$. The climate feedback parameters (λ_l and λ_o) are calibrated using model-specific data for the top of the atmosphere radiative fluxes, the mean land and ocean surface temperatures, along with an estimate of the radiative forcing modelled for the CO_2 changes."

We amend lines 227-229, showing <u>added</u> and ~~deleted~~ text "<u>As we have a model-specific estimate of the radiative forcing modelled for the CO_2 changes (see above),</u> ~~We~~<u>we</u>, therefore, attribute the spread in ΔQ to the uncertainty in the non-CO_2 radiative forcing component".

line 208: They "use" or "define" a framework?

<u>Response 1.7:</u> Accepted, missing word in "Huntingford et al. (2017) a framework"

<u>Change(s) to Paper</u>: Line 233 now reads: "Huntingford et al. (2017) <u>define</u> a framework"

line 207: "emissions"

Response 1.8: ***We will add "of greenhouse gases and short-lived climate forcers" after emissions in "model the efforts of humanity to limit emissions and, if necessary, capture atmospheric carbon"***

Change(s) to Paper: Line 234 now reads: "model the efforts of humanity to limit emissions of greenhouse gases and short-lived climate forcers, and, if necessary, capture atmospheric carbon".

lines 219-265: (section 2.3) This is very confusing and doesn't align with figure 3 or table 2. Table 2 is the most clear expression of the experimental design and should be used to organize this section and should be referenced up front. I suggest starting this section with a clear explanation of how many scenarios there are and each of the distinct components used to build them. Also, the nomenclature across the text, table 2, and figure 3 is inconsistent, adding to the confusion. It is also unclear how you reach different temperatures for control simulation, which appears to have a prescribed radiative forcing. I presume that the total radiative forcing is not prescribed, and that CO2 conc. and associated CH4 conc. feedbacks adjust to meet the prescribed temperature.

Response 1.9: ***With this and the comments from Reviewer 2, we restructure Section 2.3-2.5 to make the scenarios used clearer, to remove any inconsistencies and to avoid any repetition. See also the response below to the comment on lines 328-353.***

The reviewer is correct that "the total radiative forcing is not prescribed, … adjust to meet the prescribed temperature" .We will expand the text on the inverse version of IMOGEN to make this clear (lines 197-206).

Change(s) to Paper: We add the following text on the radiative forcing to Section 2.2.1 (lines 220-221) "In this study, we use the inverse version of IMOGEN, which follows prescribed temperature pathways (Fig. 3(a)), to derive the total radiative forcing (ΔQ [total]) and then the CO_2 radiative forcing (ΔQ [CO_2]), using Eq. 2".

We rework the original sections 2.3 and 2.5. Section 2.4 is unaffected by this. We move and integrate the first two paragraphs of the original Section 2.5 into Section 2.3. We delete the fourth and final paragraph, as this repeats material in Section 2.3 and is therefore no longer required (see also Response 2.9).

As indicated in the general comments, we define and use a consistent set of model scenario descriptors and abbreviations: Control ("CTL"), "CH_4" for the methane mitigation scenario, "BECCS" for the land-based mitigation using bioenergy with carbon capture & storage, "Natural" for the variant land-based mitigation scenario, coupled ("BECCS+CH_4") and coupled ("Natural+CH_4"), for the corresponding combined land-based and methane mitigation scenarios.

We make the following changes to Section 2.3 (lines 243-322), showing added and ~~deleted~~ text:

2.3 Scenarios and model runs

We undertake a control run, and other simulations with anthropogenic CH_4 mitigation or land-based mitigation, stabilising at either 1.5°C or 2.0°C warming without a temperature overshoot. We denote the control run as "CTL", the anthropogenic CH_4 mitigation scenario, a land-based mitigation scenario using BECCS and a variant land-based scenario focussing on AR, as "CH_4", as "BECCS", "Natural" respectively. We also undertake runs combining the CH_4 and land-based mitigation scenarios (coupled "BECCS+CH_4" and coupled "Natural+CH_4") to determine if there are any non-linearities when we combine these mitigation scenarios. We summarise the key assumptions of these scenarios in Table 1.

Commented [HGD1]: First paragraph of original Section 2.5

We use future projections of atmospheric CH_4 concentrations and LULUC from the IMAGE SSP2 projections (Doelman et al., 2018) for both the methane and land-~~use~~ based mitigation

strategies. 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). ~~We denote the RCP1.9 pathway as IM-1.9 and the "baseline" pathway as IM-BL~~.

2.3.1 Methane: baseline and mitigation scenario

The anthropogenic CH_4 emission increase from 318 Tg ~~per annum~~ yr^{-1} in 2005 to 484 Tg ~~per annum~~ yr^{-1} in 2100 in the IMAGE SSP2 baseline scenario, but fall to 162 Tg ~~per annum~~ yr^{-1} in 2100 in the IMAGE SSP2 RCP1.9 scenario. The sectoral ~~methane~~ CH_4 emissions in 2005 (Energy Supply & Demand: 113; Agriculture: 136; Other Land Use (primarily burning): 18; Waste 52, all in Tg ~~per annum~~ yr^{-1}) are in agreement with the latest estimates of the global methane cycle (Saunois et al., 2019). As summarised in Supplementary Information, Table SI.1, the reduction in CH_4 emissions from specific source sectors is achieved as follows: (a) coal production by maximising ~~methane~~ CH_4 recovery from underground mining of hard coal; (b) oil/gas production & distribution, through control of fugitive emissions from equipment and pipeline leaks, and from venting during maintenance and repair; (c) enteric fermentation, through change in animal diet and the use of more productive animal types; (d) animal waste by capture and use of the ~~methane~~ CH_4 emissions in anaerobic digesters; (e) wetland rice production, through changes to the water management regime and to the soils to reduce methanogenesis; (f) landfills by reducing the amount of organic material deposited and by capture of any ~~methane~~ CH_4 released; (g) sewage and wastewater, through using more wastewater treatment plants and also recovery of the ~~methane~~ CH_4 from such plants, and through more aerobic wastewater treatment. The levels of reduction vary between sectors, from 50% (agriculture) to 90% (fossil-fuel extraction and delivery). The abatement costs are between US$ 300-1000 (1995 US$) (Supplementary Information, Table SI.1). Figure 4 presents the IMAGE baseline and RCP1.9 CH_4 emission pathways globally and for selected IMAGE regions, including the major-emitting regions of India, USA and China (Supplementary Information, Figure SI.1 shows the emission pathways for all 26 IMAGE regions). These two methane emission pathways define our "CTL" and "CH4" scenarios, respectively.

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

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)). It represents a control scenario within which agricultural land is accrued to feed growing populations associated with the SSP2 pathway and with no deployment of BECCS. Three types of land-based climate change mitigation are implemented in the IMAGE land use mitigation scenarios (Doelman et al., 2018): (1) bioenergy; (2) reducing emissions from deforestation and degradation (REDD or avoided deforestation); and (3) reforestation of degraded forest areas. For the IM-1.9 scenario, there are high levels of REDD and full reforestation. The scenario assume a food-first policy (Daioglou et al., 2019) so that bioenergy crops are only implemented on land not required for food production (e.g., abandoned agricultural crop land, most notably, in central Europe, southern China and eastern USA, and on natural grasslands in central Brazil, eastern and southern Africa, and Northern Australia (Doelman et al., 2018)). The IM-1.9 scenario also requires bioenergy crops to replace forests in temperate and boreal regions (notably Canada and Russia). The demand for bioenergy is linked to the carbon price required to reach the mitigation target (Hoogwijk et al., 2009). In this

scenario, the area of land used for bioenergy crops expands rapidly from 2030 to 2050, reaching a maximum of 550 Mha in 2060, and then declining to 430 Mha by 2100. ~~Table 1~~ Table 2 gives the maximum area of BECCS deployed in each IMAGE region for the IM-1.9 scenario. This defines the land use in the "BECCS" scenario.

We define a third LULUC pathway, which is identical to the ~~IM-1.9 pathway~~"BECCS" scenario, except that any land allocated to bioenergy crops is allocated instead to natural vegetation, i.e., areas of natural land, which are converted to bioenergy crops, remain as natural vegetation, and areas, which are converted from food crops or pasture to bioenergy crops, return to natural vegetation. We make no allowance for any changes in the energy generation system, as this would require energy sector modelling that is beyond the scope of this study. We denote this scenario as ~~IM-1.9N~~"Natural". Table 2~~Table 1~~ also summarises the main differences in land use between the ~~IM-1.9~~BECCS and ~~IM-1.9N~~Natural scenarios for each IMAGE region.

Figure 5 presents time series of the land areas calculated for trees and prescribed for agriculture (including bioenergy crops) and bioenergy crops for the "BECCS" and "Natural" scenarios for the Russia and Brazil IMAGE regions, each as a difference to the baseline scenario (IM-BL). Supplementary Information, Figure SI.3 is equivalent to Fig. 5 for all the IMAGE regions.

2.3.3 Model runs

For each temperature pathway (1.5°C or 2.0°C) and for the baseline and each mitigation scenario, the set of factorial runs comprises a 136-member ensemble (34 GCMs x 2 ozone damage sensitivities x 2 methanogenesis Q_{10} temperature sensitivities). In all model runs, we include 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 (Comyn-Platt et al., 2018).

As shown in Fig. 1, we use a number of input or prescribed datasets: (a) time series of the annual area of land used for agriculture, including that for BECCS if appropriate; (b) time series of the global annual mean atmospheric concentrations of CH_4 (and N_2O for the radiative forcing calculations of CO_2 and CH_4); (c) time series of the overall radiative forcing by SLCFs and non-CO_2 GHGs (corrected for the radiative forcing of CH_4); and (d) time series of annual anthropogenic CH_4 emissions (used in the post-processing step). We take these from the IMAGE database for the relevant IMAGE SSP2 scenario (baseline or SSP2-1.9). Table 1 lists the factorial runs, their key features and the prescribed datasets used (for agricultural land and BECCS, anthropogenic emissions and atmospheric concentrations of methane and the non-CO_2 radiative forcing).

Commented [HGD2]: Second and third paragraphs of original Section 2.5

Figure 6~~Figure 3(c)-(h)~~ presents the effect of these scenarios on the modelled atmospheric CH_4 and CO_2 concentrations. We adjust the ~~prescribed~~ input atmospheric CH_4 concentrations to allow for the interannual variability in the wetland CH_4 emissions, as described in Sect. 2.2.1. The major control on the modelled atmospheric CH_4 concentrations is the methane emission pathway followed, with the temperature pathway (1.5° versus 2°C warming) having a minor effect. For CO_2, on the other hand, the temperature and the CH_4~~methane~~ emission pathways both lead to increased atmospheric CO_2 concentrations, with the temperature pathway having a slightly larger effect.

line 231: specify "… reduction in CH4 emissions …"

***Response 1.10:* We will amend the text as suggested.**

Change(s) to Paper: Line 265 now reads "the reduction in CH_4 emissions from specific source sectors"

line 240: figures 4 and 3 should be switched

<u>Response 1.11:</u> This may follow from the restructuring of Sections 2.3-2.5.

<u>Change(s) to Paper</u>: Following the re-working of Sections 2.3-2.5, we split Figure 3. Panels (a) and (b) of the original Figure 3 form Figure 3 in the revised paper (page 31). Figure 4 remains unchanged (page 32) and Panels (c)-(h) of the original Figure 3 form a new Figure 6 (page 34). In consequence, we have had to renumber the subsequent figures.

lines 267-281: Are you assuming that carbon stored in the atmosphere is just CO2?

<u>Response 1.12:</u> The reviewer is correct that the calculation of the atmospheric carbon store in the post-processing does not take account of CH_4. This is a reasonable approximation, however, given the relative magnitude of the atmospheric concentrations of methane (~2 ppmv at the surface) and carbon dioxide (400 ppmv).

For the contemporary period, IMOGEN retains ~50% of carbon dioxide emissions in the atmosphere, after land and ocean draw down is accounted. In that sense, there is closure of direct carbon units. For methane, a slightly different approach is used. We calculate the atmospheric CH_4 concentrations from the CH_4 emissions (from both anthropogenic and natural sources) and an atmospheric loss term, parameterised via a methane turnover lifetime. We take account of the radiative forcing of atmospheric methane and its effect on the terrestrial carbon cycle (through tropospheric O_3 production and vegetation O_3 damage).

<u>Change(s) to Paper</u>: We add the following text at line 330: " 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)".

line 296: Is there a better word than "productivity" here? Maybe "efficacy" or "mitigation potential"?

<u>Response 1.13:</u> We will amend the text along the lines suggested.

<u>Change(s) to Paper</u>: Line 358 now reads "The <u>efficacy</u> of the BECCS scheme implemented in JULES"

lines 328-353: this section 2.5 should be moved up and merged with section 2.3 (see previous comment) in order to clarify the experimental design.

<u>Response 1.14:</u> As per the responses to the comment on lines 219-265 and from Reviewer 2, we will restructure sections 2.3-2.5. Some of the existing Section 2.5 will be moved, but the material on optimisation and mitigation potential needs to come after Section 2.4.

<u>Change(s) to Paper</u>: This is covered by the "Change(s) to Paper" for Response 1.9.

<u>Results and Discussion</u>

line 367: and saturation effects?

<u>Response 1.15:</u> We reconfirm this sentence is correct, but there would also be eventual saturation. The oceanic draw down of CO_2 is based on the work of Joos et al (1996), with the equations specific to IMOGEN given in the Appendix of Huntingford et al (2004). The CO_2 draw down flux is based on the difference between atmospheric CO_2 and CO_2 concentrations near the ocean surface. The oceanic CO_2 concentration is calculated as a weighted integration in time of this flux, and where such weighting accounts for oceanic diffusive mixing. If atmospheric CO_2 rises quickly, there is a co-benefit as the oceanic draw down will rise due to the gradient between the two CO_2 concentrations. However, the reviewer is correct, that under climate stabilisation, saturation will occur and this flux will decrease to zero.

***Change(s) to Paper*: We add the underlined text to lines 434-435 "the oceanic drawdown of ~~carbon dioxide~~ CO_2 rises (although it eventually falls to zero under climate stabilisation and there would also be implications for ocean acidification)".**

lines 370-378: I would also like to see this put into the context of overall scenario uncertainty, as this is highly dependent upon human action. For example, the methane-related-mitigation AFFEB (over 85 years) is on the order of only about 6 years of late century SSP5-8.5 emissions, which is a reference scenario. In the greater context, the potential methane mitigation effects represent more of a cushion or insurance approach to meeting idealized targets.

***Response 1.16:* We use the SSP2 reference scenario as the control scenario. The baseline forcing in this scenario is slightly above 6 W m^{-2}. The SSP5 8.5 scenario is a long-way from the aspirations of the Paris agreement. This paper focusses on the more policy-relevant question of how CH_4 mitigation can contribute to meeting the Paris targets. In response to this and related comments, we make it clearer that CH_4 mitigation is in no way an alternative to CO_2 mitigation.**

***Change(s) to Paper*: We add the following sentence (lines 450-451) "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".**

lines 379-383: This appears to be true, but this may be a coincidence as the dynamics appear to be quite different between separate and coupled mitigation. The figures do not show the correct breakdowns for the linear sum.

***Response 1.17:* Although Figures 6 and 7 are correct and as the reviewer notes for Figure 6 (see below), adding the CH_4 mitigation (second bar) to any of the land-based mitigation options (bars 3-5) does not appear to give the corresponding coupled option (bars 6-8). This is because the gain in the land carbon store for the methane mitigation option is shown as a reduction from -70.8 GtC in the control run to -1.4 GtC in the methane mitigation option (median of ensemble). This then explains the positive changes shown for the land carbon stores in the coupled runs. Comparing the final two bars, there is very good agreement in the breakdown of the carbon stores for the coupled and linear (i.e., the sum of the individual) mitigation options. Thus, the dynamics and in the coupled and linear cases are almost identical.**

Although we state that "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, which is greater than the land carbon lost through land-use changes" (lines 363-365), this did not make clear of the size of the change. We will add a sentence to the text and figure caption to make the point about the change in the land carbon store for the methane mitigation option.

Figure 6

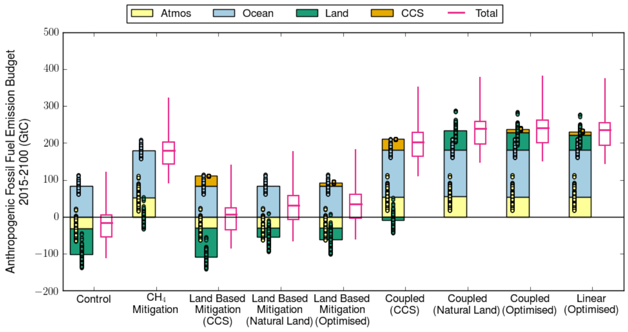
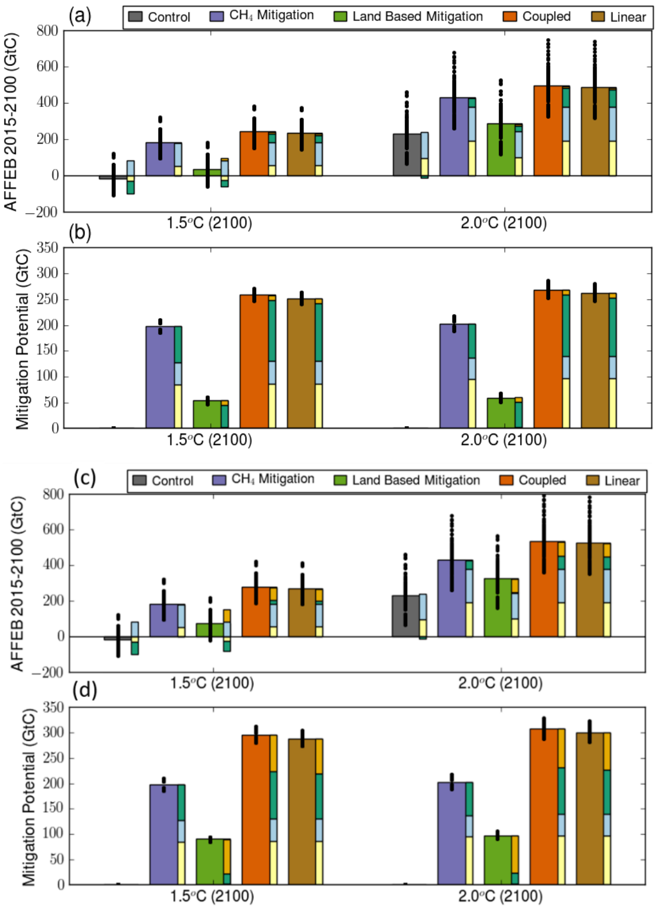


Figure 7



Change(s) to Paper: We add the following text (lines 438-441) "In both Figs. 8 and 9, it should be noted that the gain in the land carbon store for the "CH_4" mitigation option is 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). This then explains the positive changes shown for the land carbon stores in the coupled "BECCS+ CH_4" and coupled "Natural+ CH_4" scenarios ".

We also add the following text to the figure captions for the new Figures 8 (page 36) and 9 (page 37) [original Figures 6 and 7]: "Note that the gain in the land carbon store for the CH_4 scenario is 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)".

See also Response 1.26 and 1.27, which make the same comment on the figures.

lines 389-415: section 3.2 Is this for the 1.5 degree scenario only?

Response 1.18: We will amend the text and add a reference to Supplementary information, Figure 2, which shows the equivalent plot for 2°C of warming to Figure 10.

Change(s) to Paper: We add the underline text to line 464 "Globally across the two temperature targets, our simulations imply a removal of 27-30 GtC from the active carbon-cycle". We also add the following text (lines 487-488) "Supporting Information, Figure SI.3 shows the corresponding plots for the 2°C warming target".

lines 413-415: Clarify that this is the BECCS only amount (for only 1.5 degrees?), which is double the original amount. Also add the numbers for land mitigation potential shown in figure 7c-d, as these are apparently in the abstract (100 GtC) and are comparable to the numbers in the previous section. This also makes a better case for "strong sensitivity" to BECCS assumptions, although tripling productivity and reducing transport losses by 2/3 to get a doubling in reduction is hardly a "strong sensitivity."

Response 1.19: We apologise as we inadvertently gave the incorrect numbers for the carbon budgets. The correct text should read "We now find the global land-based mitigation potential to be ~~56-62~~ 88-100 GtC, as shown in Fig. 7(c) and (d). We use κ = 3 in the subsequent analysis of regional mitigation options and of BECCS water requirements." This is now consistent with the land-based bars in Figure 7d (second bar) and the upper range of 100 GtC given in the abstract. The range is based on the results from both the 1.5°C and 2°C runs for the optimised land-based mitigation.

Change(s) to Paper: We amend the text at lines 487-488: "We now find the global land-based mitigation potential to be ~~56-62~~88-100 GtC across the two temperature targets".

line 430: larger than what? the land mitigation? You should also note the exceptions here, which are abundant: canada, mexico, south america, brazil, west africa, south africa, korea, japan

Response 1.20: We were referring to the global impact of methane mitigation. As presented in Figures 9 and 10, the reviewer is correct that the land-based mitigation is larger than methane mitigation for a number of the IMAGE regions, especially when using a BECCS scaling factor κ = 3. As we are discussing the mitigation options at a regional level, we will amend lines 430-431 as shown "CH_4 mitigation ~~generally has a larger impact on emission budget reductions,~~ is an effective mitigation strategy for all regions, and especially the major methane emitting region."

Change(s) to Paper: We delete the underlined text in line 505: "CH_4 mitigation ~~generally has a larger impact on emission budget reductions ,~~ is an effective mitigation strategy for all regions".

line 473: "… regions that produce …"

***Response 1.21:* Accept text change**

***Change(s) to Paper*: We delete the underlined text in lines 554-555: "for the ~~eight~~ regions~~, which~~ that produce a substantial amount of BECCS".**

lines 481-482: This needs more explanation. It isn't clear from the figure that these three regions have water issues under this case, especially china. While two of them would use all water availability, one does not, and none appear to exceed availability.

***Response 1.22:* In the next comment, the reviewer has suggested adding the BECCS water demand and percent of available used to Table 4. We will use this information to clarify whether these IMAGE regions have issues with water availability.**

***Change(s) to Paper*: We add the following text (lines 555-559) "Tables 4a and 4b show the additional water requirements of BECCS calculated for 2060 and 2100, respectively, for the 2°C warming target. We find that the additional demand for BECCS would lead to an exceedence (or is >90%) of the available water for the Oceania and Rest of Southern Africa regions. We also find that the additional demand for BECCS is greater than the total water withdrawals from anthropogenic activities for the Canada and Brazil IMAGE regions".**

We amend the text (lines 568-570), showing added and ~~deleted~~ text: "Nevertheless, our results indicate that the additional water demand for BECCS ~~would make it impractical~~have large impacts in half of the regions substantially invested in BECCS: Oceania, Rest of South Africa, Brazil and Canada ~~and China (2060)~~".

line 469: Table 4 should include BECCS demand and percent of available used in the example cases. Then you would have a basis for the statement in lines 48-482.

***Response 1.23:* We will add these to Table4 or add as a new Table.**

***Change(s) to Paper*: We have added three additional columns to Table 4: (a) the additional water demand from BECCS; (b) the total water demand including that for BECCS, as a percentage of the available water; and (c) the water demand for BECCS as a percentage of total water demand including that for BECCS. We now have separate tables for 2060 (Table 4a, page 55) and 2100 (Table 4b, page 56).**

Conclusion

line 499: This "strong sensitivity" is not clear from the paper. The results can more clearly explain how BECCS mitigation can double, although based on tripling of productivity and a 2/3 reduction in transport losses, which nearly doubles the land mitigation potential. This is tremendous increase in BECCS efficacy to get this result, so I am not sure that it is a "strong sensitivity." And you don't show what figure 11 looks like with the original beccs values, to see how much difference the beccs efficacy makes on land cover. Also note that this has a much smaller relative effect on the total AFFEB.

***Response 1.24:* We accept the reviewer's viewpoint that our perturbations are relatively large so the changes do not necessarily imply a "strong sensitivity". We have therefore removed "strong" from line 499.**

***Change(s) to Paper*: We amend the text in line588 to "quantify ~~a strong~~ the sensitivity", deleting the text underlined.**

Tables and Figures

Figures 3 and 4 are out of order.

Response 1.25: ***This will be resolved with the restructuring of Sections 2.3-2.5. This is linked to Response 1.11.***

Change(s) to Paper*: *Following the re-working of Sections 2.3-2.5, we split Figure 3. Panels (a) and (b) of the original Figure 3 form Figure 3 in the revised paper (page 31). These show the temperature (panel a) and radiative forcing (panel b) pathways. Figure 4 remains unchanged (page 32). Panels (c)-(h) of the original Figure 3 form a new figure (Figure 6, page 34).

Figure 3 The legends and the caption and table 2 and the references in the text don't match, which makes the experimental design unclear. The CH4 plots are c, e, g

Response 1.26: ***The figure is intended to show key data inputs for or differences between the model runs to help inform reader's understanding of the paper. The titles of the panels are correct but we accept the figure and panels need careful reading. The other reviewer also commented that the figure is unclear. We will amend the figure to make it clearer (and potentially split the figure into two as part of the restructuring of Section 2.3-2.5).***

Change(s) to Paper:

We define a consistent set of model scenarios at the beginning of the revised Section 2.3 (lines 245-250) "We undertake a control run and other simulations with anthropogenic CH4 mitigation or land-based mitigation, stabilising at either 1.5°C or 2.0°C warming without a temperature overshoot. We denote the control run as "CTL", the anthropogenic CH_4 mitigation scenario as "CH_4", a land-based mitigation scenario using BECCS as "BECCS" and a variant land-based scenario focussing on AR as "Natural". We also undertake runs combining the CH_4 and land-based mitigation scenarios (Coupled "BECCS+CH_4" and Coupled "Natural+CH_4") to determine if there are any non-linearities when we combine these mitigation scenarios".

We amend the following abbreviations of the model scenarios in Table 2 (page 52): (a) "CCS" is replaced with "BECCS"; (b) "Natural Land" becomes "Natural", (c) "Coupled (CH_4+CCS)" becomes "Coupled (BECCS+CH_4)" and (d) "Coupled (CH_4+Natural Land)" becomes "Coupled (Natural+CH_4)".

Figure 6 (part of the original Figure 3) shows the modelled evolution of the atmospheric concentrations of CH_4 (the left-hand panels: a, c and e) and of CO_2 (right-hand panels: b, d and f) for the pairs of model runs: "CTL" vs "CH_4" (upper row), "BECSS" vs "BECCS+CH_4" (middle row) and "Natural" vs "Natural+CH_4". The title of each panel is the pair of model runs. The subtitle and legend use the same set of model run abbreviations (i.e., "CTL", "CH_4", "BECSS", "Natural", "BECCS+CH_4" and "Natural").

Figure 6 Is the linear optimized the sum of ch4 and land based mitigation? Is so, then the bar breakdown is incorrect, as the coupling changes the land response.

Response 1.27: ***Please see response to comment on lines 379-383 above (Response 1.17), as this is a repeat of that comment.***

Change(s) to Paper*: *We add the following text to the figure caption for the new Figures 8 (page 36): "Note that the gain in the land carbon store for the CH_4 scenario is 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 7 again the linear sum does not look correct

Response 1.28: ***Please see response to comment on lines 379-383 above (Response 1.17), as this is a repeat of that comment.***

Change(s) to Paper**: *We add the following text to the figure caption for the new Figures 9 (page 37): "Note that the gain in the land carbon store for the CH_4 scenario is 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)".***

Figures 12 and 13 I am confused about water withdrawal vs. irrigation demand. Isn't water withdrawn for irrigation? is this irrigation demand assumed to be additional water withdrawal?

Response 1.29: ***We will amend this. The reviewer is correct that irrigation is water withdrawal. The separation arose as we had separate datasets for (a) agricultural irrigation and (b) water withdrawals for energy production, use in industry and in cities. We will adjust the figure to remove any confusion.***

Change(s) to Paper**: *We amend the legends to the new Figures 13 and 14, replacing "SSP2 Irrigation Demand" and "SSP2 Water Withdrawal" with "Water Demand: Irrigation" and "Water Demand: Other" (i.e., for energy generation, industry and domestic uses), respectively.***

We also amend the captions to the new Figure 13, replacing "The water withdrawal (dark blue) and irrigation demand are taken from the SSP2-RCP2.6-IMAGE database" with "The water demand for irrigation (yellow) and for other uses (i.e., energy generation, industry and domestic; dark blue) are taken from the SSP2-RCP2.6-IMAGE database. Note there is very little BECCS additional water demand (green) in 2015".

We also amend the captions to the new Figure 14, adding the underlined text "SSP2-IMAGE water demand estimates for irrigation (yellow) and other (dark blue)".

Table 4 You should include BECCS demand and percent of available that would be used.

Response 1.30: ***Please see the response to the comment on line 469 above (Response 1.23), as this is a repeat of that comment.***

"**Regional variation in the effectiveness of methane-based and land-based climate mitigation options**"
Hayman et al. (ESD-2020-24)

Author Response to Reviewer 2 Comments

Reviewer 2

Overall, I found the paper "Regional variation in the effectiveness of methane-based and land-based climate mitigation options" interesting and relevant. I have several comments that should be addressed prior to its publication.

Thank you for the positive comments about the paper and its relevance.

Lines 21-24: Why only land-based mitigation and CH4?

Response 2.1:* *We only considered methane and land-based mitigation options as we could investigate the climate/land carbon-cycle interactions and feedbacks of these mitigation options within our modelling framework. The paper also builds on our earlier studies, as described in the Introduction (lines 83-86).

Change(s) to Paper*: *We add the underlined text to lines 21-22: "Specifically, within this IMOGEN-JULES framework, we focus on and characterise the global and regional effectiveness of land-based".

Line 40-43: Add reference

Response 2.2:* *We add reference(s). Refers to "Meeting the Paris Agreement goals will, therefore, require sustained reductions in sources of long-lived anthropogenic greenhouse gases (GHGs) and some short-lived climate forcers (SLCFs) such as methane, alongside increasingly extensive implementations of carbon dioxide removal (CDR) technologies. Accurate information is needed on the range and efficacy of options available to achieve this."

Change(s) to Paper*: *We add the underlined text to lines 46-49 "Meeting the Paris Agreement goals will…… alongside increasingly extensive implementations of carbon dioxide removal (CDR) technologies (IPCC 1998)".

Line 44-45: Add reference

Response 2.3:* *We add reference(s). Refers to "Biomass energy with carbon capture and storage (BECCS) and afforestation/reforestation (AR) are the most widely considered CDR technologies in the climate and energy literature".

Change(s) to Paper*: *We add the reference "(Minx et al., 2018)" to the end of the sentence above (line 52).

Line 51-54: This sentence as written is confusing. Why are the requirements greater if the literature says they are similar? Are you saying that within the same model and socioeconomic background land for BECCS is larger in 1.5 than 2C, but across the full literature range 2C scenarios have higher land requirements?

Response 2.4:* *We cite Smith et al. (2016) for the land needed for large-scale bioenergy crops to achieve the 2°C target. "BECCS delivering 3.3 Gt Ceq yr−1 of negative emissions would require a land area of approximately 380–700 Mha in 2100 (Table 2)". From the cited paper of van Vuuren

et al. (2018), "In the default mitigation scenario (DEF_1.9 which is compatible with the 1.5°C target), more than 600 Mha is required for bioenergy".

Our earlier paper (Harper et al., 2018) clearly shows that less land is required for bioenergy crops to achieve the 2°C warming target. This is the case within a given shared socio-economic pathway (SSP2 as used here) but there are larger differences across different SSPs. The land requirements for bio-energy productions strongly differs in the literature. Key elements include the contribution of residues and the assumed yields and yield improvement. In IMAGE, the total land use requirement in 2100 is 360 Mha for the SSP2-2.6 and similar numbers for the SSP2-1.9. Interestingly, area used for bio-energy is higher in the SSP1-2.6 scenario given the much lower land claim for food production. We will use this to amend the text.

Change(s) to Paper: We amend the text from lines 58-64, showing additions and ~~deletions~~.

"The land requirements for BECCS will be greater for the 1.5°C target within a given shared socio-economic pathway (e.g., SSP2), although published estimates are similar for the two warming targets, with between 380-700 Mha required for the 2°C target (Smith et al., 2016) and greater than 600 Mha for the 1.5°C target (van Vuuren et al., 2018). This is because the land requirements for bioenergy production differ strongly across the different SSPs, depending on assumptions about the contribution of residues, assumed yields and yield improvement,~~Other key differences are the~~ start dates of implementation and the rates of deployment".

Line 59-60: This sentence should be made more elaborated on or removed.

Response 2.5: We delete the sentence.

Change(s) to Paper: We delete the sentence "The IPCC Special Report "Climate Change and Land Use"(IPCC, 2019) provides a further synthesis and perspective on BECCS" (lines 67-68).

Lines 255-259: Do you also adjust the energy system or its emissions to account for the reduction in bioenergy?

Response 2.6: The reviewer is correct, as there would be an adjustment to the energy system. We do not account for this. We however do acknowledge this limitation for the converse case when bioenergy crops are grown (lines 416-418) "Further, we do not allow for the reduced emissions from fossil fuel combustion due to the bioenergy crop being grown, as this would require energy sector modelling that is beyond the scope of this study". We will add this as a caveat to lines 255-259 and amend lines 416-418 to cover both cases.

Change(s) to Paper: We add the following sentence "We make no allowance for any changes in the energy generation system, as this would require energy sector modelling that is beyond the scope of this study" (lines 295-296).

We add the following text (lines 584-587) "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 scenario run), as this would require energy sector modelling that is beyond the scope of this study".

Line 284: does "preferred mitigation pathway" mean lowest terrestrial emissions or lowest total emissions (including CCS)?

Response 2.7: This refers to our earlier work. "Harper et al. (2018) find that the land-use pathways do not provide a clear choice for the preferred mitigation pathway." We will amend the text.

Change(s) to Paper: We add the sentence "In such circumstances, Harper et al. (2018) find that the loss of soil carbon in regions with high carbon density makes it difficult for BECCS to deliver a net negative emission of CO_2" (lines 346-347).

Lines 286-292: Can you determine how much bioenergy (in EJ or Mt per year) you produce from this calculation?

Response 2.8: We will add this information.

Change(s) to Paper: We amend lines 364-369, showing added and ~~deleted~~ text:

"~~(~~JULES in this study and in Harper et al. (2018) simulated median average yields of ~4.8 and ~4.6 tDM ha^{-1} yr^{-1}, respectively, compared to measured median of 11.5 tDM ha^{-1} yr^{-1} and simulated average of 15.8 tDM ha^{-1} yr^{-1} in IMAGE~~)~~. The JULES yield of ~4.8 tDM ha^{-1} yr^{-1} corresponds to ~59 EJ yr-1 of primary energy, using the maximum area for BECCS from Table 2 of 637.7 Mha and an energy yield of 19.5 GJ t DM^{-1} (Daioglou et al., 2017). Bioenergy supplied 55.6 EJ yr^{-1} or ~10% of primary energy requirement worldwide in 2017 (WBA, 2019). According to Smith et al. (2016), this would increase to ~170 EJ yr^{-1} of primary energy in 2100, for negative emissions of 3.3 Gt C_{eq} yr^{-1} from BECCS (as required for a 2°C warming target)".

Lines 347-354: This seems repetitive with previous text.

Response 2.9: It was intended as a summary but we accept that it repeat texts in previous sections. In reply to the comments from Reviewer 1, we restructure Sections 2.3-2.5 to remove any duplication.

Change(s) to Paper: We delete the paragraph (lines 414-421) "The difference in anthropogenic fossil fuel emission budget (AFFEB) between the mitigated pathway and the control simulation gives an estimate of the Mitigation Potential (MP) of the mitigation strategy. The IM-1.9 scenario relies on a combination of BECCS, reduced emissions from deforestation and degradation (REDD), and reforestation of degraded forest areas to achieve a 1.5°C climate target, while IM-BL has limited land-based mitigation via moderate levels of REDD and AR. We develop an additional land-based mitigation scenario (IM-1.9N) where any bioenergy cropland area in IM-1.9 is replaced by natural vegetation (Sect. 2.3). We then derive an optimal land-based mitigation pathway in a post-processing step by selecting the option, (a) BECCS or (b) natural vegetation, which has the more positive impact on the AFFEB in each grid cell (Sect. 2.4.1)"

Lines 384-387: This paragraph needs some editing for clarity. The analysis you are doing is focused on the climate sensitivity of mitigation options, not an analysis of their economics or how that would change under different temperature targets. I don't think you can say that these are "worthwhile mitigation approaches" given your analysis. But, you can say that across the range of temperatures you analyzed there is no noticeable difference in the potential or performance of these mitigation strategies.

Response 2.10: We accept that worthwhile has a value judgement. We amend the text

"Despite the substantial differences in the absolute AFFEBs for the 1.5° and 2°C targets, the mitigation potential of the CH_4 and land-based strategies is similar for the two temperature scenarios considered. This similarity suggests that the ~~investment in such strategies~~ mitigation strategies are robust to the target temperature; whether the international community aims for the 1.5° or 2°C target, afforestation, reforestation, reduced deforestation and CH_4 mitigation are all ~~worthwhile~~ beneficial mitigation approaches".

Change(s) to Paper: We make the above changes at lines 457-461.

Lines 464-465: Why are those regions different?

Response 2.11: ***We use information in the cited paper by Postel et al. (2016) to assume that "only 5% of the total runoff is accessible for the Brazil, Russia and Canada IMAGE regions and 40% elsewhere". Postel et al. adjusted the total runoff for geographic and temporal inaccessibility. Specifically, the Amazon River "accounts for 15% of global runoff (11). It is currently accessible, however, to -25 million people (12) - 0.4% of world population-and no massive expansion of irrigation is likely that would warrant major diversions from it. We thus consider 95% of its flow inaccessible". For rivers in the boreal zone, "The final subtraction is for the remote rivers of North America and Eurasia, 55 of which have no dams on their main channels (13). Most of this river flow is in tundra and taiga biomes that are remote from population centers. The combined average annual flow of these northern untapped rivers is 1815 km^3/year, and we subtract 95% of it". We will add a sentence about the adjustments made to the total runoff for geographic and temporal inaccessibility.***

Change(s) to Paper: We amend lines 543-544: "Following Postel et al. (1996), we derive the accessible runoff, ~~assuming~~ using their assumptions that only 5% of the total runoff is geographically and/or temporally accessible for the Brazil, Russia and Canada IMAGE regions, and 40% elsewhere

Lines 468-471: What does "take the water requirements" mean? Do you use the water per unit of output from those studies and apply it to the IMAGE outputs? Or do you use the total water from those studies? If the latter, is it consistent? Also, does this mean you use the RCP2.6 water for the baseline and 1.9 simulations here? Is that water from the IMAGE-LPJmL model (which you note is low) or are you overwriting the IMAGE-LPJmL with the values from those papers?

Response 2.12: ***We take the water requirements for agricultural irrigation (Rost et al., 2008) and for other human activities (Bijl et al., 2016) (Table 4), as the total water withdrawal for each IMAGE region from the IMAGE-SSP2-RCP2.6 scenario. We use this for all our scenarios and add to this the additional water requirements for BECCS in the relevant scenarios. We acknowledge that this introduces new caveats and will add these to those already listed (lines 474-478).***

Additional comment: ***We do not need the baseline (or control, "CTL") scenario for this evaluation, We only derive the water demand for the optimised land-based mitigation scenario. The IMAGE-SSP2-RCP2.6 scenario used for the water demand for agricultural irrigation, energy generation, industry and domestic usage is compatible with the 2°C warming target. We assume that it can also be used the 1.5°C warming target.***

Change(s) to Paper: We amend lines 548-552, showing added and deleted text: "**We use** ***~~as the total~~ the water withdrawals for each IMAGE region ~~from~~ given in the IMAGE-SSP2-RCP2.6 scenarios for the water ~~requirements~~ demand for agricultural irrigation (Rost et al., 2008) and for other human activities, such as energy generation, industry and domestic usage (Bijl et al., 2016), between 2015 and 2100 (~~Table 4~~Tab. 4a and 4b), ~~We note Bijl et al. (2016)that the irrigation water withdrawal, derived using the coupled IMAGE-LPJmL models, are low compared to other estimates in the literature~~We assume the same water demands from these sectors for both the 1.5°and 2°C warming targets".***

We add lines 565-567 "We also note from Bijl et al. (2016) that the water demand for irrigation, derived using the coupled IMAGE-LPJmL models, is low compared to other estimates in the literature. Higher water demand for irrigation existing agriculture would be an additional constraint on the water available for BECCS".

Commented [HGD3]: Moved to next paragraph, as caveat

Lines 472-482: It would be nice to have one sentence in this paragraph reporting the quantitative results before you go through the caveats.

<u>Response 2.13:</u> Reviewer 1 has suggested adding the BECCS water demand and percent of available used to Table 4. We will use this information to add a sentence or two with quantitative results.

<u>Change(s) to Paper</u>: We add the following <u>text</u> (lines 555-559) "… for the optimised land-based mitigation. Tables 4a and b show the additional water requirements of BECCS calculated for 2060 and 2100, respectively, for the 2°C warming target. We find that the additional demand for BECCS would lead to an exceedence (or use >90%) of the available water for the Oceania and Rest of Southern Africa regions. We also find that the additional demand for BECCS is greater than the total water withdrawals from anthropogenic activities for the Canada and Brazil IMAGE regions"

Figure 3: Should the titles of panels d, f, and h say "Carbon Dioxide" instead of "Methane"? In general, I find the naming in this figure difficult since you have 1.5C and 2C on a baseline panel and 2C on 1.5C panels.

<u>Response 2.14:</u> The figure is intended to show key data inputs for or differences between the model runs to help inform reader's understanding of the paper. The titles of the panels are correct but we accept the figure and panels need careful reading. We will amend the figure to make it clearer (and potentially split the figure into two as part of the restructuring of Section 2.3-2.5).

<u>Change(s) to Paper</u>:

We define a consistent set of model scenarios at the beginning of the revised Section 2.3 (lines 245-250) "We undertake a control run and other simulations with anthropogenic CH_4 mitigation or land-based mitigation, stabilising at either 1.5°C or 2.0°C warming without a temperature overshoot. We denote the control run as "CTL", the anthropogenic CH_4 mitigation scenario as "CH_4", a land-based mitigation scenario using BECCS as "BECCS" and a variant land-based scenario focussing on AR as "Natural". We also undertake runs combining the CH_4 and land-based mitigation scenarios ("BECCS+CH_4" and "Natural+CH_4") to determine if there are any non-linearities when we combine these mitigation scenarios".

Figure 6 (part of the original Figure 3) shows the modelled evolution of the atmospheric concentrations of CH_4 (the left-hand panels: a, c and e) and of CO_2 (right-hand panels: b, d and f) for the pairs of model runs: "CTL" vs "CH_4" (upper row), "BECSS" vs "BECCS+CH_4" (middle row) and "Natural" vs "Natural+CH_4". The title of each panel is the pair of model runs. The subtitle and legend use the same set of model run abbreviations (i.e., "CTL", "CH_4", "BECSS", "Natural", "BECCS+CH_4" and "Natural").

See also Response 1.26, which address the same point.

Figure 7: Some of the detail in the caption would be good to include in the figure. In particular, the difference between panels a & c OR b & d.

<u>Response 2.15:</u> These are a pair of plots for different BECCS efficiency scale factors (Panels a & b are for κ =1 and Panels c & d for κ = 3). The caption can be shortened by deleting "a & b are for the standard JULES BECCS productivity and efficiency (κ=1, Sect. 2.4.3), in c & d the BECCS productivity and efficiency uses κ=3" and adding BECCS κ =1 and κ =3 to the figure.

<u>Change(s) to Paper</u>: We add (1) BECCS Scale Factor (κ) = 1 above panels (a) and (b); (2) BECCS Scale Factor (κ) = 3 above panels (c) and (d). We shorten the figure caption, showing the <u>additions</u> and ~~deletions~~:

"Figure 9 | ~~Allowable anthropogenic fossil fuel emission budgets and mitigation potential for the factorial simulation experiment.~~Panels (a & c): The allowable anthropogenic fossil fuel

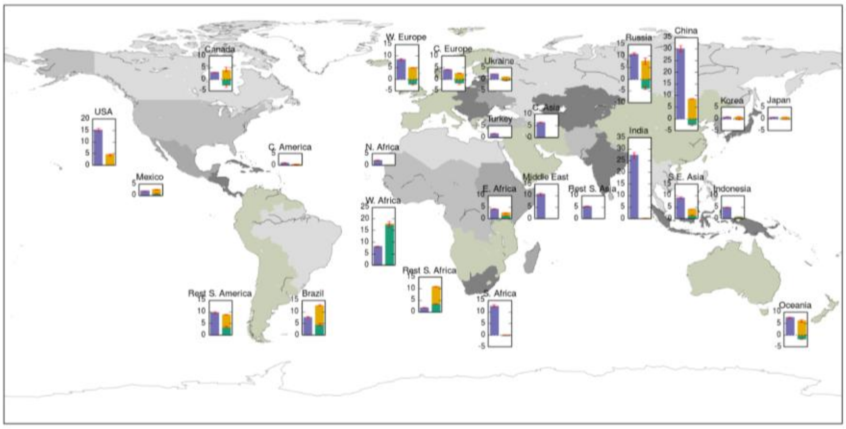
emission budgets (AFFEBs; GtC) for the control (grey), ~~methane~~CH_4 mitigation (purple), land-based mitigation (green), coupled methane and land-based mitigation (orange) and the linearly summed methane and land-based mitigation (brown), for 2 temperature pathways asymptoting at 1.5°C (left) and 2.0°C (right). (b & d) The mitigation potential (GtC) as the increase in AFFEB from the corresponding control run. ~~a & b are for the standard JULES BECCS productivity and efficiency (κ=1, Sect. 2.4.3), in c & d the BECCS productivity and efficiency uses κ=3.~~ The breakdown of the 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".

From Response 1.28, we add to the end of the caption "Note that the gain in the land carbon store for the CH_4 scenario is 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 9: This figure is pretty busy. Do you need the map? Or if you want the map, do you need the colors on the map? It is hard to see the bars and axes.

Response 2.16: ***Figure 9 presents the regional mitigation options superimposed on a map of the IMAGE regions. The colours identify the different IMAGE regions. We accept that the colours used for specific regions make it hard to distinguish the bar charts for that region (the colours for the mitigation options are consistent with the colour scheme used throughout the paper for the methane and land-based mitigation). We will amend the figure by either using grey shading for the IMAGE regions or alternatively placing the bar charts around the edge of the plot.***

Change(s) to Paper: We use a grey scale for the IMAGE regions in the new Figure 11 (page 41) and also for Supporting Information, Figure SI.4.



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

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Abstract. Scenarios avoiding global warming greater than 1.5 or 2°C, as stipulated in the Paris Agreement, may require the combined mitigation of anthropogenic greenhouse gas emissions alongside enhancing negative emissions through approaches such as afforestation/reforestation (AR) and biomass energy with carbon capture and storage (BECCS). We use the JULES land-surface model coupled to an inverted form of the IMOGEN climate emulator to investigate mitigation scenarios that achieve the 1.5 or 2°C warming targets of the Paris Agreement. Specifically, within this IMOGEN-JULES framework, we focus on and characterise the global and regional effectiveness of land-based (BECCS and/or AR) and anthropogenic methane (CH_4) emission mitigation, separately and in combination, on the anthropogenic fossil fuel carbon dioxide (CO_2) emission budgets (AFFEBs) to 2100, using consistent data and socio-economic assumptions from the IMAGE integrated assessment model. 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.

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. ~~but~~ Further, both the effectiveness and the preferred land-management strategy (i.e., AR or BECCS) have strong regional dependencies. Additional analysis shows extensive BECCS could adversely affect water security for several regions. ~~Our results highlight the extra potential CO_2 emissions that can occur, while still keeping global warming below key warming thresholds, by investment in regionally appropriate mitigation strategies~~ Although the primary requirement remains mitigation of fossil fuel

Commented [HGD4]: Reviewer comment 2.1. DONE, why focus on CH4 and land-based mitigation

Commented [HGD5]: Reviewer comment 1.2: DONE, added BECCS sensitivity

Commented [HGD6]: Reviewer comment 1.1: DONE, added text to make clear the need for removal of fossil carbon emissions.

emissions, our results highlight the unrealised potential for the mitigation of CH_4 emissions to make the Paris climate targets more achievable~~.~~

1 Introduction

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The stated aims of the Paris Agreement of the United Nations Framework Convention on Climate Change (UNFCCC, 2015) are "to hold the increase in global average temperature to well below 2°C and to pursue efforts to limit the increase to 1.5°C". The global average surface temperature for the decade 2006-2015 was 0.87°C above pre-industrial levels and is likely to reach 1.5°C between the years 2030 and 2052, if global warming continues at current rates (IPCC, 2018). The IPCC Special Report on Global Warming of 1.5°C (IPCC, 2018) gives the median remaining carbon budgets between 2018 and 2100 as 770 $GtCO_2$ (210 GtC) and 1690 $GtCO_2$ (~461 GtC) to limit global warming to 1.5°C and 2°C, respectively. These budgets represent ~20 and ~41 years at present-day emission rates. The actual budgets could however be smaller, as they exclude Earth system feedbacks such as CO_2 released by permafrost thaw or CH_4 released by wetlands. Meeting the Paris Agreement goals will, therefore, require sustained reductions in sources of fossil carbon emissions, other long-lived anthropogenic greenhouse gases (GHGs) and some short-lived climate forcers (SLCFs) such as methane (CH_4), alongside increasingly extensive implementations of carbon dioxide removal (CDR) technologies (IPCC, 2018). Accurate information is needed on the range and efficacy of options available to achieve this.

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Biomass energy with carbon capture and storage (BECCS) and afforestation/reforestation (AR) are among the most widely considered CDR technologies in the climate and energy literature (Minx et al., 2018). For scenarios consistent with a 2°C warming target, the review by Smith et al. (2016) finds this may require (1) a median removal of 3.3 GtC yr^{-1} from the atmosphere through BECCS by 2100 and (2) a mean CDR through AR of 1.1 GtC yr^{-1} by 2100, giving a total CDR equivalent to 47% of present-day emissions from fossil fuel and other industrial sources (Le Quéré et al., 2018). Although there are fewer scenarios that look specifically at the 1.5°C pathway, BECCS is still the major CDR approach (Rogelj et al., 2018). For the default assumptions in Fuss et al. (2018), BECCS would remove a median of 4 GtC yr^{-1} by 2100 and a total of 41-327 GtC from the atmosphere during the twenty-first century, equivalent to about 4-30 years of current annual emissions. The land requirements for BECCS will be greater for the 1.5°C target within a given shared socio-economic pathway (e.g., SSP2), although published estimates are similar for the two warming targets, with between 380-700 Mha required for the 2°C target (Smith et al., 2016) and greater than 600 Mha for the 1.5°C target (van Vuuren et al., 2018). This is because the land requirements for bioenergy production differ strongly across the different SSPs, depending on assumptions about the contribution of residues, assumed yields and yield improvement,~~Other key differences are the~~ start dates of implementation and the rates of deployment. While the CDR figures assume optimism about the mitigation potential of BECCS, concerns have been raised about the potentially detrimental impacts of BECCS on food production, water availability and biodiversity, e.g., (Krause et al., 2017;Heck et al., 2018). Others note the risks and query the feasibility of large-scale deployment of BECCS

Commented [HGD9]: Reviewer comment 2.3: DONE, added reference

Commented [HGD10]: Reviewer comment 2.4: DONE, text added on areas e.g. (Anderson and Peters, 2016;Vaughan and Gough, 2016;Vaughan et al., 2018). The IPCC Special Report "Climate Change and Land Use"(IPCC, 2019) provides a further synthesis and perspective on BECCS.

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Harper et al. (2018) find the overall effectiveness of BECCS to be strongly dependent on the assumptions concerning yields, the use of initial above-ground biomass that is replaced and the calculated fossil-fuel emissions that are offset in the energy system. Notably, if BECCS involves replacing ecosystems that have higher carbon contents than energy crops, then AR and avoided deforestation can be more efficient than BECCS for atmospheric CO_2 removal over this century (Harper et al., 2018).

Mitigation of the anthropogenic emissions of non-CO_2 GHGs such as methane (CH_4) and of SLCFs such as black carbon have been shown to be attractive strategies with the potential to reduce projected global mean warming by 0.22-0.5°C by 2050 (Shindell et al., 2012;Stohl et al., 2015). It should be noted that these were based on scenarios with continued use of fossil fuels. Through the link to tropospheric ozone (O_3), there are additional co-benefits of CH_4 mitigation for air quality, plant productivity and food production (Shindell et al., 2012) and carbon sequestration (Oliver et al., 2018). Control of anthropogenic CH_4 emissions leads to rapid decreases in its atmospheric concentration, with an approximately 9-year removal lifetime, and as such is an SLCF. Furthermore, many CH_4 mitigation options are inexpensive or even cost negative through the co-benefits achieved (Stohl et al., 2015), although expenditure becomes substantial at high levels of mitigation (Gernaat et al., 2015). The extra "allowable" carbon emissions from CH_4 mitigation can make a substantial difference to the feasibility or otherwise of achieving the Paris climate targets (Collins et al., 2018).

Some increases in atmospheric CH_4 are not related to direct anthropogenic activity, but indirectly to climate change triggering natural carbon and methane-climate feedbacks. These effects could act as positive feedbacks, and thus in the opposite direction to the mitigation of anthropogenic methane CH_4 sources. Wetlands are the largest natural source of methaneCH_4 to the atmosphere and these emissions respond strongly to climate change (Melton et al., 2013;Gedney et al., 2019). A second natural feedback is from permafrost thaw. In a warming climate, the resulting microbial decomposition of previously frozen organic carbon is potentially one of the largest feedbacks from terrestrial ecosystems (Schuur et al., 2015). As the carbon and CH_4 climate feedbacks from natural wetlands and permafrost thaw could be substantial, this causes a reduction in anthropogenic CO_2 emission budgets compatible with climate change targets (Comyn-Platt et al., 2018;Gasser et al., 2018).

For the first time, we combine these elements (land-based mitigation, anthropogenic CH_4 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 CH_4 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. 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 ~~methane~~ 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 2.5 lists the model runs undertaken and the key assumptions and datasets used.

2.1 The JULES model

We use the JULES land surface model (Best et al., 2011;Clark et al., 2011), release version 4.8, but with a number of additions required specifically for our analysis:

1. Land use: We adopt the approach used by Harper et al. (2018) and prescribe *managed* land-use and land-use change (LULUC). On land used for agriculture, C3 and C4 grasses are allowed to grow to represent crops and pasture. The land-use mask consists of an annual fraction of agricultural land in each grid cell. Historical LULUC is based on the HYDE 3.1 dataset (Klein Goldewijk et al., 2011), and future LULUC is based on two scenarios (SSP2 RCP-1.9 and SSP2 baseline), which were developed for use in the IMAGE integrated assessment model (IAM) (van Vuuren et al., 2017;Doelman et al., 2018) (see also Sect. 2.3).

   Natural vegetation is represented by nine plant functional types (PFTs): broadleaf deciduous trees, tropical broadleaf evergreen trees, temperate broadleaf evergreen trees, needle-leaf deciduous trees, needle-leaf evergreen trees, C3 and C4 grasses, deciduous and evergreen shrubs (Harper et al., 2016). These PFTs are in competition for space in the non-agricultural fraction of grid cells, based on the TRIFFID (Top-down Representation of Interactive Foliage and Flora Including Dynamics) dynamic vegetation module within JULES (Clark et al., 2011). A further four PFTs are used to represent agriculture (C3 and C4 crops, and C3 and C4 pasture), and harvest is calculated separately for food and bioenergy crops (see Sect. 2.4.3, where we describe the modelling of carbon removed via bioenergy with CCS). When natural vegetation is converted to managed agricultural land, the vegetation carbon removed is placed into woody product pools that decay at various rates back into the atmosphere (Jones et al., 2011). Hence, the carbon flux from LULUC is not lost from the system. There are also four non-vegetated surface types: urban, water, bare soil and ice.

2. Soil carbon: Following Comyn-Platt et al. (2018), we also use a 14 layered soil column for both hydro-thermal (Chadburn et al., 2015) and carbon dynamics (Burke et al., 2017a). Burke et al. (2017b) demonstrated that modelling the soil carbon fluxes as a multi-layered scheme improves estimates of soil carbon stocks and net ecosystem exchange. In addition to the vertically discretised respiration and litter input terms, the soil-carbon balance calculation also includes a diffusivity term to represent cryoturbation/bioturbation processes. The freeze-thaw process of cryoturbation is particularly important in cold permafrost-type soils (Burke et al., 2017b). Following Burke et al. (2017a), we diagnose permafrost wherever the deepest soil layer is below 0°C (assuming that this layer is below the depth of zero annual amplitude). Further, for permafrost regions, there is an additional variable to trace or diagnose "old" carbon and its release from permafrost as it thaws.

The multi-layered methanogenesis scheme improves the representation of high latitude ~~methane~~ CH_4 emissions, where previous studies underestimated production at cold permafrost sites during "shoulder seasons" (Zona et al., 2016). Figure 2 shows the annual cycle in the observed and modelled wetland ~~methane~~ CH_4 emissions at the Samoylov Island field site (panel a) and a comparison of observed and modelled annual mean fluxes at this and other sites (panel b). The range of uncertainty used in our study (JULES low Q_{10} - JULES high Q_{10}) captures the range of uncertainty in the observations. Further, the layered methane scheme used in this work gives a better description of the shoulder season emissions when compared with the original, non-layered methane scheme in JULES. The multi-layered scheme allows an insulated sub-surface layer of active methanogenesis to continue after the surface has frozen. These model developments not only improve the seasonality of the emissions, but more importantly for this study capture the release of carbon as CH_4 from deep soil layers, including thawed permafrost. Further evaluation of the multi-layer scheme can be found in ~~Chadburn et al. (2020a)~~;Chadburn et al. (2020b).

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3. Methane from wetlands: Following Comyn-Platt et al. (2018), we also use the multi-layered soil carbon scheme described in (2) above to give the local land-atmosphere CH_4 flux, E_{CH4} (kg C m^{-2} s^{-1}):

$$E_{CH4} = k \cdot f_{wetl} \cdot \sum_{i=1}^{n\ C_s\ pools} \kappa_i \cdot \sum_{z=0\text{m}}^{z=3\text{m}} e^{-\gamma z} C_{s_{i,z}} \cdot Q_{10}\left(T_{soil_z}\right)^{0.1\left(T_{soil_z} - T_0\right)} \quad (1)$$

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where *k* is a dimensionless scaling constant such that the global annual wetland CH_4 emissions are 180 Tg CH_4 in 2000 (as described in Comyn-Platt et al. (2018)), *z* is the depth in soil column (in m), *i* is the soil carbon pool, f_{wetl} (-) is the fraction of wetland area in the grid cell, κ_i (s^{-1}) is the specific respiration rate of each pool (Table 8 of Clark et al. (2011)), C_s (kg m^{-2}) is soil carbon, T_{soil} (K) is the soil temperature. The decay constant γ (= 0.4 m^{-1}) describes the reduced contribution of CH_4 emission at deeper soil layers due to inhibited transport and increased oxidation through overlaying soil layers. This representation of inhibition and of the pathways for ~~methane~~ CH_4 release to the atmosphere (e.g., by diffusion, ebullition and vascular transport) is a simplification. However, previous work which explicitly represented these processes showed little to no improvement when compared with in-situ observations (McNorton et al., 2016). We do not model ~~methane~~ CH_4 emissions from freshwater lakes (and oceans).

Comyn-Platt et al. (2018) varied Q_{10} in Eq. 1 to encapsulate a range of methanogenesis process uncertainty. They derive Q_{10} values for each GCM configuration to represent two wetland types identified in Turetsky et al. (2014) ('poor-fen' and 'rich-fen'). They also include a third 'low-Q_{10}', which gives increased importance to high latitude emissions. Their ensemble spread was able to describe the magnitude and distribution of present-day CH_4 emissions from natural wetlands, according to the models used in the then-current global methane assessment (Saunois et al., 2016). Here, we use the 'low-Q_{10}' value of Comyn-Platt et al. (2018) (=2.0) and adopt a 'high-Q_{10}' value of ~4.8 from the rich-fen parameterisation. The two Q_{10} values used here still capture the full range of the methanogenesis process uncertainty.

4. Ozone vegetation damage: We use a JULES configuration including ozone deposition damage to plant stomata, which affects land-atmosphere CO_2 exchange (Sitch et al., 2007). JULES requires surface atmospheric ozone concentrations, O_3 (ppb), for the duration of the simulation period (1850-2100). As in Collins et al. (2018), we do not model tropospheric ozone production from CH_4 explicitly in IMOGEN. Instead, we use two sets of monthly near-surface O_3 concentration fields (January-December) from HADGEM3-A GA4.0 model runs, with the sets corresponding to~~we take two sets of monthly near-surface O_3 concentration fields calculated using the HADGEM3-A GA4.0 model for~~ low (1285 ppbv) and high (2062 ppbv) global mean atmospheric CH_4 concentrations (Stohl et al., 2015). We assume that the atmospheric O_3 concentration in each grid cell responds linearly to the atmospheric CH_4 concentration. We derive separate linear relationships for each month and grid cell, and use these to calculate the surface O_3 concentration from the corresponding global atmospheric CH_4 concentration as it evolves during the IMOGEN run.~~We regrid these fields (1.875°x1.25° horizontal grid) to the spatial grid of IMOGEN-JULES (3.75°x2.5° horizontal grid). We then linearly interpolate between the respective months in the regridded O_3 fields using the global annual atmospheric CH_4 concentration~~. We use the CH_4 concentration profile from the prescribed SSP2_RCP-1.9_IMAGE scenario, adjusted for natural methane sources (see 3 above and Sect. 2.3.3). We undertake runs using both the 'high' and 'low' vegetation ozone-damage parameter sets (Sitch et al., 2007).

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2.2 The IMOGEN intermediate complexity climate model

2.2.1 IMOGEN

The IMOGEN climate impacts model (Huntingford et al., 2010) uses "pattern-scaling" to estimate changes to the seven meteorological variables required to drive JULES. Huntingford et al. (2010) assume that changes in local temperature, precipitation, humidity, wind-speed, surface shortwave and longwave radiation and pressure are linear in global warming. Spatial patterns of each variable (based on the 34 GCM simulations in CMIP5 (Comyn-Platt et al., 2018)) are multiplied by the amount of global warming over land, ΔT_L, to give local monthly predictions of climate change. When using IMOGEN in forward mode, ΔT_L is calculated with an Energy Balance Model (EBM) as a function of the overall changes in radiative forcing, ΔQ (W m^{-2}). ~~The EBM includes a simple representation of the ocean uptake of heat and CO_2.~~ ΔQ is the sum of the atmospheric greenhouse gas contributions (Eq. 2) (Etminan et al., 2016), which in the forward mode are either calculated (CO_2 and CH_4) or prescribed (for other atmospheric contributors) on a yearly time step.

$$\Delta Q(total) = \Delta Q(CO_2) + \Delta Q(non\ CO_2\ GHGs) + \Delta Q(aerosols\ and\ other\ climate\ forcers) \quad (2)$$

The EBM includes a simple representation of the ocean uptake of heat and CO_2 and uses a separate set of four parameters for each climate and Earth system model emulated (Huntingford et al., 2010): the climate feedback parameters over land and ocean, λ_l and λ_o (W m^{-2} K^{-1}) respectively, the oceanic "effective thermal diffusivity", κ (W m^{-1} K^{-1}) representing the ocean thermal inertia and a land-sea temperature contrast parameter, ν, linearly relating warming over land, ΔT_l (K) to warming over ocean, ΔT_o (K), as $\Delta T_l = \nu \Delta T_o$. The climate feedback parameters (λ_l and λ_o) are calibrated using model-specific data for the top of the atmosphere radiative fluxes, the mean land and ocean surface temperatures, along with an estimate of the radiative forcing modelled for the CO_2 changes.

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 ~~methane~~ 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 CH_4 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).

In this study, we use the inverse version of IMOGEN, which follows prescribed temperature pathways (Fig. 3(a)), to derive the total radiative forcing (ΔQ [total]) and then.the CO_2 radiative forcing (ΔQ [CO_2]), using Eq. 2. Comyn-Platt et al. (2018) describe the changes made to the EBM to create the inverse version. ~~Each~~ As each of the 34 GCMs that IMOGEN emulates has a different set of EBM parameters~~. Hence~~, each GCM has a different time-evolving radiative forcing (ΔQ) estimate for a given temperature pathway, $\Delta T_G(t)$. When IMOGEN is forced with a historical record of ΔT_G , the range of ΔQ for the near present day (year 2015) from the 34 GCMs is 1.13 W m^{-2}. To ensure a smooth transition to the modelled future, we require the historical period, 1850-2015, to match observations of both ΔT_G and atmospheric composition for all GCMs.

As we have a model-specific estimate of the radiative forcing modelled for the CO_2 changes (see above), ~~We~~we, therefore, attribute the spread in ΔQ to the uncertainty in the non-CO_2 radiative forcing component, particularly the atmospheric aerosol contribution, which has an uncertainty range of -0.5 to -4 Wm^{-2} (Stocker et al., 2013). Apart from our modelled CH_4 and CO_2 radiative forcings and the potential future balances between them, we use the projections from the IMAGE SSP2 baseline or RCP1.9 scenario for the radiative forcing of other atmospheric contributors (Fig. 3(b)).

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2.2.2 Temperature Profile Formulation

Huntingford et al. (2017) define a framework to create trajectories of global temperature increase, based on two parameters, and which model the efforts of humanity to limit emissions of greenhouse gases and short-lived climate forcers, and, if necessary, capture atmospheric carbon. These profiles have the mathematical form of:

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Commented [HGD17]: Reviewer comment 1.8: DONE

$$\Delta T(t) = \Delta T_0 + \gamma t - (1 - e^{-\mu(t)t})[\gamma t - (\Delta T_{Lim} - \Delta T_0)] \quad (3)$$

where $\Delta T(t)$ is the change in temperature from pre-industrial levels at year t, ΔT_0 is the temperature change at a given initial point (in this case $\Delta T_0 = 0.89$°C for 2015), ΔT_{Lim} is the final prescribed warming limit and

$$\mu(t) = \mu_0 + \mu_1 t \text{ and } \gamma = \beta - \mu_0(\Delta T_{Lim} - \Delta T_0) \quad (4)$$

where β (= 0.00128) is the current rate of warming and μ_0 and μ_1 are tuning parameters which describe anthropogenic attempts to stabilise global temperatures (Huntingford et al., 2017). The parameter values used for the two profiles are: (a) 1.5°C profile: ΔT_{lim} = 1.5°C; μ_0 = 0.1 and μ_1 = 0.0; (b) 2°C profile: ΔT_{lim} = 2°C; μ_0 = 0.08 and μ_1 = 0.0.

2.3 Scenarios and model runs

Commented [HGD18]: Reviewer comment 1.9: DONE, restructure moved first 2 paragraphs of Section 2.5 to Section 2.3.

~~2.2.3 Methane and land-based mitigation scenarios~~

We undertake a control run and other simulations with anthropogenic CH_4 mitigation or land-based mitigation, stabilising at either 1.5°C or 2.0°C warming without a temperature overshoot. We denote the control run as "CTL", the anthropogenic CH_4 mitigation scenario, a land-based mitigation scenario using BECCS and a variant land-based scenario focussing on AR, as "CH_4", as "BECCS", "Natural" respectively. We also undertake runs combining the CH_4 and land-based mitigation scenarios (coupled "BECCS+CH_4" and coupled "Natural+CH_4") to determine if there are any non-linearities when we combine these mitigation scenarios. We summarise the key assumptions of these scenarios in Table 1.

We use future projections of atmospheric CH_4 concentrations and LULUC from the IMAGE SSP2 projections (Doelman et al., 2018)~~,~~ for both the methane and land-~~use~~ based mitigation strategies. 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). We denote the RCP1.9 pathway as IM-1.9 and the “baseline” pathway as IM-BL.

2.3.1 Methane: baseline and mitigation scenario

The anthropogenic CH_4 emission increase from 318 Tg per annumyr^{-1} in 2005 to 484 Tg yr^{-1}per annum in 2100 in the IMAGE SSP2 baseline scenario, but fall to 162 Tg yr^{-1}per annum in 2100 in the IMAGE SSP2 RCP1.9 scenario. The sectoral CH_4methane emissions in 2005 (Energy Supply & Demand: 113; Agriculture: 136; Other Land Use (primarily burning): 18; Waste 52, all in Tg yr^{-1}per annum) are in agreement with the latest estimates of the global methane cycle (Saunois et al., 2019). As summarised in Supplementary Information, Table SI.1, the reduction in CH_4 emissions from specific source sectors is achieved as follows: (a) coal production by maximising CH_4methane recovery from underground mining of hard coal; (b) oil/gas production & distribution, through control of fugitive emissions from equipment and pipeline leaks, and from venting during maintenance and repair; (c) enteric fermentation, through change in animal diet and the use of more productive animal types; (d) animal waste by capture and use of the CH_4methane emissions in anaerobic digesters; (e) wetland rice production, through changes to the water management regime and to the soils to reduce methanogenesis; (f) landfills by reducing the amount of organic material deposited and by capture of any CH_4methane released; (g) sewage and wastewater, through using more wastewater treatment plants and also recovery of the CH_4methane from such plants, and through more aerobic wastewater treatment. The levels of reduction vary between sectors, from 50% (agriculture) to 90% (fossil-fuel extraction and delivery). The abatement costs are between US$ 300-1000 (1995 US$) (Supplementary Information, Table SI.1). Figure 4 presents the IMAGE baseline and RCP1.9 CH_4 emission pathways globally and for selected IMAGE regions, including the major-emitting regions of India, USA and China (Supplementary Information, Figure SI.1 shows the emission pathways for all 26 IMAGE regions). These two methane emission pathways define our “CTL” and “CH_4” scenarios, respectively.

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

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)). It represents a control scenario within which agricultural land is accrued to feed growing populations associated with the SSP2 pathway and with no deployment of BECCS. Three types of land-based climate change mitigation are implemented in the IMAGE land use mitigation scenarios (Doelman et al., 2018): (1) bioenergy; (2) reducing emissions from deforestation and degradation (REDD or avoided deforestation); and (3) reforestation of degraded forest areas. For the IM-1.9 scenario, there are high levels of REDD and full reforestation. The scenario assumes a food-first policy (Daioglou et al., 2019) so that bioenergy crops are only implemented on land not required for food production (e.g., abandoned agricultural crop land, most notably, in central Europe, southern China and eastern USA,

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and on natural grasslands in central Brazil, eastern and southern Africa, and Northern Australia (Doelman et al., 2018)). The IM-1.9 scenario also requires bioenergy crops to replace forests in temperate and boreal regions (notably Canada and Russia). The demand for bioenergy is linked to the carbon price required to reach the mitigation target (Hoogwijk et al., 2009). In this scenario, the area of land used for bioenergy crops expands rapidly from 2030 to 2050, reaching a maximum of 550 Mha in 2060, and then declining to 430 Mha by 2100. Table 2~~Table 1~~ gives the maximum area of BECCS deployed in each IMAGE region for the IM-1.9 scenario. This defines the land use in the "BECCS" scenario.

We define a third LULUC pathway, which is identical to the ~~IM-1.9 pathway~~"BECCS" scenario, except that any land allocated to bioenergy crops is allocated instead to natural vegetation, i.e., areas of natural land, which are converted to bioenergy crops, remain as natural vegetation, and areas, which are converted from food crops or pasture to bioenergy crops, return to natural vegetation. We make no allowance for any changes in the energy generation system, as this would require energy sector modelling that is beyond the scope of this study. We denote this scenario as ~~IM-1.9N~~"Natural". Table 2~~Table 1~~ also summarises the main differences in land use between the ~~IM-1.9~~BECCS and ~~IM-1.9N~~Natural scenarios for each IMAGE region.

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Figure 5 presents time series of the land areas calculated for trees and prescribed for agriculture (including bioenergy crops) and bioenergy crops for the "BECCS" and "Natural" scenarios for the Russia and Brazil IMAGE regions, each as a difference to the baseline scenario (IM-BL). Supplementary Information, Figure SI.3 is equivalent to Fig. 5 for all the IMAGE regions.

2.3.3 Model runs

For each temperature pathway (1.5°C or 2.0°C) and for the baseline and each mitigation scenario, the set of factorial runs comprises a 136-member ensemble (34 GCMs x 2 ozone damage sensitivities x 2 methanogenesis Q_{10} temperature sensitivities). In all model runs, we include 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 (Comyn-Platt et al., 2018).

As shown in Fig. 1, we use a number of input or prescribed datasets: (a) time series of the annual area of land used for agriculture, including that for BECCS if appropriate; (b) time series of the global annual mean atmospheric concentrations of CH_4 (and N_2O for the radiative forcing calculations of CO_2 and CH_4); (c) time series of the overall radiative forcing by SLCFs and non-CO_2 GHGs (corrected for the radiative forcing of CH_4); and (d) time series of annual anthropogenic CH_4 emissions (used in the post-processing step). We take these from the IMAGE database for the relevant IMAGE SSP2 scenario (baseline or SSP2-1.9). Table 1 lists the factorial runs, their key features and the prescribed datasets used (for agricultural land and BECCS, anthropogenic emissions and atmospheric concentrations of CH_4 and the non-CO_2 radiative forcing).

Figure 6~~Figure 3(c)-(h)~~ presents the effect of these scenarios on the modelled atmospheric CH_4 and CO_2 concentrations. We adjust the ~~prescribed~~ input atmospheric CH_4 concentrations to allow for the interannual variability in the wetland CH_4 emissions, as described in Sect. 2.2.1. The major control on the modelled atmospheric CH_4 concentrations is the ~~methane~~ CH_4 emission pathway followed, with the temperature pathway (1.5° versus 2°C warming) having a minor effect. For CO_2, on the other hand, the temperature and the CH_4~~methane~~ emission pathways both lead to increased atmospheric CO_2 concentrations, with the temperature pathway having a slightly larger effect.

~~2.3~~2.4 Post-processing

~~2.3.1~~2.4.1 Anthropogenic Fossil Fuel Emission Budget and Mitigation Potential

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

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$$AFFEB_i = [C^{land}(2100) - C^{land}(2015)]_i + [C^{ocean}(2100) - C^{ocean}(2015)]_i + [C^{atmos}(2100) - C^{atmos}(2015)]_i + BECCS(2015:2100)_i \quad (5)$$

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).

For brevity in the subsequent discussion, we use the following shorthand where the terms on the RHS of Eq. 5 are equivalent to those on the RHS of Eq. 6:

$$AFFEB_i = \Delta C_i^{land} + \Delta C_i^{ocean} + \Delta C_i^{atmos} + BECCS_i \quad (6)$$

We define the mitigation potential (MP) for a mitigation strategy, *j*, as the difference between a control AFFEB ($AFFEB_{ctl}$) and the AFFEB resulting from applying the strategy i.e.:

$$MP_j = AFFEB_j - AFFEB_{ctl} \quad (7)$$

which can be broken down into its component parts as:

$$MP_j = MP_j^{land} + MP_j^{ocean} + MP_j^{atmos}$$

$$MP_j = (\Delta C_j^{land} - \Delta C_{ctl}^{land}) + (\Delta C_j^{ocean} - \Delta C_{ctl}^{ocean}) + (\Delta C_j^{atmos} - \Delta C_{ctl}^{atmos}) + BECCS_j \quad (8)$$

~~2.3.2~~2.4.2 Optimisation of the land-based mitigation

Harper et al. (2018) find that the land-use pathways do not provide a clear choice for the preferred mitigation pathway. The key issue is that replacing natural vegetation with bioenergy crops often results in large emissions of soil carbon and the loss of the benefits of maintaining forest carbon stocks. In such circumstances, Harper et al. (2018) find that the loss of soil

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carbon in regions with high carbon density makes it difficult for BECCS to deliver a net negative emission of CO_2. Hence, to optimise the land-based mitigation (LBM), we compare the land-carbon stocks in the BECCS~~IM-1.9~~ and ~~IM-1.9N~~Natural scenarios. We then select the optimum land-management option for each grid cell simulated as that, which maximises the *AFFEB* by year 2100. That is:

$$AFFEB_{LBM} = \Delta C_{IM1.9}^{atmos} + \Delta C_{IM1.9}^{ocean} + \Delta C_{LBM}^{land} \quad (9)$$

with

$$\Delta C_{LBM}^{land} = \begin{cases} \sum_{l}^{grid\ cells} \Delta C_{IM1.9}^{land} + BECCS_{IM1.9} & \text{where } \Delta C_{IM1.9N}^{land} < \Delta C_{IM1.9}^{land} + BECCS_{IM1.9} \\ & or \\ \sum_{l}^{grid\ cells} \Delta C_{IM1.9N}^{land} & \text{where } \Delta C_{IM1.9N}^{land} > \Delta C_{IM1.9}^{land} + BECCS_{IM1.9} \end{cases} \quad (10)$$

where $\Delta C_{pathway}^{store}$ is the change in carbon between 2015 and 2100 for the 'store' (= atmosphere, ocean or land) for the LULUC pathway. We use the ocean and atmosphere contributions from the ~~IM-1.9~~BECCS simulations as the changes in store size between the ~~IM-1.9~~BECCS and ~~IM-1.9N~~Natural simulations are negligible (i.e. <2GtC).

~~2.3.3~~2.4.3 Assumptions about BECCS efficiency

The ~~productivity~~ efficacy of the BECCS scheme implemented in JULES is significantly lower than that of other implementations (Harper et al., 2018), reflecting the importance of assumptions about the efficiency of the BECCS process and bioenergy crop yields in determining their ability to contribute to climate mitigation. More specifically, there is (1) large uncertainty in carbon losses from farm to final storage (Harper et al. (2018) assumed a 40% loss compared to 13-52% loss found in other studies); and (2) a large range in potential productivity of second-generation lignocellulosic bioenergy crops, with JULES falling on the low end. ~~(~~JULES in this study and in Harper et al. (2018) simulated median average yields of ~4.8 and ~4.6 tDM ha^{-1} yr^{-1}, respectively, compared to measured median of 11.5 tDM ha^{-1} yr^{-1} and simulated average of 15.8 tDM ha^{-1} yr^{-1} in IMAGE~~)~~. The JULES yield of ~4.8 tDM ha^{-1} yr^{-1} corresponds to ~59 EJ yr^{-1} of primary energy, using the maximum area for BECCS from Table 2 of 637.7 Mha and an energy yield of 19.5 GJ t DM^{-1} (Daioglou et al., 2017). Bioenergy supplied 55.6 EJ yr^{-1} or ~10% of primary energy requirement worldwide in 2017 (WBA, 2019). According to Smith et al. (2016), this would increase to ~170 EJ yr^{-1} of primary energy in 2100, for negative emissions of 3.3 Gt Ceq yr^{-1} from BECCS (as required for a 2°C warming target).

As both of these components are assumed to be diagnostics of the simulations, we can modify the contribution of BECCS to the AFFEB via a post-processing scaling factor, κ, which represents the efficiency of (1) and (2) with respect to the JULES parameterisation. That is, Eq. 10 becomes:

$$\Delta C_{LBM}^{land} = \begin{cases} \sum_{l}^{grid\ cells} \Delta C_{IM1.9}^{land} + \kappa\ BECCS_{IM1.9} & \text{where } \Delta C_{IM1.9N}^{land} < \Delta C_{IM1.9}^{land} + \kappa\ BECCS_{IM1.9} \\ & or \\ \sum_{l}^{grid\ cells} \Delta C_{IM1.9N}^{land} & \text{where } \Delta C_{IM1.9N}^{land} > \Delta C_{IM1.9}^{land} + \kappa\ BECCS_{IM1.9} \end{cases} \quad (11)$$

Commented [HGD24]: Reviewer comment 2.8: DONE in next section. This comment is on the energy production from BECCS. It sits better but in the next section than here.

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Commented [HGD26]: Reviewer comment 2.8: DONE, bioenergy (in EJ or Mt per year) produced.

Figure 7Figure 5 presents maps of the scaling factor required for BECCS to be the preferable mitigation option, as opposed to natural land carbon uptake, for each grid cell for warming of 1.5°C or 2°C. There are large factors in the northern temperate and boreal regions, parts of Africa and Australia. As discussed in Harper et al. (2018), this follows from the loss of soil carbon in the tropics and at high northern latitude leading to long recovery or payback times (10-100+ years and >100 years, respectively, Fig. 6(c) in their paper). The payback time is however insignificant when bioenergy crops replace existing agriculture, for example in Europe and eastern North America.

Additionally, we define a threshold efficiency factor, κ^*, which represents the required BECCS efficiency for BECCS to be a preferable mitigation strategy for a given grid-cell, i.e.:

$$\kappa^* = \frac{\Delta C^{land}_{IM1.9N} - \Delta C^{land}_{IM1.9}}{BECCS_{IM1.9}} \quad (12)$$

This increased efficiency can be considered to be the additional bioenergy harvest (H) and/or the reduced carbon losses from farm to storage needed to pay back the carbon debt accrued due to land-use change (since carbon removed via BECCS = Hε, where ε is the assumed efficiency factor for farm to storage carbon conservation and H is the simulated biomass harvest). In addition, κ^* implies a new threshold (or break-even) level of BECCS:

$$BECCS^* = \kappa^* * BECCS_{IM1.9} \quad (13)$$

In other words, BECCS* is equivalent to the carbon loss due to the land use change to grow the bioenergy crops. 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:

$BECCS^* = 0.87\ H^*$ and $BECCS_{IM1.9} = 0.60\ H$

So:

$$H^* = \kappa^* * \frac{0.6}{0.87} * H \quad (14)$$

We discuss this further in Sect. 3.2.

2.42.5 Model Runs

We undertake control runs and other simulations, with (1) anthropogenic CH_4 mitigation, (2) land-based mitigation or (3) both, stabilising at either 1.5°C or 2.0°C warming without a temperature overshoot, based on the IMAGE SSP2 1.9 (denoted IM-1.9) and baseline (IM-BL) scenarios (Riahi et al., 2017;Doelman et al., 2018) (Sect. 2.3). Table 2 lists the factorial runs, their key features and the prescribed datasets used (for agricultural land and BECCS, anthropogenic emissions and atmospheric concentrations of methane and the non-CO_2 radiative forcing). We denote the anthropogenic CH_4 mitigation scenario as

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"CH4", the land-based mitigation scenario using BECCS as "CCS" and "Natural Land" as focussing on AR. We also undertake coupled runs to see if there are any non-linearities when we combine the methane and land-based mitigation scenarios.

For each temperature pathway (1.5°C or 2.0°C) and for the baseline and each mitigation scenario, the set of factorial runs comprises a 136-member ensemble (34 GCMs x 2 ozone damage sensitivities x 2 methanogenesis Q_{10} temperature sensitivities). In all model runs, we include 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 (Comyn-Platt et al., 2018).

As shown in Fig. 1 and discussed in previous sections (Sects 2.2.1 and 2.3), we use a number of prescribed datasets: (a) time series of the annual area of land used for agriculture, including that for BECCS if appropriate; (b) time series of the global annual mean atmospheric concentrations of CH_4 (and N_2O for the radiative forcing calculations of CO_2 and CH_4); (c) time series of the overall radiative forcing by SLCFs and non-CO_2 GHGs (corrected for the radiative forcing of CH_4); and (d) time series of annual anthropogenic methane emissions (used in the post-processing step). We take these from the IMAGE database for the relevant IMAGE SSP2 scenario (baseline or SSP2-1.9). The prescribed datasets used in the different factorial runs are given in Table 2.

The difference in anthropogenic fossil fuel emission budget (AFFEB) between the mitigated pathway and the control simulation gives an estimate of the Mitigation Potential (MP) of the mitigation strategy. The IM-1.9 scenario relies on a combination of BECCS, reduced emissions from deforestation and degradation (REDD), and reforestation of degraded forest areas to achieve a 1.5°C climate target, while IM-BL has limited land-based mitigation via moderate levels of REDD and AR. We develop an additional land-based mitigation scenario (IM-1.9N) where any bioenergy cropland area in IM-1.9 is replaced by natural vegetation (Sect. 2.3). We then derive an optimal land-based mitigation pathway in a post-processing step by selecting the option, (a) BECCS or (b) natural vegetation, which has the more positive impact on the AFFEB in each grid cell (Sect. 2.4.1).

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3 Results and Discussion

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 present in Fig. 6 8 the median and ensemble member spread of the AFFEB (as box and whiskers), and the individual GCM/ESM contributions to the AFFEBs from the four carbon pools shown (points), for each of the factorial experiments. 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 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. 3(c)-(h)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, which is greater than the land carbon lost through land-use changes. We also find that there is increased uptake of CO_2 by the oceans for all scenarios. A further co-benefit of reducing the CH_4 emissions and allowing more CO_2 emissions is that the oceanic drawdown of CO_2~~carbon dioxide~~ rises (although it eventually falls to zero under climate stabilisation and there would also be implications for ocean acidification). In Fig. ~~7~~9(a), we compare the AFFEBs for both the 1.5°C and 2°C temperature pathways. We find that the absolute AFFEBs are 200-300 GtC larger for the 2°C target than the 1.5°C target. These budgets are in agreement with other estimates, which include corrections to the historical period (Millar et al., 2017). In both Figs. 8 and 9, it should be noted that the gain in the land carbon store for the "CH_4" mitigation option is 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). This then explains the positive changes shown for the land carbon stores in the coupled "BECCS+ CH_4" and coupled "Natural+ CH_4" scenarios.

Figure 9~~Figure 7~~(b) shows the mitigation potential of each strategy, calculated as the change in the AFFEB from the corresponding control simulation, for the two temperature pathways (Sect. 2.4.1, Eq. 7 and 8). Methane mitigation is a highly effective strategy; the AFFEBs are increased by 188-206 GtC and 193-212 GtC for the 1.5°C and 2°C scenarios, respectively, where the range represents the interquartile range from the 136-member ensemble (34 GCMs x 2 Q_{10} x 2 ozone sensitivities). This AFFEB increase equates to roughly 20-24 years of emissions at current rates for the 1.5°C target. Land-based mitigation strategies also provide significant increases of 51-57 GtC and 56-62 GtC for the 1.5°C and 2°C AFFEB estimates, respectively. This is equivalent to 6-7 years of emissions at current rates. For our BECCS assumptions (see also below), we find that the BECCS contribution is small for the optimised land-based mitigation pathway and that AR are more effective land-based mitigation strategies (Fig. ~~7~~9(b)). 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.

Furthermore, the CH_4 and land-based mitigation strategies show little interaction and their potential can be summed to give a comparable result to the coupled simulation (coupled vs linear in Fig. ~~7~~9(a) and (b)). This decoupling is despite the ~~methane~~ CH_4 emissions from the agricultural sector being influenced by land use choices. We can effectively treat the two mitigation strategies as independent, and their sum approximates the combined potential. Such linearity enables simpler and more direct comparisons.

Despite the substantial differences in the absolute AFFEBs for the 1.5° and 2°C targets, the mitigation potential of the CH_4 and land-based strategies is similar for the two temperature scenarios considered. This similarity suggests that the mitigation~~investment in such~~ strategies ~~is~~ are robust to the target temperature; whether the international community aims for the 1.5° or 2°C target, afforestation, reforestation, reduced deforestation and CH_4 mitigation are ~~worthwhile~~ beneficial mitigation approaches.

3.2 Sensitivity to BECCS Efficiency

The BECCS parameterisation used here makes BECCS less effective compared to those in other studies (van Vuuren et al., 2018). Globally across the two temperature targets, our simulations imply a removal of 27-30 GtC from the active carbon-cycle ~~atmosphere~~ via BECCS in the original ~~IM-1.9 simulation~~ "BECCS" scenario run, which is reduced to ~7-12 GtC after

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we optimise the land-use scenario. These removal rates are significantly lower than other estimates based on the same land-use scenarios: 73 GtC in a similar dynamic global vegetation model (LPJ-GUESS) and 130 GtC in IMAGE (Harper et al., 2018). We find that doubling the carbon captured with BECCS in our simulations (Sect. 2.4.3, κ=2) has a relatively small impact on the total mitigation potential in the optimised scenario (Fig. ~~8~~10(a)). This low sensitivity is because the increased carbon removed by BECCS often accompanies a comparable decrease in the carbon uptake from the "natural" vegetation that it replaces. It is only when setting the BECCS carbon sequestration at 3-5 times its original value that there is a notable increase of the global AFFEB. Further, as shown in Fig. ~~8~~10(b), there is reduction in soil carbon in specific regions (e.g. Northern temperate and boreal regions), which makes BECCS less effective for carbon sequestration than natural land management options (or there is a long payback time as discussed in Harper et al. (2018)).

Increased carbon removal with BECCS could be realised through either (1) minimizing the loss of carbon from farm to final storage (ε in Sect. 2.4.3), or (2) maximizing the productivity of the bioenergy crop. 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). The bioenergy crop yields in JULES (Fig. ~~8~~10(c)) are lower than the median yield of Miscanthus (11.5 tons of dry matter (ton DM) ha^{-1} yr^{-1}), measured from 990 mostly European plots (Li et al., 2018), and are about half the productivity of those in the IMAGE simulations. 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. ~~8~~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, the required yield increases from <10 to 10-20 ton DM ha^{-1} yr^{-1} are achievable, but yields of > 30 ton DM ha^{-1} yr^{-1} would be more difficult to realise (Li et al., 2018).

We conclude that our uncorrected simulations are a lower estimate for the potential of carbon removal via BECCS. We provide a more optimistic estimate of the BECCS potential using κ = 3, which results from doubling the JULES yields and increasing the efficiency ε from 0.6 to 0.87 (i.e., κ ~ 2 × 0.87 / 0.6). We now find the global land-based mitigation potential to be ~~56-62~~88-100 GtC across the two temperature targets, as shown in Fig. ~~7~~9(c) and (d). Supporting Information, Figure SI.3 shows the corresponding plots for the 2°C warming target. We use κ = 3 in the subsequent analysis of regional mitigation options and of BECCS water requirements.

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3.3 Regional Analysis

We consider the sub-continental implications of CH_4 and land-based mitigation options, using the 26 regions of the IMAGE model (Stehfest et al., 2014). Figure 11~~Figure 9~~ shows the contributions of the three mitigation options - CH_4, carbon uptake through AR and BECCS - to the AFFEBs for each IMAGE region and for the temperature pathway stabilising at 1.5°C.

We estimate the regional land-based mitigation as the change in the land-carbon stores plus the carbon removal via BECCS for each IMAGE region in the IMOGEN-JULES model output. In this accounting, the region where the bioenergy crops are grown is credited with the carbon removal via BECCS. We assume a three-fold increase in carbon removal via BECCS compared to our default simulations (κ=3) to highlight regions where BECCS is potentially viable. Figure 12~~Figure 10~~ shows the sensitivity of the global AFFEBs and Mitigation Potential for κ = 1, 2 and 3 for 1.5°C of warming (Supplementary Information, Figure SI.2 is the corresponding figure for 2°C of warming). For CH_4, we derive the regional contribution to the changes in the global atmospheric CH_4 concentration, and therefore the CH_4 mitigation potential, using regional fractions of the global difference in anthropogenic CH_4 emissions (2020-2100) between the IMAGE SSP2-Baseline and SSP2-1.9 scenarios (van Vuuren et al., 2017) (Table 3). These two CH_4 scenarios are consistent with the CH_4 concentration pathways considered in the CH_4 factorial simulations (Sect. 2.3).

CH_4 mitigation ~~generally has a larger impact on emission budget reductions,~~ is an effective mitigation strategy for all regions, and especially the major methane emitting regions: India, S. Africa, USA, China and Australasia. Figure 4 presented time series of the anthropogenic ~~methane~~ CH_4 emissions for selected IMAGE region from 2000 to 2100 (and Supplementary Information, Figure SI.1 presents emission time series for all IMAGE regions). The mitigation of CH_4 emissions from fossil-fuel production, distribution and use for energy is the largest contributor for India, S. Africa, USA, China and Australasia. The emissions from agriculture-cattle (for India, USA and China) and rice production (China and other Asian regions) make smaller contributions.

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The impact of the land-based mitigation options links strongly to the managed land-use and land-use change (LULUC). As discussed in Sect. 2.3.2, we list in Table 2~~Table 1 lists~~ the maximum area of BECCS deployed in each IMAGE region and the main differences in land use between the ~~IM-1.9~~BECCS and ~~IM-1.9N~~Natural scenarios. Figure 5~~Figure 11~~ presents time series of the land areas calculated for trees and prescribed for agriculture (including bioenergy crops) and bioenergy crops for the ~~IM-1.9~~BECCS and ~~IM-1.9N~~Natural scenarios for the Russia and Brazil IMAGE regions, each as a difference to the baseline scenario (IM-BL) (see Supplementary Information, Figure SI.3 ~~is equivalent to Fig. 11~~ ~~13~~ for all the IMAGE regions). The West Africa region shows the largest natural land carbon uptake (WAF in Fig. ~~10~~12). Here, there is conversion of crop and pasture to forest, with little land used for bioenergy crops for BECCS. For Brazil (Fig. ~~11~~5(a)) and the rest of South America, both bioenergy crops and forest expand at the expense of agricultural land. For many other regions, notably Canada, Russia, W. & C. Europe, China, Oceania, there is less carbon uptake from the 'land' in the optimised mitigation scenario, even though the overall carbon uptake has increased. For Canada and Russia, this results from the loss of forest in the BECCS land use scenario (see Fig. ~~11~~5(b) and Supplementary Information, Figure SI.3). 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 κ only affects the 'BECCS' term (Sect. 2.4.3, Eq. 11), 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. ~~10~~ 12 (and Supplementary Information, Figure SI.~~2~~ 3 for 2°C warming). The version of JULES used in this study currently lacks a fire regime. There will be risks to long-term storage of carbon stored in vegetation in regions with significant areas of fire-dominated vegetation cover (e.g. savannah in Brazil and Africa). Further, this version of JULES does not include a nitrogen cycle, which has been implemented in more recent versions of the model. This will enable the impact of changes in land use and agriculture on N_2O emissions to be integrated into the assessments.

There is relatively little difference in the additional allowable carbon emission budgets introduced by CH_4 and/or the land-based mitigation between 2015 and 2100 for the two temperature scenarios considered (Supplementary Information, Figure SI.4 for the contributions at 2°C of warming).

3.4 Water Resources

Smith et al. (2016) estimate the global water requirements for different negative emission technologies, including BECCS. We also derive the water requirements from the carbon uptake by BECCS for our optimised land-based mitigation scenarios. The IM-1.9 land use scenario (Sect. 2.3.2) assumes that bioenergy crops are grown sustainably and are rain-fed (Hoogwijk et al., 2005;Daioglou et al., 2019). Our land surface modelling system explicitly accounts for this. We derive the additional water requirements for BECCS, using ~~We set~~ κ = 3 and ~~assume~~ assuming (a) a marginal increase in water use of 80 m^3 (tC eq)$^{-1}$ yr^{-1} when replacing the average short vegetation (i.e., C3/C4 grasses in JULES) by a biomass energy crop (Smith et al., 2016); and (b) 450 m^3 (tC eq)$^{-1}$ yr^{-1} for the CCS component (Smith et al., 2016).

Following Postel et al. (1996), we derive the accessible runoff, ~~assuming~~ using their assumptions that only 5% of the total runoff is geographically and/or temporally accessible for the Brazil, Russia and Canada IMAGE regions, and 40% elsewhere. Our present-day estimates of the global annual runoff (43,000-44,200 km^3 yr^{-1}) and the accessible runoff for human use (11,400-11,720 km^3 yr^{-1}) (see Fig. ~~12~~13) are both in agreement with the values given in Postel et al. (1996), i.e., total and accessible runoffs of 40,700 and 12,500 km^3 yr^{-1}, respectively.

We use ~~as the total~~ the water withdrawals for each IMAGE region ~~from~~ given in the IMAGE-SSP2-RCP2.6 scenario~~s~~ for the water ~~requirements~~ demand for agricultural irrigation (Rost et al., 2008) and for other human activities, such as energy generation, industry and domestic usage (Bijl et al., 2016), between 2015 and 2100 (Table 4a and 4b)~~,. We note Bijl et al. (2016)that the irrigation water withdrawal, derived using the coupled IMAGE-LPJmL models, are low compared to other estimates in the literature~~. We assume the same water demands from these sectors for both the 1.5°and 2°C warming targets.

Figure 14~~Figure 13~~ compares the accessible water with the water demand for BECCS and other human activities for the ~~eight~~ regions~~, which~~ that produce a substantial amount of BECCS: Canada, USA, Brazil, Europe, Russia, China, Southern Africa and Oceania for the optimised land-based mitigation. Table 4a and b show the additional water requirements of BECCS calculated for 2060 and 2100, respectively, for the 2°C warming target. We find that the additional demand for BECCS would lead to an exceedence (or use >90%) of the available water for the Oceania and Rest of Southern Africa regions. We also find that the additional demand for BECCS is greater than the total water withdrawals from anthropogenic activities for the Canada and Brazil IMAGE regions. Our estimates represent a maximum possible water usage for BECCS as (i) the SSP2 scenario used already accounts for the lower power generation efficiencies and hence higher water requirements in switching from fossil fuels to bioenergy crops (which could be up to 20-25%) and (ii) the figure used for the CCS component does not allow for future technological improvements in water use. For example, Fajardy and Mac Dowell (2017) indicate a 30-fold reduction in water use when changing from a once-through to a recirculating cooling tower. Our results are less severe than other studies considering BECCS water requirements (Séférian et al., 2018;Yamagata et al., 2018), because the carbon removed by BECCS

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Commented [HGD37]: Reviewer comment 1.23: DONE, BECCS water demand added to Table.

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Commented [HGD39]: Reviewer comment 1.21. DONE. Text changed.

Commented [HGD40]: Reviewer comment 2.13: DONE, added quantitative statements in this study (30 GtC) is already limited to regions where it is more beneficial to the AFFEB than forest-based mitigation options. We also note from Bijl et al. (2016) that the water demand for irrigation, derived using the coupled IMAGE-LPJmL models, is low compared to other estimates in the literature. Higher water demand for irrigation existing agriculture would be an additional constraint on the water available for BECCS. Nevertheless, our results indicate that the additional water demand for BECCS would make it impracticalhave large impacts in half of the regions substantially invested in BECCS: Oceania, Rest of South Africa, Brazil and Canada and China (2060).

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4 Conclusions

Our paper brings together previous studies that looked separately into the potential of methane mitigation (Collins et al., 2018) and land-management options (especially forest conservation and BECCS) (Harper et al., 2018), into a single unified framework. Uniquely, this allows us to compare these options at local and regional scales. We utilise the detailed JULES land-surface model, which includes the temperature sensitivity of methanogenesis (Comyn-Platt et al., 2018) and the effect of methane CH_4 emissions on land carbon storage via ozone impacts on vegetation (Sitch et al., 2007), and also span the range of climate model projections using the IMOGEN ESM-emulator. For each temperature pathway and each of the three mitigation options, the set of factorial runs comprises a 136-member ensemble (34 GCMs x 2 ozone damage sensitivities x 2 methanogenesis Q_{10} temperature sensitivities).

This analysis quantifies the regional differences in potential CH_4 and land-based strategies to aid mitigation of climate change. 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 vegetation damage. We acknowledge that 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 quantify a strong 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. For boreal forest regions there is a preference for avoided deforestation, whereas in tropical forest regions both AR and avoided deforestation offer significant potential. From a carbon sequestration perspective, growing bioenergy crops for BECCS is only preferable where it replaces existing agricultural land. BECCS has particular potential if productivities and power production efficiencies are towards the upper limit of expected photosynthetic capability, whilst noting the strong water demand of such crops requires consideration in the context of a growing population.

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Our overarching finding is however robust to these uncertainties. We conclude that CH_4 mitigation can be a highly effective route to meeting the Paris Agreement targets, and could offset up to 188-212 GtC of anthropogenic CO_2 emissions.

It is effective globally and especially so for the major CH_4-emitting regions of India, USA and China 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. We conclude that CH_4 mitigation would be effective globally and especially so for the major CH_4-emitting regions of India, USA and China.

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Code and Data Availability

The 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 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).

All code, data and parameterisations are available on request to the corresponding author.

Author Contributions

G.H., C.H., E.C-P., A.H., P.C., T.P., J.H., W.C., J.L. and S.C. designed the IMOGEN runs. All authors contributed to the interpretation of the results and to the writing of or review of the paper. C.H. provided IMOGEN parameters calibrated against the CMIP5 database, and E.C-P and C.H. led the development of the inverse IMOGEN model version. The following specific contributions were also made: (a) E.B., S.C. and N.G.: code and expertise on permafrost, soil carbon and wetland methane modelling, respectively; (b) A.H. and T.P.: land use change data; (c) W.C. and C.W.: ozone ancillary data; (d) D.P.vV. and J.C.D.: IMAGE scenario data on land use, anthropogenic methane emissions and water consumption and withdrawals, and (e) S.S.: expertise on the ozone damage effects.

Competing interests

The authors declare no competing interests.

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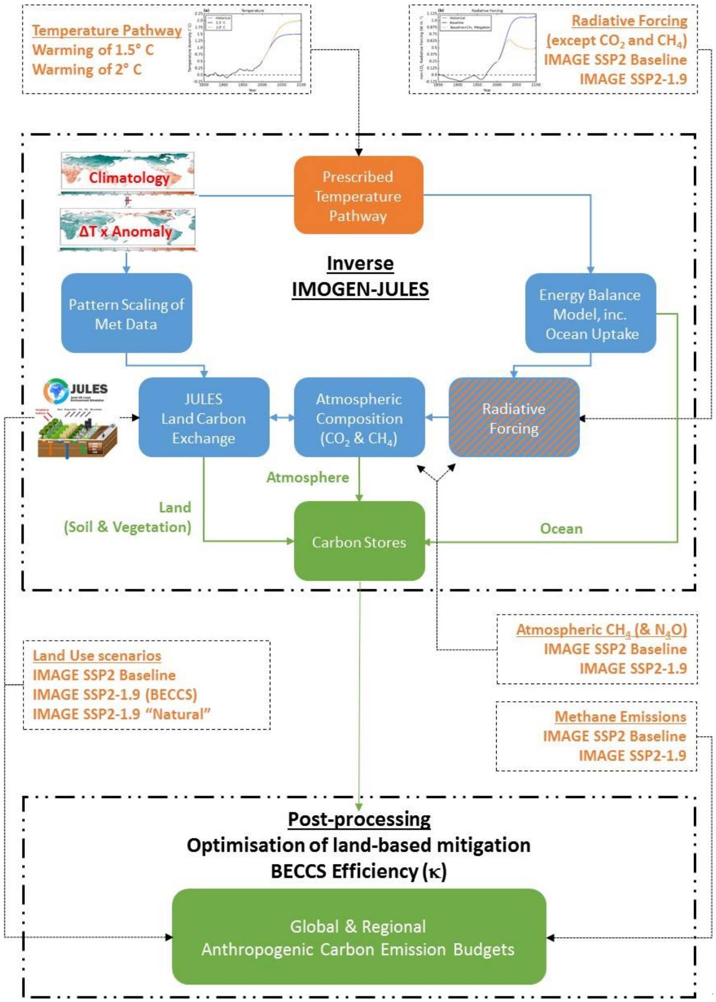
Figures


Temperature Pathway
Warming of 1.5° C
Warming of 2° C
Radiative Forcing
(except CO_2 and CH_4)
IMAGE SSP2 Baseline
IMAGE SSP2-1.9
Climatology
ΔT x Anomaly
Prescribed Temperature Pathway
Inverse
IMOGEN-JULES
Pattern Scaling of Met Data
Energy Balance Model, inc. Ocean Uptake
JULES
JULES Land Carbon Exchange
Atmospheric Composition (CO_2 & CH_4)
Radiative Forcing
Atmosphere
Land
(Soil & Vegetation)
Carbon Stores
Ocean
Atmospheric CH_4 (& N_2O)
IMAGE SSP2 Baseline
IMAGE SSP2-1.9
Land Use scenarios
IMAGE SSP2 Baseline
IMAGE SSP2-1.9 (BECCS)
IMAGE SSP2-1.9 "Natural"
Methane Emissions
IMAGE SSP2 Baseline
IMAGE SSP2-1.9
Post-processing
Optimisation of land-based mitigation
BECCS Efficiency (κ)
Global & Regional
Anthropogenic Carbon Emission Budgets

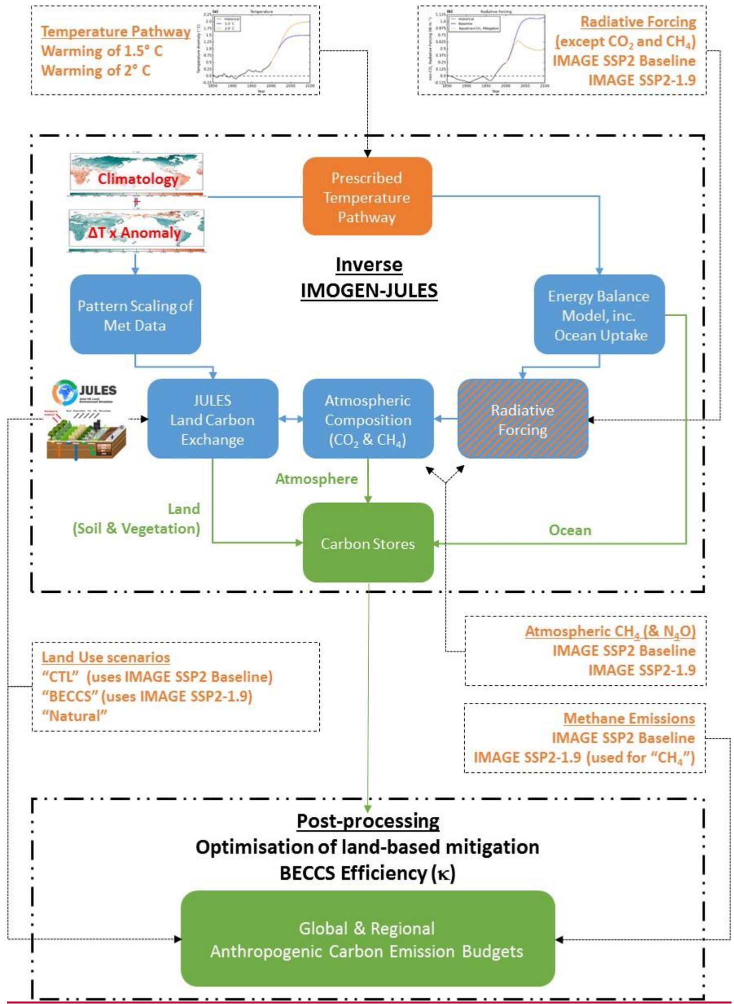
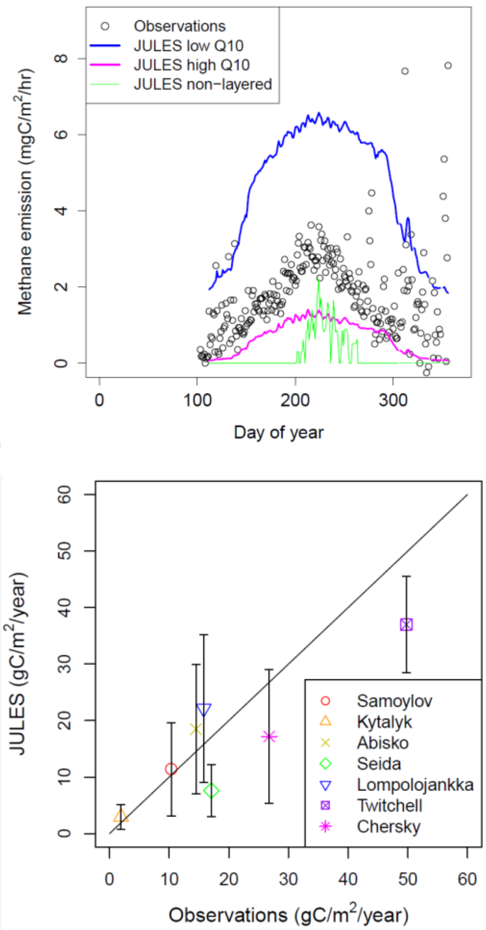


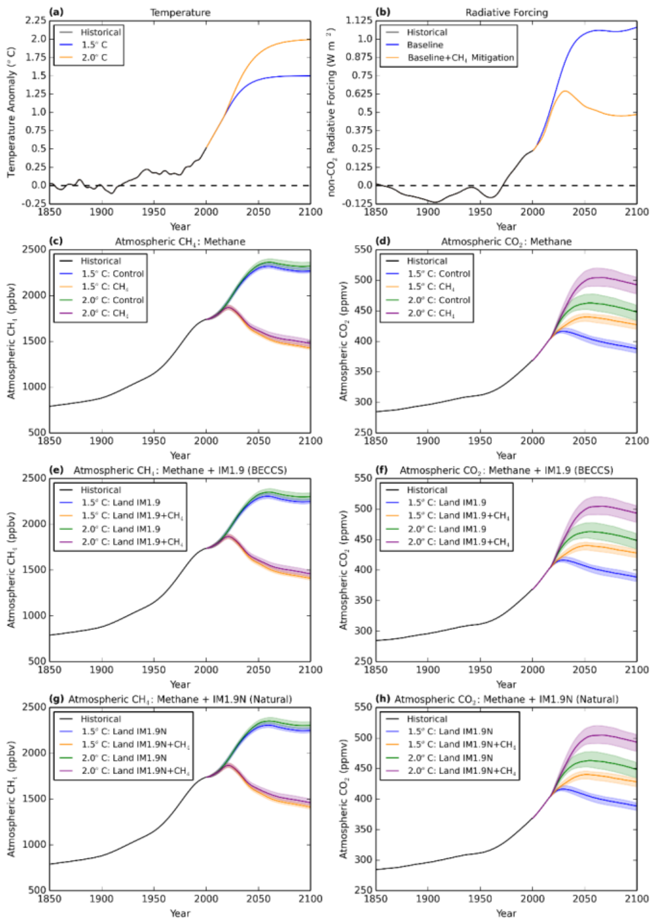
Figure 1 | Schematic of the modelling approach and the workflow. The coloured boxes and text show (a) the key components of the inverted IMOGEN-JULES model (blue), the prescribed data used in this study (orange) and the outputs (green).



(a)

(b)

Figure 2 | (a) Observed (circles) and modelled wetland methane emissions at the Samoylov Island field site. Modelled wetland methane emissions are shown for the standard JULES non-layered soil carbon configuration (green) and for the JULES layered soil carbon configurations with the low (blue line) and high (magenta line) Q_{10} temperature sensitivities; the low Q_{10} configuration gives higher methane emissions at high-latitude sites such as the Samoylov Island field site. The methane emission data is preliminary and was provided by Lars Kutzbach and David Holl. (b) Comparison of observed and modelled annual mean wetland CH_4 emission fluxes at a number of northern high-latitude and temperate sites.



(a) Temperature
Historical
1.5° C
2.0° C
Temperature Anomaly (° C)
Year
(b) Radiative Forcing
Historical
Baseline
Baseline+CH4 Mitigation
non-CO2 Radiative Forcing (W m⁻²)
Year
(c) Atmospheric CH4: Methane
Historical
1.5° C: Control
1.5° C: CH4
2.0° C: Control
2.0° C: CH4
Atmospheric CH4 (ppbv)
Year
(d) Atmospheric CO2: Methane
Historical
1.5° C: Control
1.5° C: CH4
2.0° C: Control
2.0° C: CH4
Atmospheric CO2 (ppmv)
Year
(e) Atmospheric CH4: Methane + IM1.9 (BECCS)
Historical
1.5° C: Land IM1.9
1.5° C: Land IM1.9+CH4
2.0° C: Land IM1.9
2.0° C: Land IM1.9+CH4
Atmospheric CH4 (ppbv)
Year
(f) Atmospheric CO2: Methane + IM1.9 (BECCS)
Historical
1.5° C: Land IM1.9
1.5° C: Land IM1.9+CH4
2.0° C: Land IM1.9
2.0° C: Land IM1.9+CH4
Atmospheric CO2 (ppmv)
Year
(g) Atmospheric CH4: Methane + IM1.9N (Natural)
Historical
1.5° C: Land IM1.9N
1.5° C: Land IM1.9N+CH4
2.0° C: Land IM1.9N
2.0° C: Land IM1.9N+CH4
Atmospheric CH4 (ppbv)
Year
(h) Atmospheric CO2: Methane + IM1.9N (Natural)
Historical
1.5° C: Land IM1.9N
1.5° C: Land IM1.9N+CH4
2.0° C: Land IM1.9N
2.0° C: Land IM1.9N+CH4
Atmospheric CO2 (ppmv)
Year

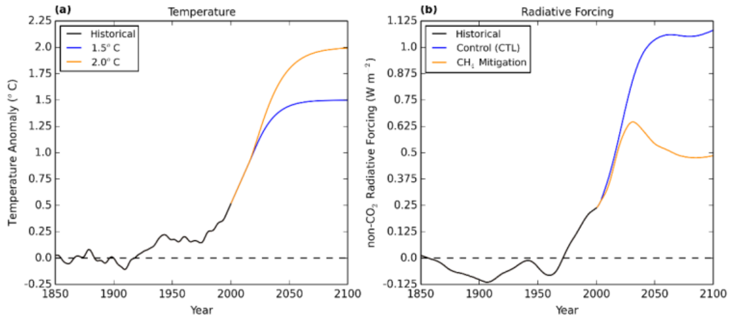


Figure 3 | Time series of (a) the temperature profiles used to represent warming of 1.5°C (blue) and 2°C (~~red~~orange); (b) the non-CO_2 greenhouse gas radiative forcing (W m^{-2}) for the ~~baseline~~ control (~~red~~orange) and methane mitigation (blue) scenarios~~; (c, e, f) the ensemble median atmospheric CH_4 concentrations (with interquartile range as spread) derived for each land use scenario: (c) IM-BL, (e) IM-1.9, (g) IM-1.9N. In each panel, time series are shown for the baseline (IM-BL) and methane mitigation (IM1.9) scenarios for each temperature profile. (d, f, h) the corresponding time series for the atmospheric CO_2 concentrations~~.

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Reviewer comment 1.26: DONE, checked consistency of scenarios.

Reviewer comment 2.14: DONE, checked figure titles & captions.

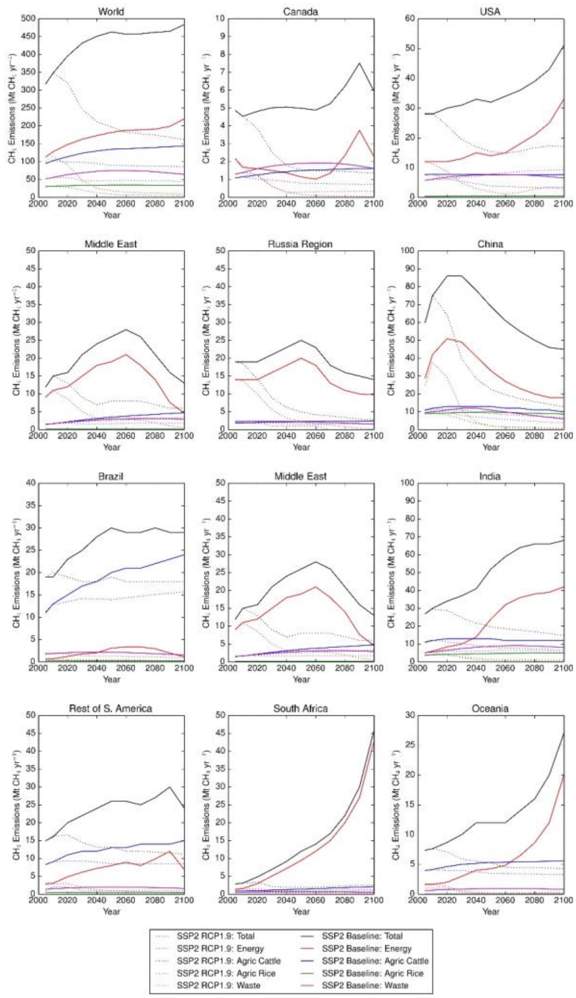
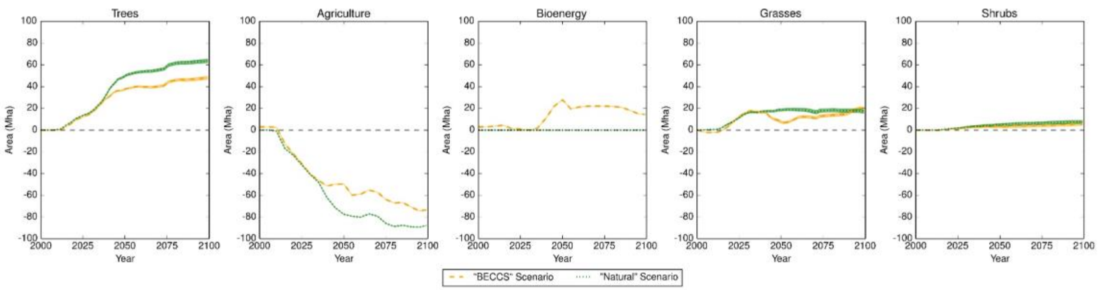


Figure 4 | Time series of annual methane emissions between 2005 and 2100 from all and selected anthropogenic sources according to the IMAGE SSP2 Baseline (solid lines) and SSP2-RCP1.9 (dotted lines) scenarios, globally and for selected IMAGE regions, with total emissions in black, energy sector in red, agriculture-cattle in blue, agriculture-rice in green and waste in magenta. Note the y-axes have different scales for clarity.

(~~b~~a) IMAGE Brazil Region



(~~a~~b) IMAGE Russia Region

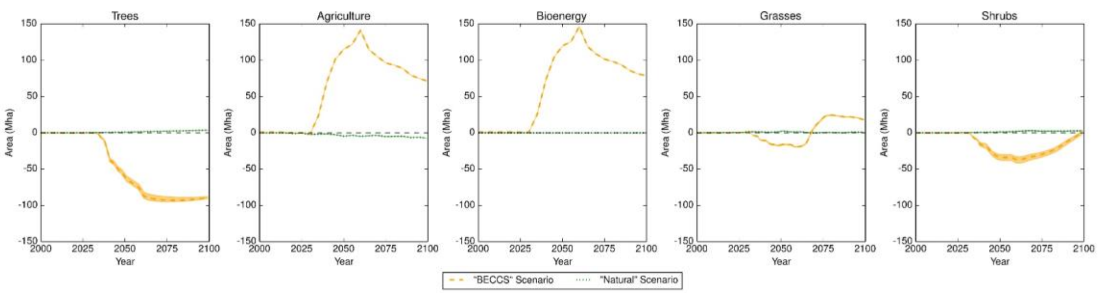


Figure 5 | Time series of the land areas (in Mha) calculated for trees and prescribed for agriculture (including bioenergy crops) and bioenergy crops for the 'BECCS' (orange) and'Natural, (green), as a difference to the baseline scenario (IM-BL), for Brazil ~~the Russia~~ (panel a) and the Russia~~Brazil~~ (panel b) IMAGE regions between 2000 and 2100. The dotted lines are the median and the spread the interquartile range for the 34 GCMs emulated and 4 factorial sensitivity simulations.

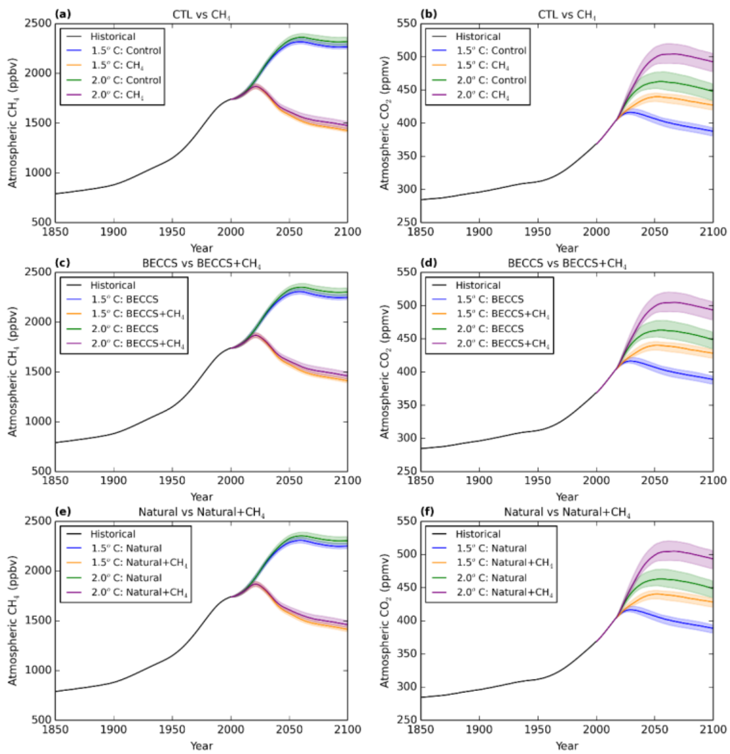


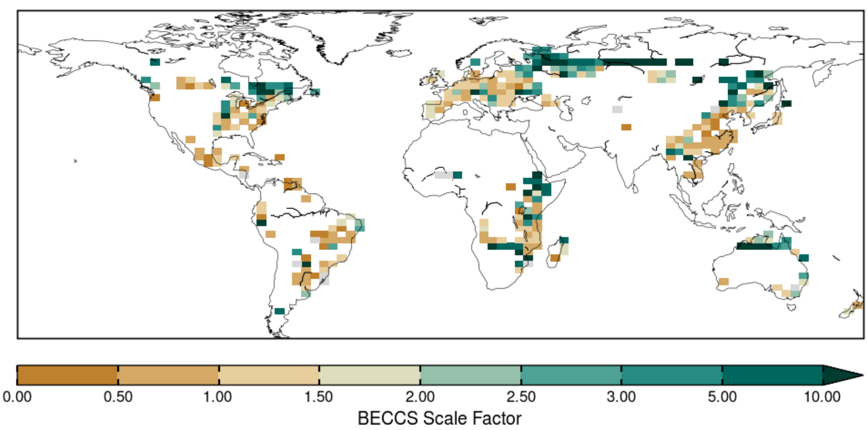
Figure 6 | (a, c, e) Time series of the ensemble median atmospheric CH_4 concentrations (with interquartile range as spread) derived for each temperature profile for the scenarios: (a) "CTL" and "CH_4", (c) "BECCS" and "BECCS+CH_4", (g) "Natural" and "Natural+ CH_4". (d, f, h) show the corresponding time series for the atmospheric CO_2 concentrations.

Commented [HGD47]: Reviewer comment 1.25: DONE, split original Figures 3

Reviewer comment 1.26: DONE, amended to ensure consistency of scenario notation.

Reviewer comment 2.14: DONE, amended figure titles & captions.

(a)



(b)

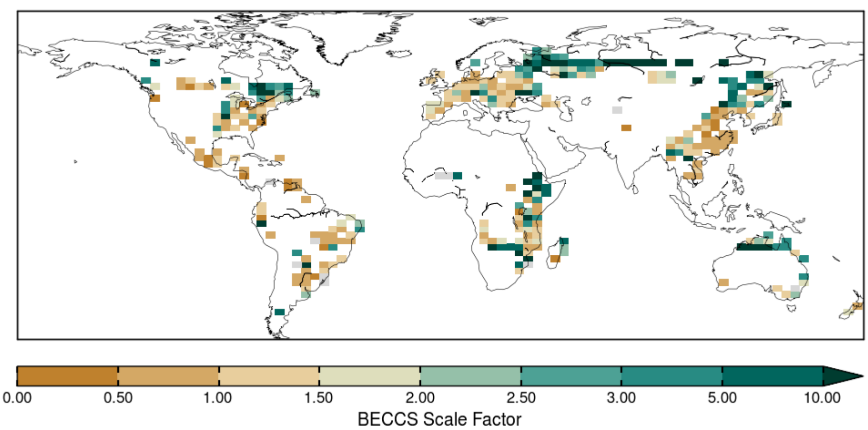


Figure 7 | Scale factor required for BECCS to be the preferable mitigation option, as opposed to natural land carbon uptake. The data represents the median of the 136 member ensemble for the optimised land-based mitigation simulation. Panel (a) is for stabilisation at 1.5°C and panel (b) is for stabilisation at 2°C.

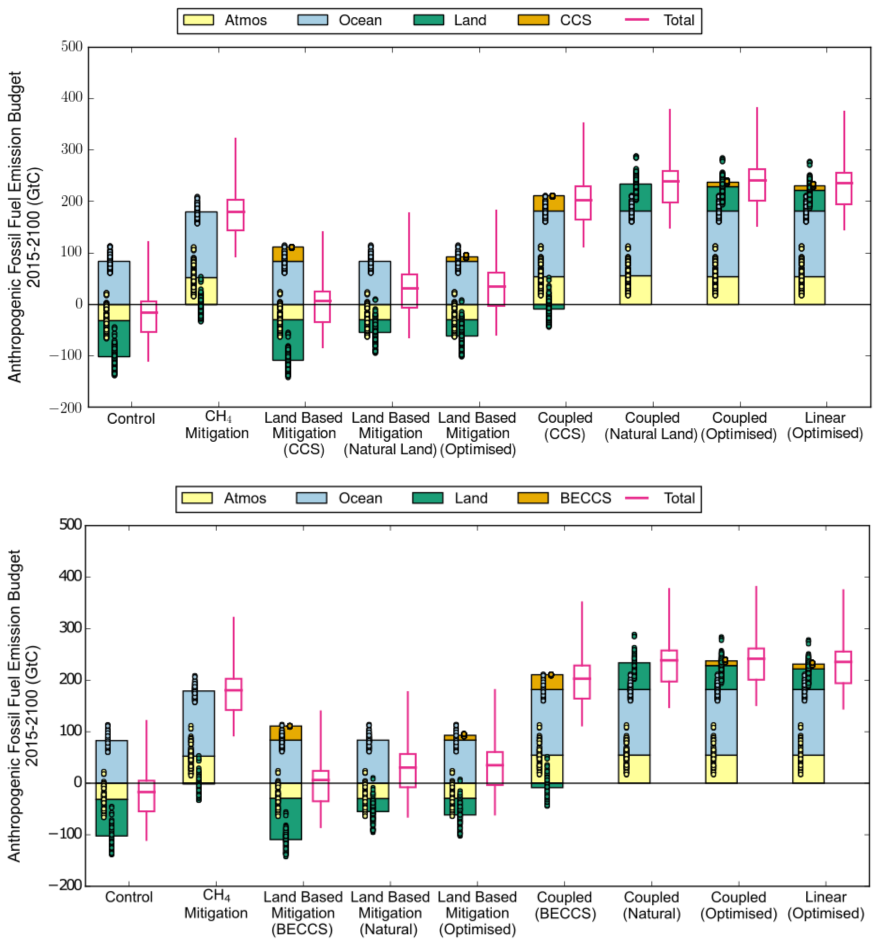
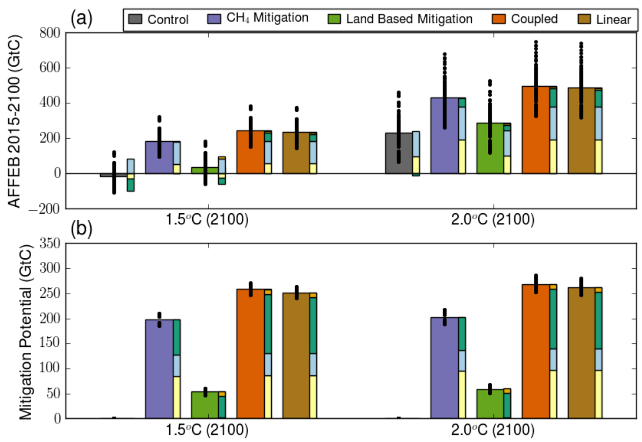


Figure 8 | The contribution to the allowable anthropogenic fossil fuel emission budget (AFFEBs, GtC) from the changes in the different carbon stores (atmosphere, ocean, land and BECCS) for the various control and mitigation runs, illustrated using the temperature pathways reaching 1.5°C without overshoot. 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 is 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).

Commented [HGD48]: Reviewer comment 1.27: DONE, added note about land-carbon store for CH4 scenarios (See also next figure).

BECCS Scale Factor (κ) = 1



BECCS Scale Factor (κ) = 3

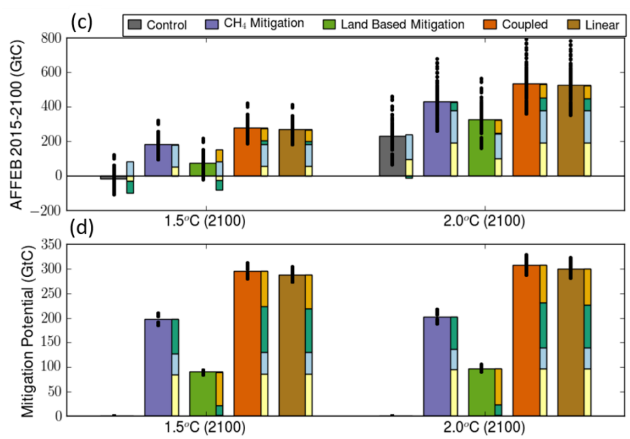


Figure 9 | ~~Allowable anthropogenic fossil fuel emission budgets and mitigation potential for the factorial simulation experiment.~~Panels (a & c): The allowable anthropogenic fossil fuel emission budgets (AFFEBs; GtC) for the control (grey), ~~methane~~ CH_4 mitigation (purple), land-based mitigation (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. ~~a & b are for the standard JULES BECCS productivity and efficiency (κ=1, Sect. 2.4.3), in c & d the BECCS productivity and efficiency uses κ=3.~~ The

Commented [HGD49]: Reviewer comment 1.28: As 1.27. DONE, added note about land-carbon store for CH4 scenarios (See previous figure).

Reviewer comment 2.15. DONE, moved some of figure caption.

breakdown of ~~the~~ 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 scenario is 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).

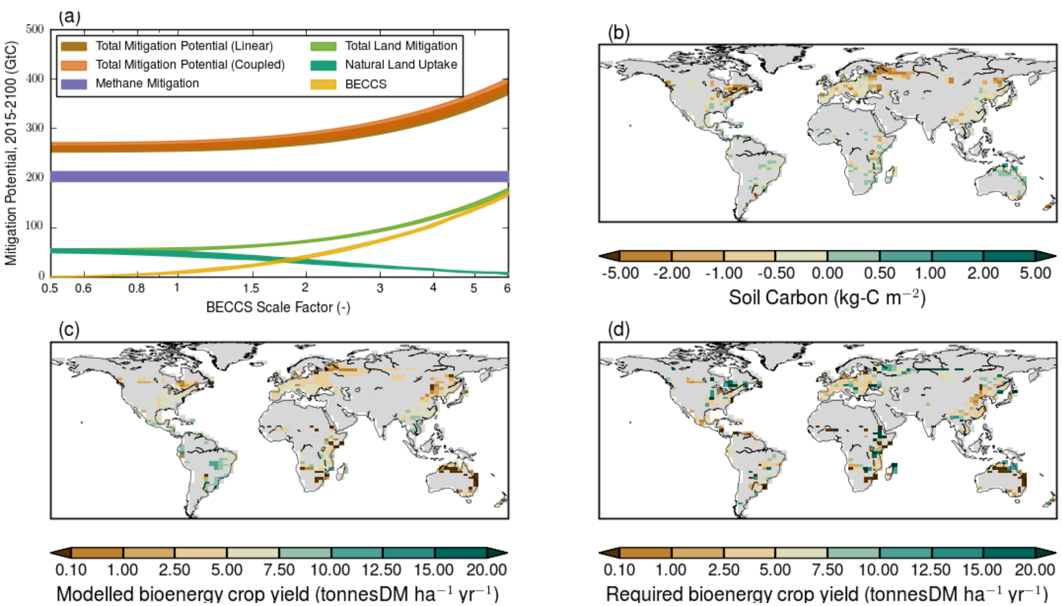
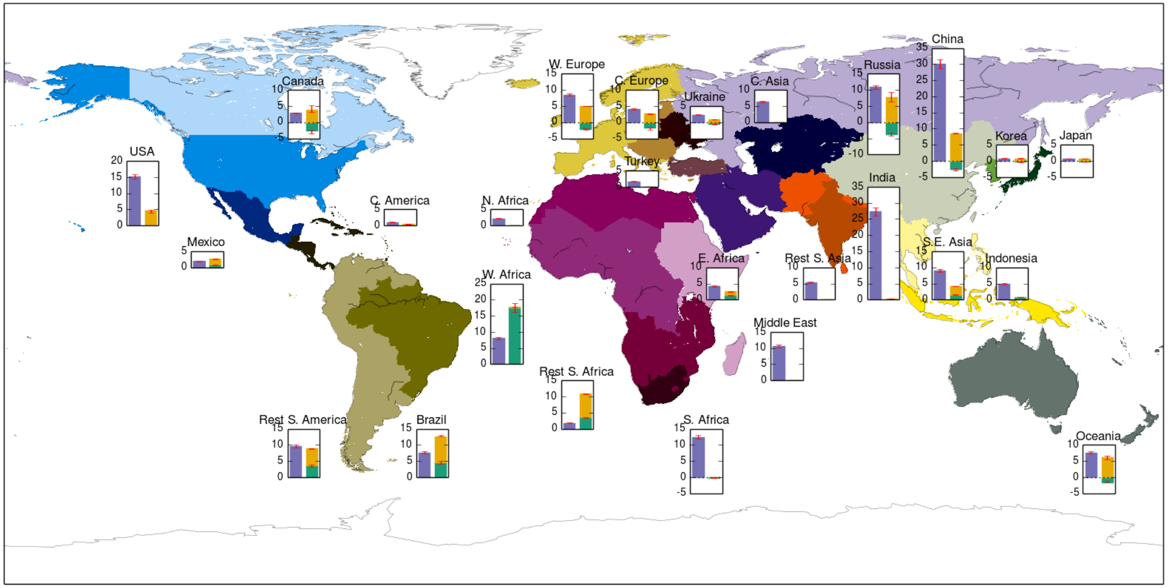


Figure 10| (a) The total and component mitigation potential (GtC) for different mitigation options, involving methane and land use, as a function of the BECCS efficiency factor (κ, Sect. 2.4.3) for the temperature pathway reaching 1.5°C. The spread of the functions represent the interquartile range of the sensitivity ensemble. Maps of (b) the change of the modelled soil carbon (kg-C m^{-2}) between 2015 and 2099, as the difference between the scenario with BECCS and the natural land-management scenario; (c) the modelled mean bioenergy crop yield in the JULES simulations (κ = 1) and (d) the required bioenergy crop yield for BECCS to provide a larger carbon uptake than forest regrowth/afforestation (assuming κ = κ* and 87% efficiency of BECCS). Grid cells which do not exceed 1% BECCS cover for any year in the simulation are masked grey.

948



China
Russia
W. Europe
C. Europe
C. Asia
Canada
Ukraine
USA
Korea
Japan
Turkey
India
C. America
N. Africa
Mexico
S.E. Asia
E. Africa
Rest S. Asia
Indonesia
W. Africa
Middle East
Rest S. Africa
Rest S. America
Brazil
S. Africa
Oceania

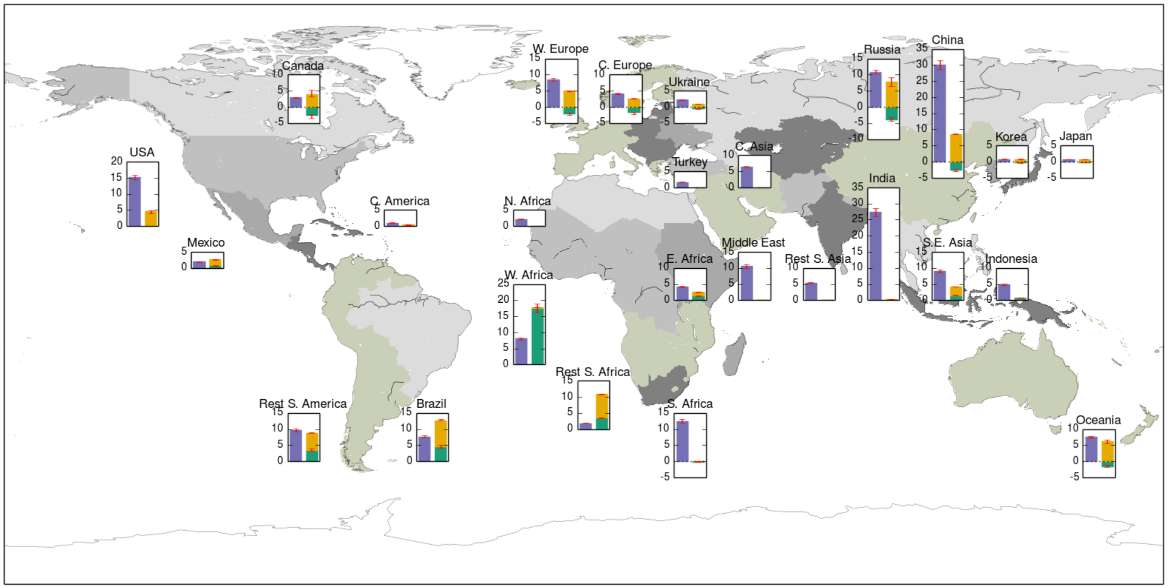
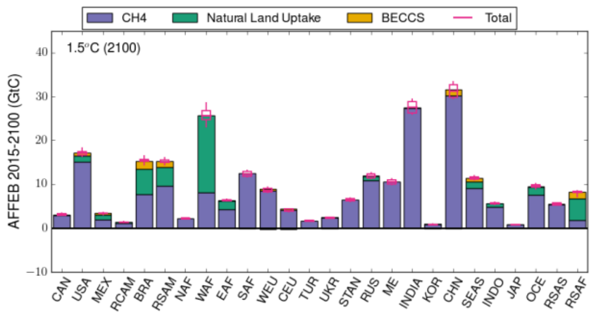
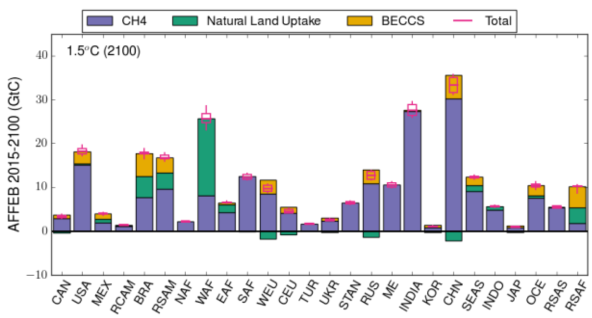


Figure 11 | The contribution to the allowable carbon emission budgets (GtC) between 2015 and 2100 for each of the 26 IMAGE IAM regions from methane mitigation (purple bars) and land-based mitigation options (green: natural land uptake; yellow: BECCS with κ = 3), for the temperature pathway stabilising at 1.5° warming without overshoot. The bars and error bars respectively show the median and the interquartile range, from the 34 GCMs emulated and 4 factorial runs.

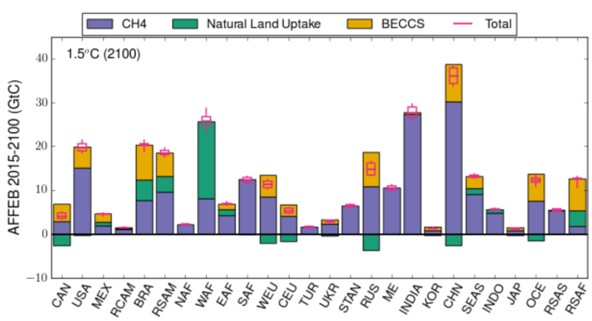
Commented [HGD50]: Reviewer comment 2.16: DONE, IMAGE regions use grey-scale.



(a)



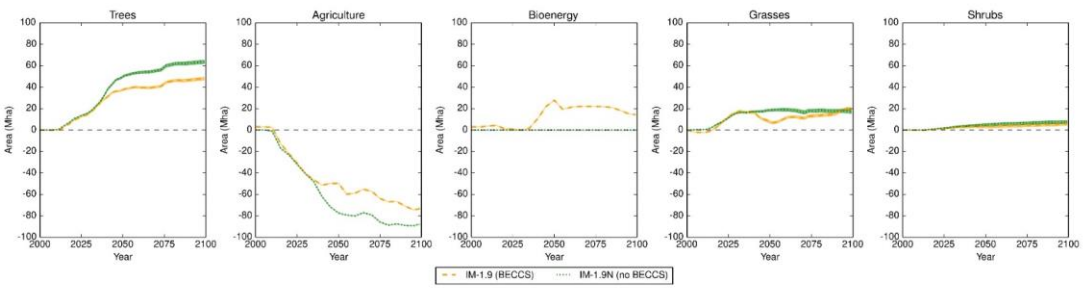
(b)



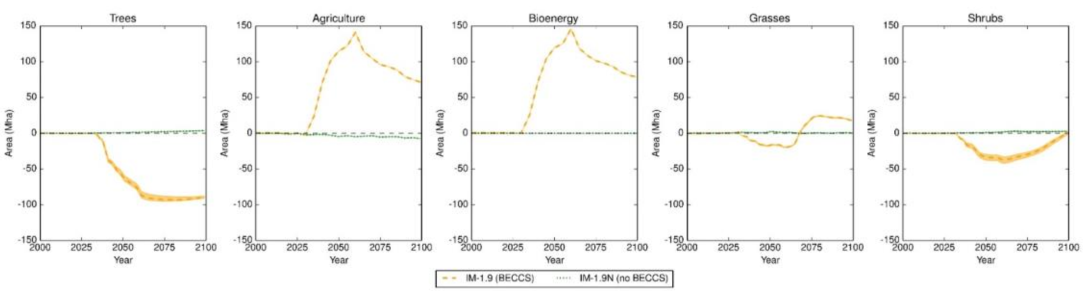
(c)

Figure 12 | Contribution of different mitigation options to the increase in allowable anthropogenic fossil fuel emission budgets by IMAGE region to meet the 1.5°C target. The stacked bars represent the median methane mitigation potential (purple bars) and median land-based mitigation potential (natural land uptake, green; BECCS, brown). Panel (a) is based on a BECCS scaling factor of unity, (b) a BECCS scaling factor of 2 and (c) a BECCS scaling factor of 3. The total (pink) shows the median and interquartile range for the 34 GCMs emulated and 4 factorial sensitivity simulations.

(a)

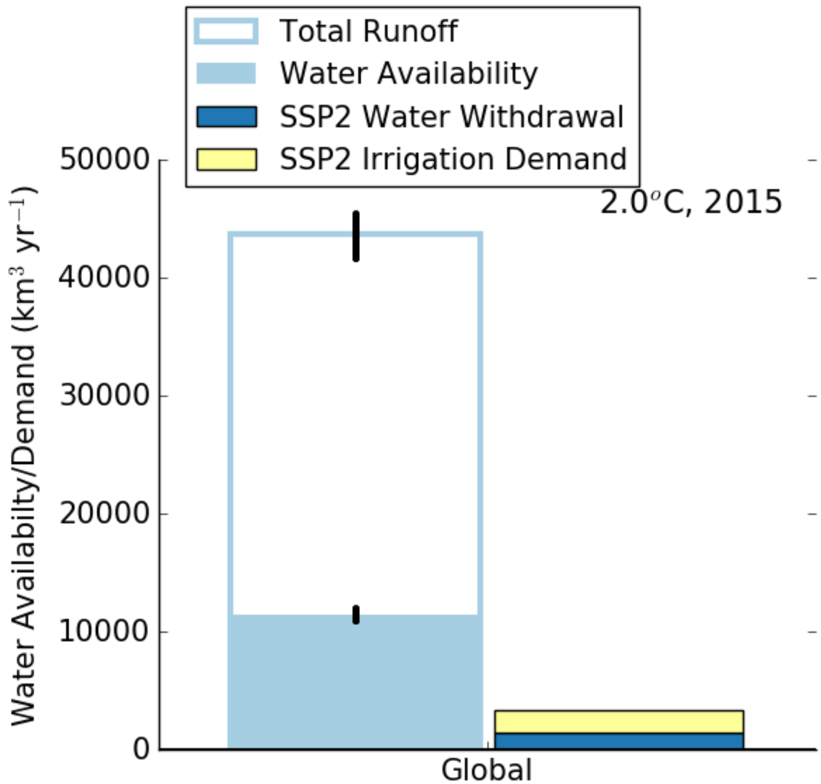


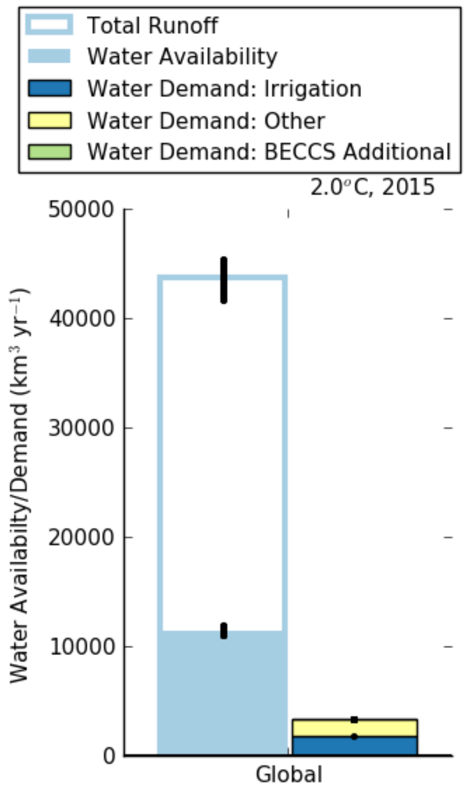
(b)



~~**Figure 11 | Time series of the land areas (in Mha) calculated for trees and prescribed for agriculture (including bioenergy crops) and bioenergy crops for the scenarios IM-1.9 ('BECCS', orange) and IM-1.9N ('no BECCS', green), as a difference to the baseline scenario (IM-BL), for the Russia (panel a) and Brazil (panel b) IMAGE regions between 2000 and 2100. The dotted lines are the median and the spread the interquartile range for the 34 GCMs emulated and 4 factorial sensitivity simulations.**~~

Commented [HGD51]: Moved to new Figure 5, as referenced earlier (in Section 2.3).


Total Runoff
Water Availability
SSP2 Water Withdrawal
SSP2 Irrigation Demand
2.0^{o}C, 2015
Water Availabilty/Demand (km^3 yr^{-1})
50000
40000
30000
20000
10000
0
Global

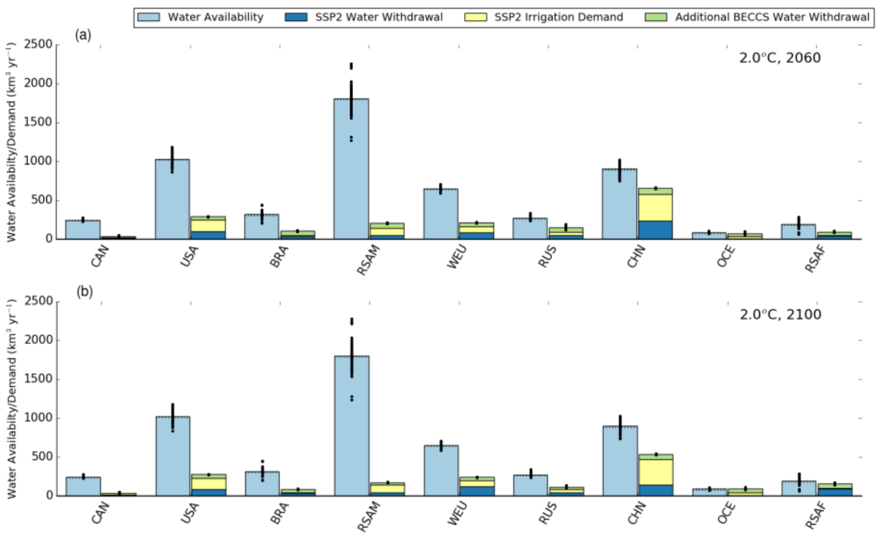


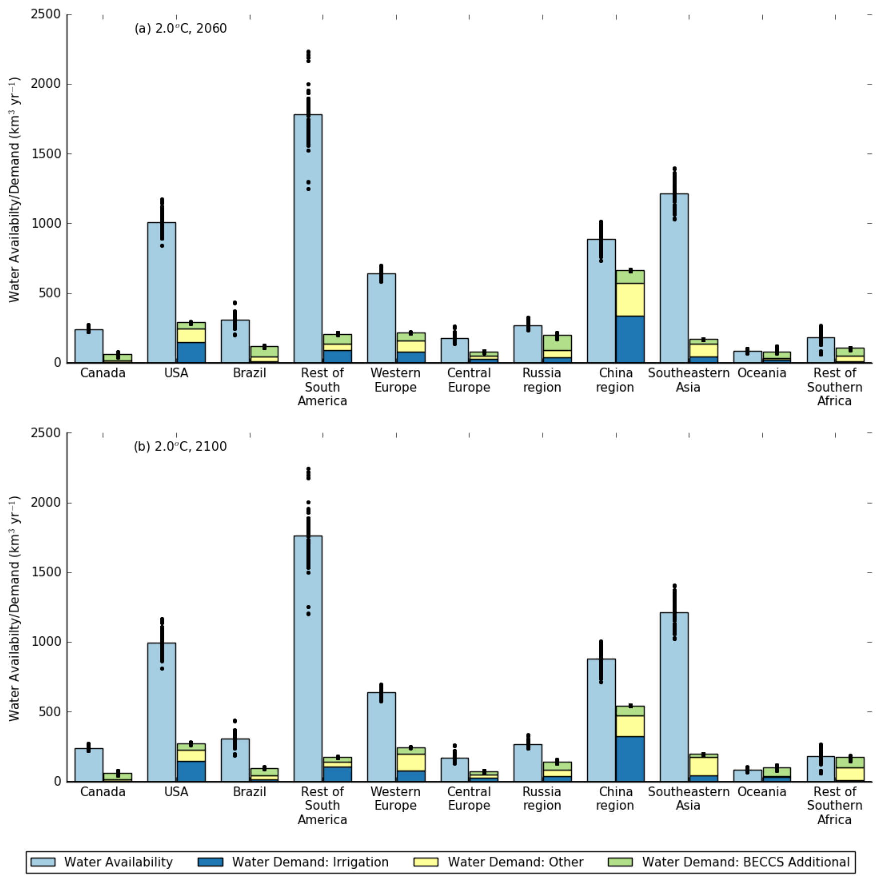
~~Figure 12~~

Figure 13

| Global water availability (filled light blue bar) as a regionally dependent fraction of runoff (hollow light blue bar) for the year 2015. ~~The water withdrawal (dark blue) and irrigation demand~~ The water demand for irrigation (~~yellow~~dark blue) and for other uses (i.e., energy generation, industry and domestic; ~~dark blue~~yellow), are taken from the SSP2-RCP2.6-IMAGE database. Note there is very little BECCS additional water demand (green) in 2015.

Commented [HGD52]: Reviewer comment 1.29: DONE, amended legend


Water Availability
SSP2 Water Withdrawal
SSP2 Irrigation Demand
Additional BECCS Water Withdrawal
(a)
2.0°C, 2060
Water Availabilty/Demand (km³ yr⁻¹)
2500
2000
1500
1000
500
0
CAN
USA
BRA
RSAM
WEU
RUS
CHN
OCE
RSAF
(b)
2.0°C, 2100
Water Availabilty/Demand (km³ yr⁻¹)
2500
2000
1500
1000
500
0
CAN
USA
BRA
RSAM
WEU
RUS
CHN
OCE
RSAF



~~Figure 13~~

Figure 14

| Water availability (light blue), SSP2-IMAGE water demand estimates for irrigation (dark blue), other uses (i.e., energy generation, industry and domestic; yellow) and the additional water demand from BECCS (green) for the years 2059-2060 and 2099-2100 for the 2.0°C warming target, with a BECCS κ factor of 3. The points are the individual results from the 34 GCMs emulated and 4 factorial runs, while the bars are the corresponding median values of the different GCM/factorial ensembles.

Commented [HGD53]: Reviewer comment 1.29: TO DO, water withdrawal

Tables

Table 1 | The IMOGEN-JULES factorial runs, key features and IMAGE input/prescribed datasets.

Factorial Run	Abbreviation
1. **Control**: • IMAGE SSP2 baseline scenario • 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}~~per annum~~ in 2005 to 484 Tg yr^{-1}~~per annum~~ in 2100 • IMAGE SSP2 baseline scenario for atmospheric concentrations of CH_4 and non-CO_2 radiative forcing	CTL
2. **Methane mitigation**: • IMAGE SSP2 RCP1.9 scenario for CH_4 • Agricultural land-use as in Control • Anthropogenic CH_4 emissions decline from 318 Tg yr^{-1}~~per annum~~ in 2005 to 162 Tg yr^{-1}~~per annum~~ in 2100 • IMAGE SSP2-1.9 scenario for atmospheric concentrations of CH_4 and non-CO_2 radiative forcing	CH_4
3. **Land-based mitigation, including BECCS**: • Land use from IMAGE SSP2 RCP1.9 scenario • High levels of REDD and full reforestation • Food-first policy so that bioenergy crops are only implemented on land not required for food production • Anthropogenic CH_4 emissions as in Control • IMAGE SSP2 baseline scenario for atmospheric concentrations of CH_4 and non-CO_2 radiative forcing	BECCS
4. **Land-based mitigation with no BECCS** (Natural): • As 3, except any land allocated to bioenergy crops is set to zero, allowing expansion of natural vegetation • Anthropogenic CH_4 emissions as in Control • IMAGE SSP2 baseline scenario for atmospheric concentrations of CH_4 and non-CO_2 radiative forcing	Natural~~ Land~~
5. **Combined methane & land-based mitigation**: • Combines CH_4 mitigation of 2 with land-based mitigation of 3 • IMAGE SSP2-1.9 scenario for atmospheric concentrations of CH_4 and non-CO_2 radiative forcing	Coupled (BECCS+CH_4~~+CCS~~)
6. **Combined methane & land-based mitigation with no BECCS** (Natural) • Combines CH_4 mitigation of 2 with land use scenario of 4 • IMAGE SSP2-1.9 scenario for atmospheric concentrations of CH_4 and non-CO_2 radiative forcing	Coupled (~~CH_4+~~Natural ~~Land~~+CH_4)

Note: Each factorial run comprises a 136-member ensemble: 34 GCMs x 2 ozone damage sensitivities x 2 methanogenesis Q_{10} temperature sensitivities.

Commented [HGD54]: Tables 1 and 2 switched, with merging of Sections 2.5 into 2.3.

Table 2 | IMAGE regions, the maximum area of BECCS deployed (Mha) and the main differences in land use between the ~~IM-1.9~~BECCS and ~~IM-1.9N~~ Natural scenarios.

Region	Abbreviation	Max. area of bioenergy crops (Mha)	Main land-use difference between ~~IM-1.9~~BECCS and ~~IM-1.9N~~Natural scenarios
Canada	CAN	65.9	Forest to BECCS in ~~IM-1.9~~BECCS scenario
USA	USA	39.0	Agricultural land and forest to BECCS (~~IM-1.9~~BECCS). Agricultural land to forest (~~IM-1.9N~~Natural)
Mexico	MEX	7.1	Agricultural land to BECCS and forest (~~IM-1.9~~BECCS). Agricultural land to forest (~~IM-1.9N~~Natural)
Central America	RCAM	0.5	Little BECCS. Agricultural land to forests in both scenarios.
Brazil	BRA	27.8	Agricultural land to BECCS and forest (~~IM-1.9~~BECCS). Agricultural land to forest (~~IM-1.9N~~Natural)
Rest of South America	RSAM	20.3	Agricultural land to BECCS and forest (~~IM-1.9~~BECCS). Agricultural land to forest (~~IM-1.9N~~Natural)
Northern Africa	NAF	0.0	No BECCS. No real differences between scenarios
Western Africa	WAF	3.1	Little BECCS. Agricultural land to forests in both scenarios.
Eastern Africa	EAF	33.9	Agricultural land to BECCS and forest (~~IM-1.9~~BECCS). Agricultural land to forest (~~IM-1.9N~~Natural)
South Africa	SAF	1.0	Little BECCS. Agricultural land to forests in both scenarios.
Rest of Southern Africa	RSAF	63.7	Agricultural land to BECCS and forest (~~IM-1.9~~BECCS). Agricultural land to forest (~~IM-1.9N~~Natural)
Western Europe	WEU	23.6	Forest to BECCS in ~~IM-1.9~~BECCS scenario
Central Europe	CEU	19.3	Forest to BECCS in ~~IM-1.9~~BECCS scenario
Turkey	TUR	0.0	No BECCS. No real differences between scenarios
Ukraine Region	UKR	11.4	Forest to BECCS in ~~IM-1.9~~BECCS scenario
Central Asia	STAN	0.7	Little BECCS. No real differences between scenarios
Russia Region	RUS	146.1	Forest to BECCS in ~~IM-1.9~~BECCS scenario
Middle East	ME	0.0	No BECCS. No real differences between scenarios
India	INDIA	6.0	Forest to BECCS in ~~IM-1.9~~BECCS scenario
Korea Region	KOR	4.3	Forest to BECCS in ~~IM-1.9~~BECCS scenario
China	CHN	58.1	Forest to BECCS in ~~IM-1.9~~BECCS scenario
South East Asia	SEAS	24.5	Forest to BECCS in ~~IM-1.9~~BECCS scenario. Agricultural land to forest (~~IM-1.9N~~Natural)
Indonesia	INDO	0.0	No BECCS. Agricultural land to forests in both scenarios.
Japan	JAP	2.7	Forest to BECCS in ~~IM-1.9~~BECCS scenario
Rest of South Asia	RSAS	0.0	No BECCS. No real differences between scenarios
Oceania	OCE	78.7	Forest to BECCS in ~~IM-1.9~~BECCS scenario

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

Region	Abbreviation	Projected Anthropogenic CH_4 Emissions 2020-2100 (PgCH4)		Difference	Scale Factor
		SSP2-Baseline	SSP2-RCP1.9		
Canada	CAN	0.497	0.169	0.328	0.01471
USA	USA	3.281	1.573	1.708	0.07670
Mexico	MEX	0.542	0.320	0.222	0.00995
Central America	RCAM	0.312	0.195	0.117	0.00525
Brazil	BRA	2.502	1.638	0.865	0.03884
Rest of South America	RSAM	2.249	1.159	1.090	0.04896
Northern Africa	NAF	0.533	0.286	0.247	0.01110
Western Africa	WAF	2.035	1.128	0.907	0.04074
Eastern Africa	EAF	1.722	1.245	0.478	0.02146
South Africa	SAF	1.615	0.207	1.408	0.06324
Rest of Southern Africa	RSAF	1.883	0.924	0.959	0.04307
Western Europe	WEU	0.683	0.220	0.463	0.02081
Central Europe	CEU	0.409	0.219	0.190	0.00854
Turkey	TUR	0.387	0.128	0.259	0.01163
Ukraine Region	UKR	1.021	0.299	0.722	0.03241
Central Asia	STAN	1.743	0.514	1.228	0.05517
Russia Region	RUS	1.910	0.720	1.190	0.05343
Middle East	ME	4.873	1.788	3.085	0.13856
India	INDIA	0.170	0.081	0.089	0.00400
Korea Region	KOR	5.757	2.351	3.406	0.15296
China	CHN	1.923	0.908	1.015	0.04558
South East Asia	SEAS	1.005	0.457	0.547	0.02458
Indonesia	INDO	0.160	0.077	0.082	0.00369
Japan	JAP	1.316	0.460	0.856	0.03846
Rest of South Asia	RSAS	1.496	0.893	0.603	0.02710
Oceania	OCE	0.657	0.455	0.202	0.00907
World	World	40.680	18.415	22.265	1.00000

Table 4a | Comparison by IMAGE region of the ~~Projected total anthropogenic~~ modelled available water (km^3 yr^{-1}), the projected water withdrawals (km^3 yr^{-1}) for ~~and~~ irrigation ~~demand~~ and for other anthropogenic activities (energy generation, industry, domestic) from the IMAGE SSP2-RCP2.6 scenario, and the additional water required for BECCS (km^3 yr^{-1} and as percentages of the net available water and of the water withdrawals for irrigation and other), for the years 2060.~~, 2100 by IMAGE region from the IMAGE SSP2-RCP2.6 scenario and~~ The percentage of runoff available for human use by IMAGE region is also included.

~~Region~~	~~Abbreviation~~	~~Projected Water Withdrawals (km^3 yr^{-1})~~		~~Projected Irrigation Demand (km^3 yr^{-1})~~		~~% of Runoff Available~~
		~~2060~~	~~2100~~	~~2060~~	~~2100~~	
~~Canada~~	~~CAN~~	~~14.21~~	~~11.72~~	~~3.39~~	~~4.31~~	~~5 %~~
~~USA~~	~~USA~~	~~96.07~~	~~81.35~~	~~149.55~~	~~148.57~~	~~40 %~~
~~Mexico~~	~~MEX~~	~~25.56~~	~~23.78~~	~~76.58~~	~~77.27~~	~~40 %~~
~~Central America~~	~~RCAM~~	~~15.49~~	~~13.96~~	~~8.16~~	~~8.74~~	~~40 %~~
~~Brazil~~	~~BRA~~	~~34.44~~	~~30.80~~	~~12.24~~	~~12.31~~	~~5 %~~
~~Rest of South America~~	~~RSAM~~	~~46.49~~	~~38.34~~	~~93.50~~	~~103.97~~	~~40 %~~
~~Northern Africa~~	~~NAF~~	~~54.63~~	~~56.98~~	~~61.60~~	~~57.89~~	~~40 %~~
~~Western Africa~~	~~WAF~~	~~118.83~~	~~262.07~~	~~28.29~~	~~37.23~~	~~40 %~~
~~Eastern Africa~~	~~EAF~~	~~63.10~~	~~128.33~~	~~53.92~~	~~58.96~~	~~40 %~~
~~South Africa~~	~~SAF~~	~~9.28~~	~~7.50~~	~~13.45~~	~~13.43~~	~~40 %~~
~~Rest of Southern Africa~~	~~RSAF~~	~~82.01~~	~~118.64~~	~~78.72~~	~~80.39~~	~~40 %~~
~~Western Europe~~	~~WEU~~	~~22.32~~	~~20.63~~	~~27.46~~	~~26.90~~	~~40 %~~
~~Central Europe~~	~~CEU~~	~~15.86~~	~~12.87~~	~~60.35~~	~~60.49~~	~~40 %~~
~~Turkey~~	~~TUR~~	~~25.90~~	~~19.58~~	~~11.73~~	~~10.40~~	~~40 %~~
~~Ukraine Region~~	~~UKR~~	~~32.62~~	~~37.90~~	~~88.26~~	~~82.08~~	~~40 %~~
~~Central Asia~~	~~STAN~~	~~51.60~~	~~43.82~~	~~42.30~~	~~40.25~~	~~40 %~~
~~Russia Region~~	~~RUS~~	~~40.97~~	~~39.30~~	~~149.55~~	~~136.63~~	~~5 %~~
~~Middle East~~	~~ME~~	~~501.06~~	~~585.48~~	~~374.18~~	~~388.69~~	~~40 %~~
~~India~~	~~INDIA~~	~~9.75~~	~~5.47~~	~~6.20~~	~~7.41~~	~~40 %~~
~~Korea Region~~	~~KOR~~	~~236.89~~	~~144.80~~	~~338.81~~	~~326.62~~	~~40 %~~
~~China~~	~~CHN~~	~~92.99~~	~~131.95~~	~~46.52~~	~~45.46~~	~~40 %~~
~~South East Asia~~	~~SEAS~~	~~113.87~~	~~114.33~~	~~8.18~~	~~15.08~~	~~40 %~~
~~Indonesia~~	~~INDO~~	~~18.99~~	~~13.29~~	~~2.79~~	~~2.12~~	~~40 %~~
~~Japan~~	~~JAP~~	~~8.91~~	~~8.77~~	~~24.99~~	~~30.57~~	~~40 %~~
~~Rest of South Asia~~	~~RSAS~~	~~154.42~~	~~227.85~~	~~259.95~~	~~245.78~~	~~40 %~~
~~Oceania~~	~~OCE~~	~~41.36~~	~~89.87~~	~~10.03~~	~~11.20~~	~~40 %~~
~~World~~	~~World~~	~~1927.62~~	~~2269.39~~	~~2030.70~~	~~2032.74~~	

Commented [HGD55]: Reviewer comment 1:30: DONE, added BECCS water requirements. Separate tables for 2060 and 2100

Region	Abbreviation	% of Regional Runoff Available	Available Water ($km^3\ yr^{-1}$)	Water Demand			Total Demand as % of Available Water	BECCS Demand as % of Total Demand
				Irrigation ($km^3\ yr^{-1}$)	Other ($km^3\ yr^{-1}$)	BECCS ($km^3\ yr^{-1}$)		
Canada	CAN	40%	243.19	3.39	14.21	44.45	25.5%	71.6%
USA	USA	5%	1,010.82	149.55	96.07	44.55	28.7%	15.4%
Mexico	MEX	5%	75.89	76.58	25.56	24.48	166.8%	19.3%
Central America	RCAM	5%	185.92	8.16	15.49	2.28	13.9%	8.8%
Brazil	BRA	40%	310.65	12.24	34.44	73.12	38.6%	61.0%
Rest of South America	RSAM	5%	1,779.42	93.50	46.49	67.66	11.7%	32.6%
Northern Africa	NAF	5%	0.11	61.60	54.63	0.00	-	-
Western Africa	WAF	5%	1,962.47	28.29	118.83	0.39	7.5%	0.3%
Eastern Africa	EAF	5%	485.18	53.92	63.10	2.45	24.6%	2.1%
South Africa	SAF	5%	0.60	13.45	9.28	0.48	3868.3%	2.1%
Rest of Southern Africa	RSAF	5%	182.48	10.03	41.36	56.02	58.9%	52.2%
Western Europe	WEU	5%	642.34	78.72	82.01	56.22	33.8%	25.9%
Central Europe	CEU	5%	176.27	27.46	22.32	29.68	45.1%	37.4%
Turkey	TUR	5%	29.98	60.35	15.86	0.00	-	-
Ukraine Region	UKR	5%	67.47	11.73	25.90	12.28	74.0%	24.6%
Central Asia	STAN	5%	20.57	88.26	32.62	0.00	-	-
Russia Region	RUS	40%	270.32	42.30	51.60	103.87	73.2%	52.5%
Middle East	ME	5%	8.65	149.55	40.97	0.00	-	-
India	INDIA	5%	319.36	374.18	501.06	0.00	-	-
Korea Region	KOR	5%	42.85	6.20	9.75	12.64	66.7%	44.2%
China	CHN	5%	887.26	338.81	236.89	87.73	74.8%	13.2%
South East Asia	SEAS	5%	1,212.00	46.52	92.99	31.56	14.1%	18.4%
Indonesia	INDO	5%	1,293.05	8.18	113.87	0.00	-	-
Japan	JAP	5%	209.49	2.79	18.99	7.69	14.1%	26.1%
Rest of South Asia	RSAS	5%	74.57	259.95	154.42	0.00	-	-
Oceania	OCE	5%	85.46	24.99	8.91	48.06	95.9%	58.6%

Table 4b | As Table 4a for 2100

Region	Abbreviation	% of Regional Runoff Available	Available Water ($km^3 yr^{-1}$)	Water Demand: Irrigation ($km^3 yr^{-1}$)	Water Demand: Other ($km^3 yr^{-1}$)	Water Demand: BECCS ($km^3 yr^{-1}$)	Total Demand as % of Available Water	BECCS Demand as % of Total Demand
Canada	CAN	40%	240.14	4.31	11.72	45.21	25.5%	73.8%
USA	USA	5%	993.09	148.57	81.35	45.45	27.7%	16.5%
Mexico	MEX	5%	72.79	77.27	23.78	11.14	154.1%	9.9%
Central America	RCAM	5%	182.12	8.74	13.96	0.66	12.8%	2.8%
Brazil	BRA	40%	307.53	12.31	30.80	54.89	31.9%	56.0%
Rest of South America	RSAM	5%	1,765.14	103.97	38.34	32.65	9.9%	18.7%
Northern Africa	NAF	5%	0.11	57.89	56.98	0.00	-	-
Western Africa	WAF	5%	1,953.10	37.23	262.07	0.62	15.4%	0.2%
Eastern Africa	EAF	5%	485.02	58.96	128.33	20.54	42.8%	9.9%
South Africa	SAF	5%	0.60	13.43	7.50	0.45	3563.3%	2.1%
Rest of Southern Africa	RSAF	5%	179.63	11.20	89.87	74.85	97.9%	42.5%
Western Europe	WEU	5%	637.68	80.39	118.64	45.25	38.3%	18.5%
Central Europe	CEU	5%	171.05	26.90	20.63	23.19	41.3%	32.8%
Turkey	TUR	5%	29.52	60.49	12.87	0.00	-	-
Ukraine Region	UKR	5%	66.45	10.40	19.58	8.62	58.1%	22.3%
Central Asia	STAN	5%	19.67	82.08	37.90	0.00	-	-
Russia Region	RUS	40%	266.36	40.25	43.82	58.40	53.5%	41.0%
Middle East	ME	5%	8.60	136.63	39.30	0.00	-	-
India	INDIA	5%	320.08	388.69	585.48	0.00	-	-
Korea Region	KOR	5%	42.73	7.41	5.47	0.00	-	-
China	CHN	5%	881.00	326.62	144.80	72.75	61.8%	13.4%
South East Asia	SEAS	5%	1,213.01	45.46	131.95	19.49	16.2%	9.9%
Indonesia	INDO	5%	1,291.53	15.08	114.33	0.00	-	-
Japan	JAP	5%	208.43	2.12	13.29	6.94	10.7%	31.1%
Rest of South Asia	RSAS	5%	74.19	245.78	227.85	0.00	0.0%	0.0%
Oceania	OCE	5%	85.46	30.57	8.77	62.96	136.5%	160.0%

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

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Supplementary Information

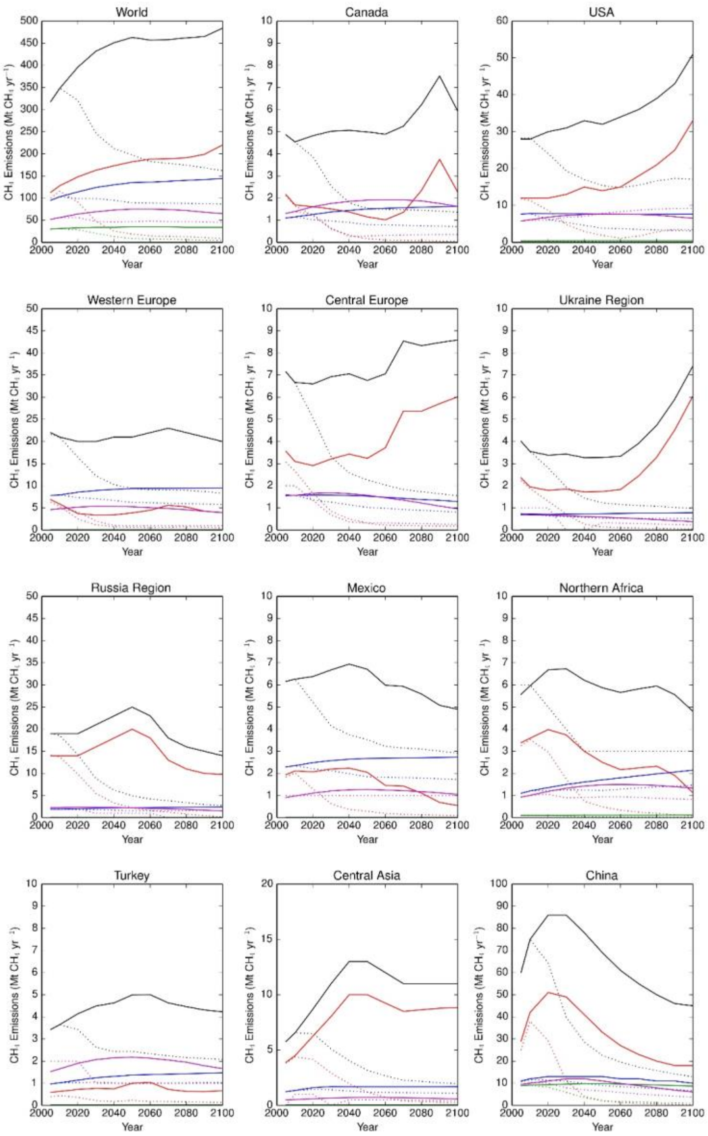

Fig. SI.1 | Time series of annual methane emissions between 2005 and 2100 from all and selected anthropogenic sources according to the IMAGE SSP2 Baseline (solid lines) and SSP2-RCP1.9 (dotted lines) scenarios, globally and for each of the 26 IMAGE regions, with total emissions in black, energy sector in red, agriculture-cattle in blue, agriculture-rice in green and waste in magenta. Note the y-axes have different scales for clarity.

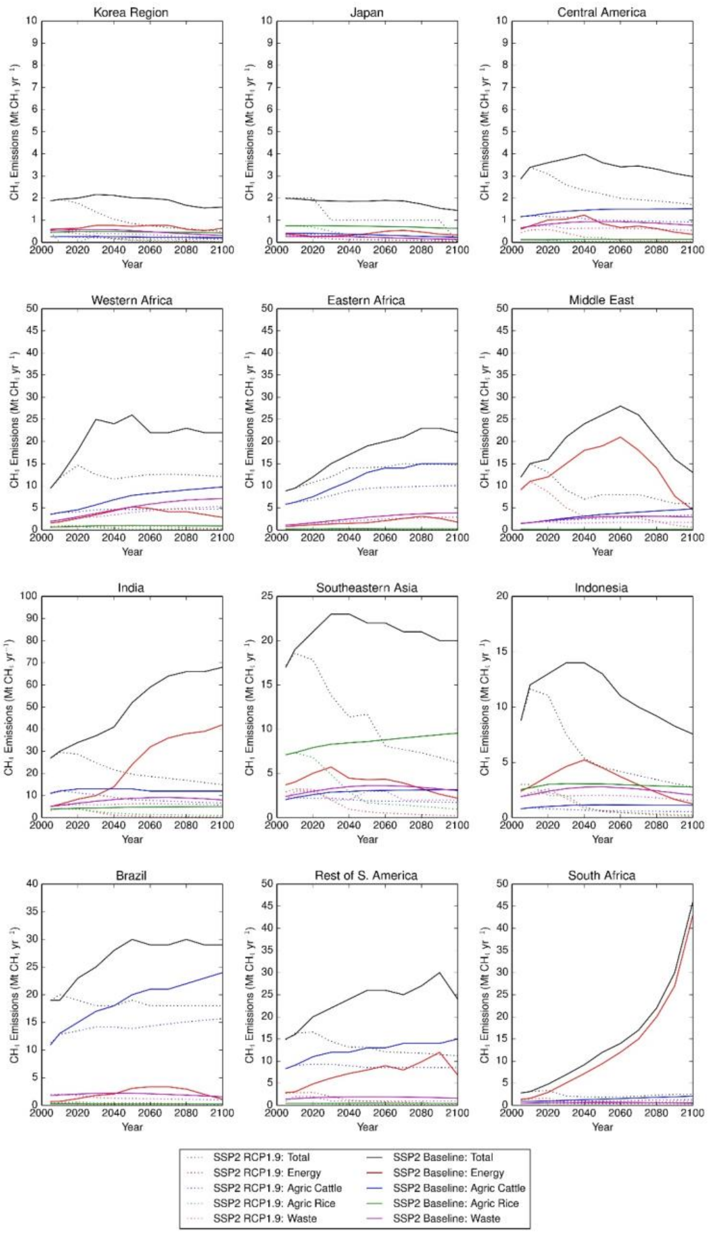

Fig. SI.1 (continued) | Time series of annual methane emissions between 2005 and 2100 from all and selected anthropogenic sources. Note the y-axes have different scales for clarity.

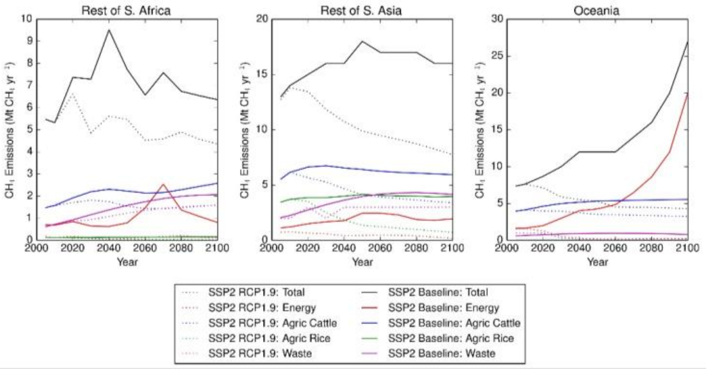

Fig. SI.1 (continued) | Time series of annual methane emissions between 2005 and 2100 from all and selected anthropogenic sources. Note the y-axes have different scales for clarity.

Fig. ~~**SI.3**~~**SI.2** | Time series of the land areas (in Mha) calculated for trees and prescribed for agriculture (including bioenergy crops) and bioenergy crops for the ~~scenarios IM-1.9 (‘BECCS’,~~ “BECCS” (orange) and ~~IM-1.9N (‘no BECCS’,~~ “NATURAL” (green~~),~~) scenarios, as a difference to the baseline scenario ~~(~~(“CTL” = IM-BL), for the 26 IMAGE regions between 2000 and 2100. The dotted lines are the median and the spread the interquartile range for the 34 GCMs emulated and 4 factorial sensitivity simulations.

a) Canada
b) USA
c) Mexico
d) Central America
e) Brazil
f) Rest of South America
g) Northern Africa
h) Western Africa
i) Eastern Africa
j) South Africa
k) Rest of Southern Africa
l) Western Europe
m) Central Europe
n) Turkey
o) Ukraine Region
p) Central Asia
q) Russia Region
r) Middle East
s) India
t) Rest of South Asia
~~t)~~u) China
~~u)~~v) Korea Region China
w) Japan
~~v)~~x) South East Asia
~~w)~~y) Indonesia
~~x)a) Japan~~
~~y)a) Rest of South Asia~~
z) Oceania

Fig. ~~SI.3~~SI.2a: Canada

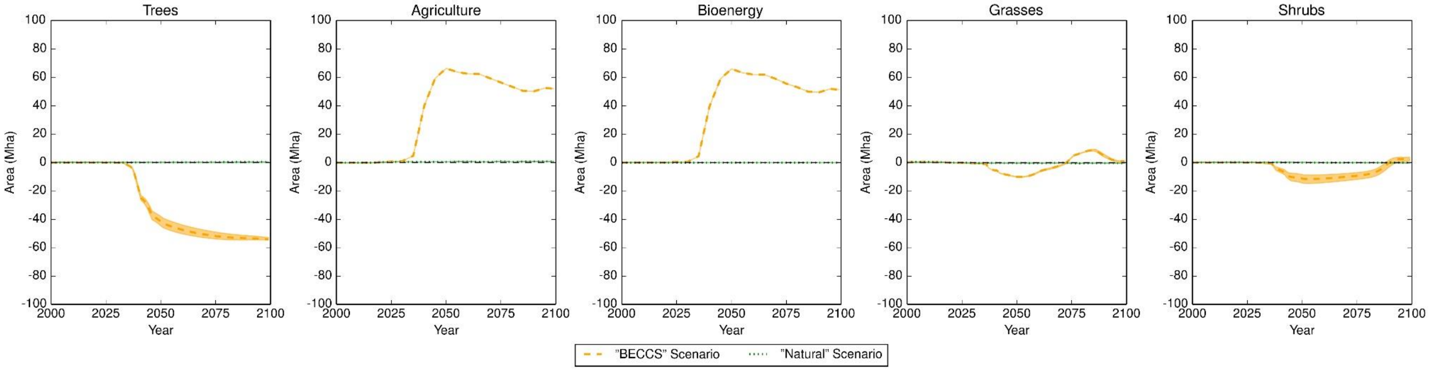

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Fig. ~~SI.3~~SI.2b: USA

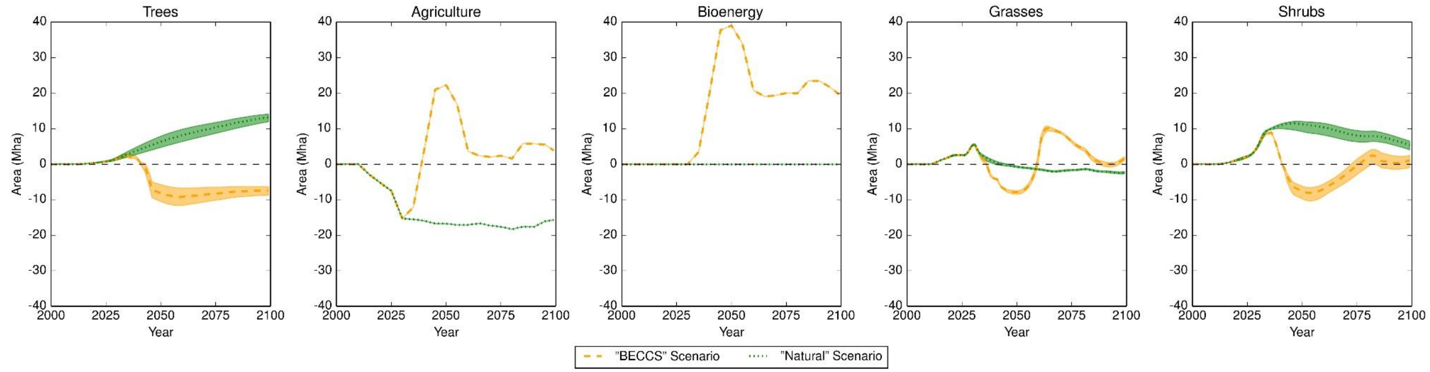

Fig. ~~SI.3~~SI.2c: Mexico

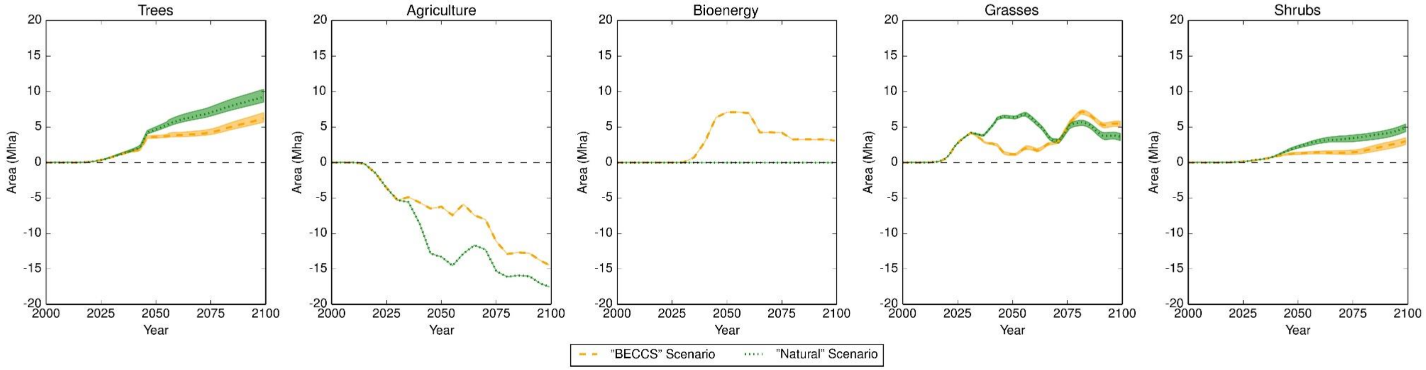

Fig. ~~SI.3~~SI.2d: Central America

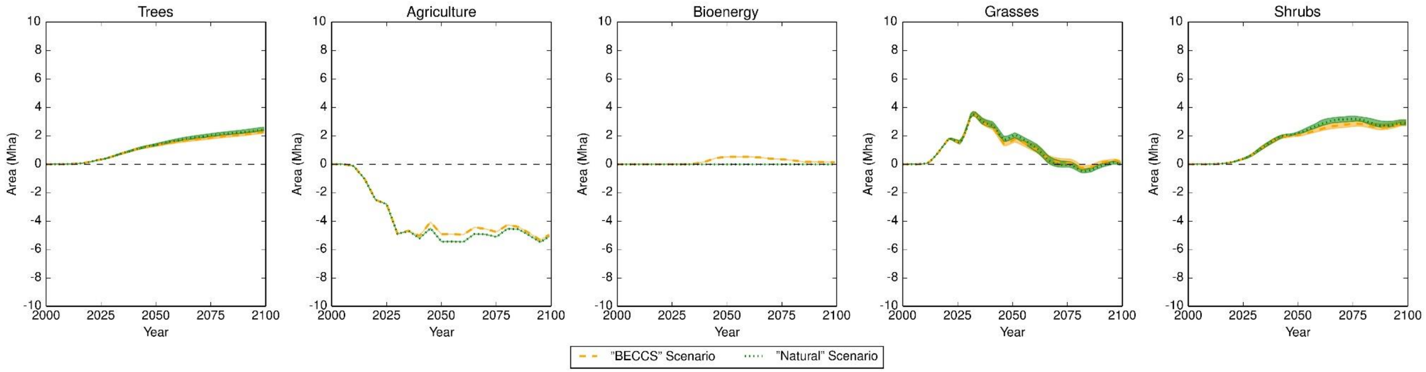

Fig. ~~SI.3~~SI.2e: Brazil

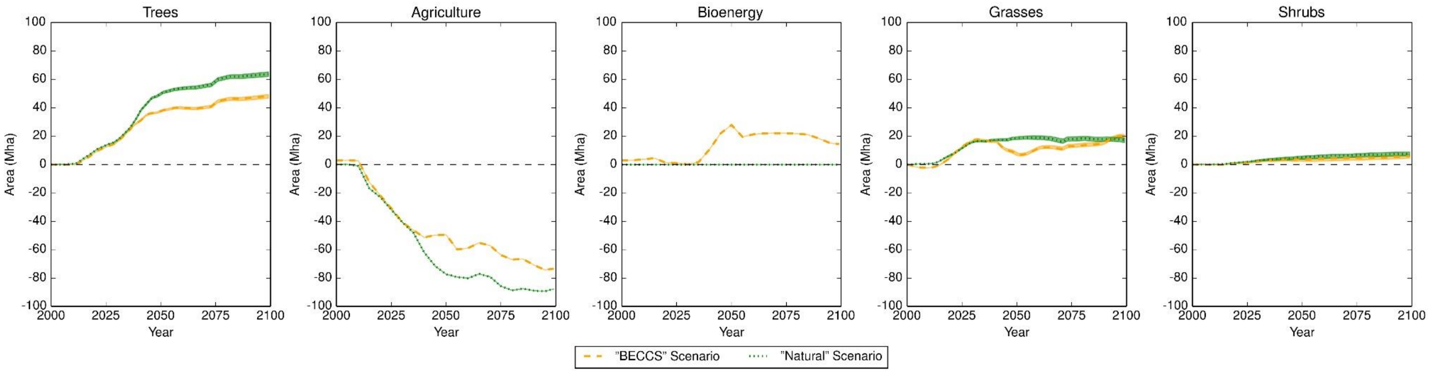

Fig. ~~SI.3~~SI.2f: Rest of South America

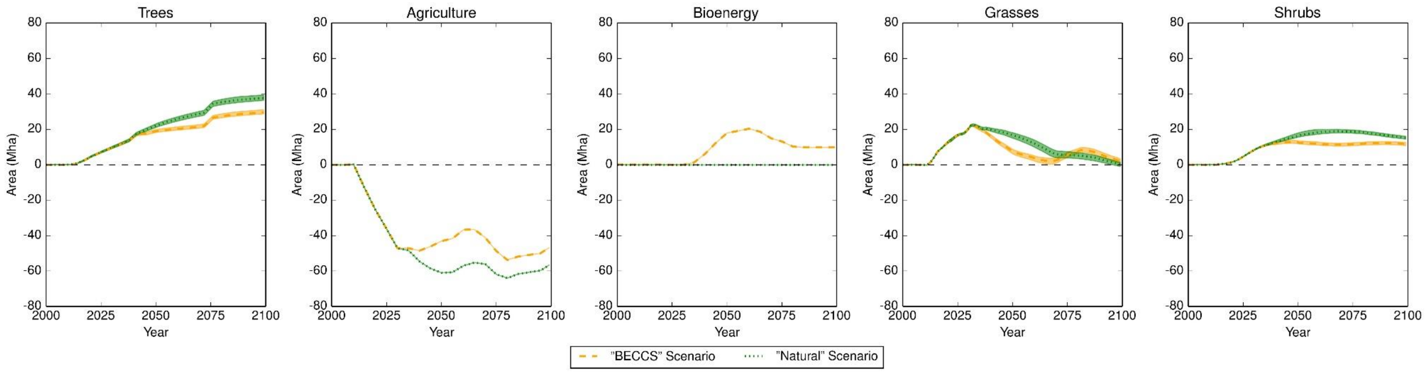

Fig. ~~SI.3~~SI.2g: Northern Africa

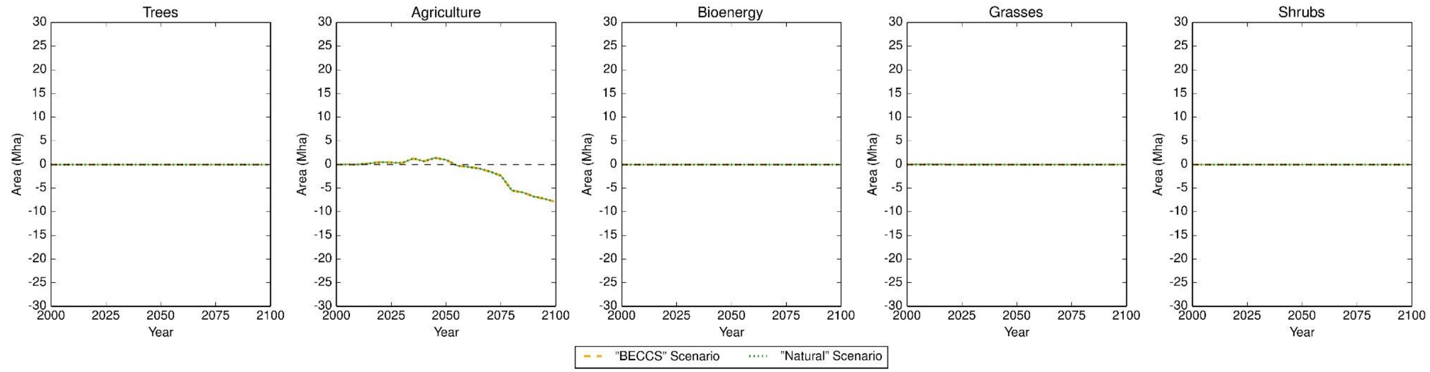

Fig. ~~SI.3~~SI.2h: Western Africa

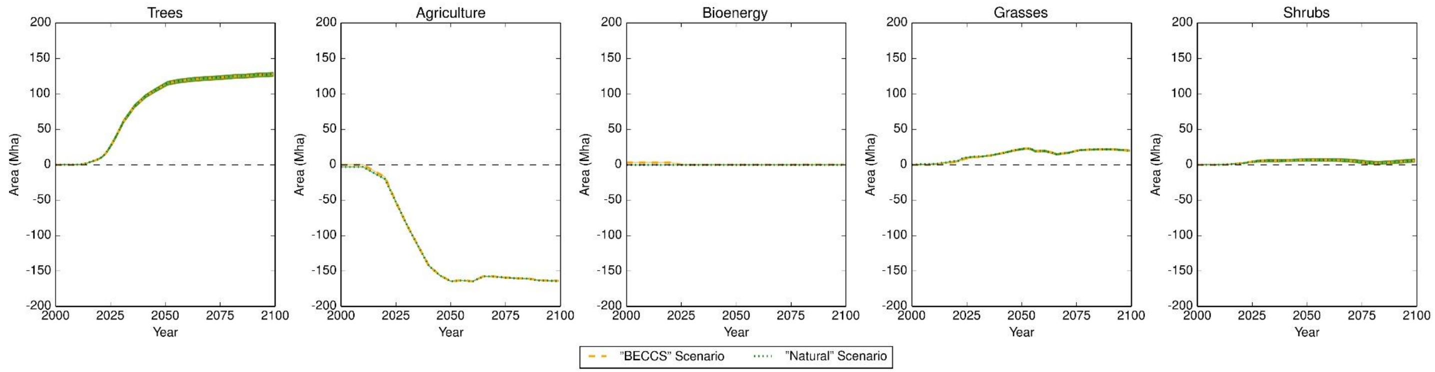

Fig. ~~SI.3~~SI.2i: Eastern Africa

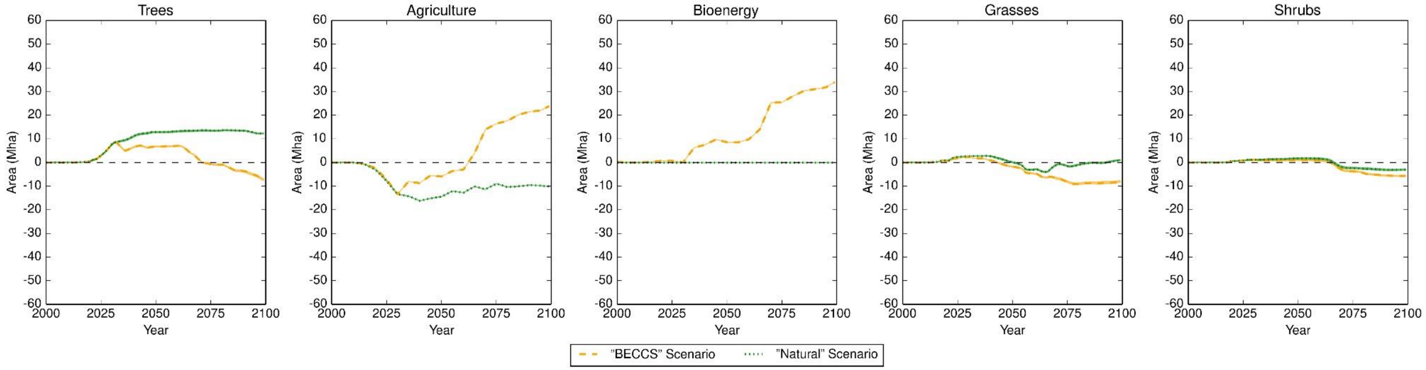

Fig. ~~SI.3~~SI.2j: South Africa

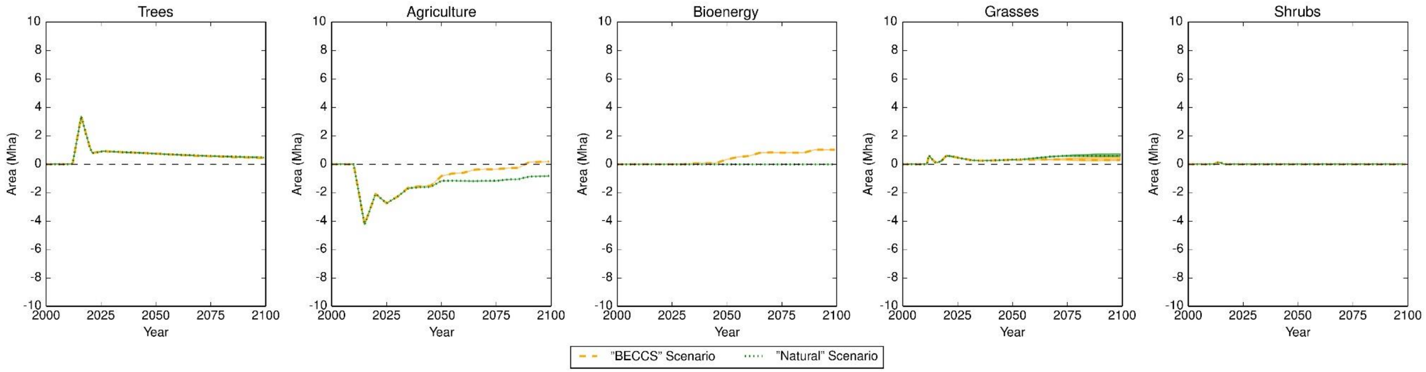

Fig. ~~SI.3~~SI.2k: Rest of Southern Africa

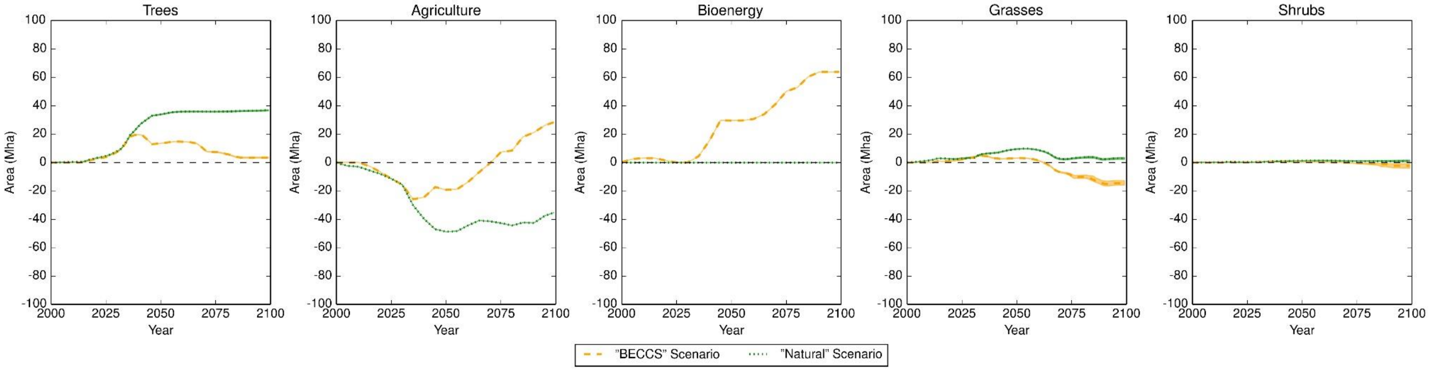

Fig. ~~SI.3~~SI.2l: Western Europe

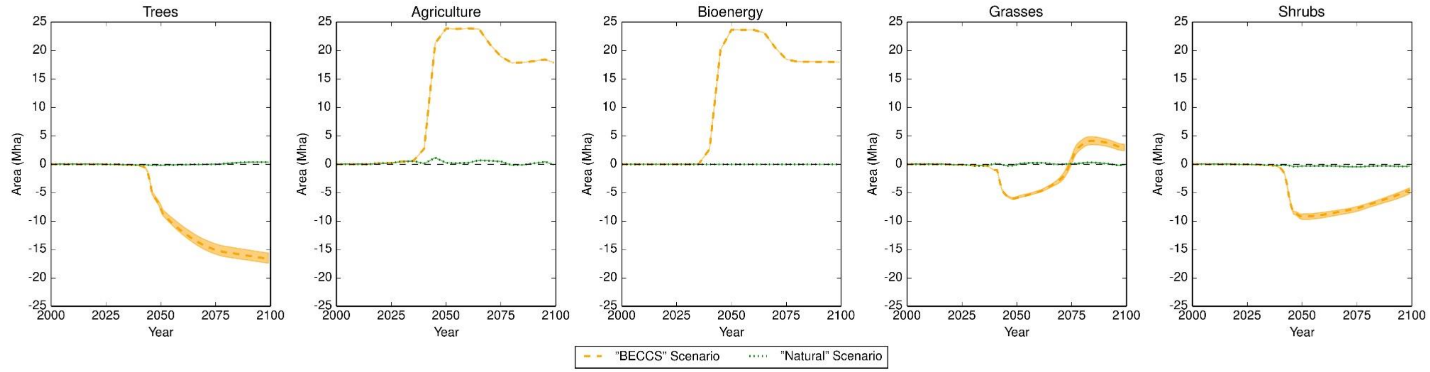

Fig. ~~SI.3~~SI.2m: Central Europe

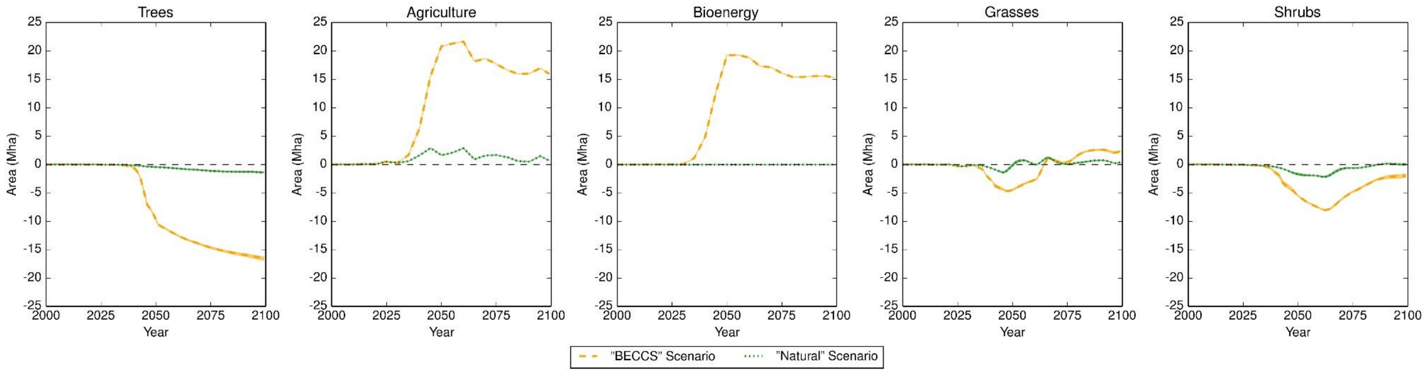

Fig. ~~SI.3~~SI.2n: Turkey

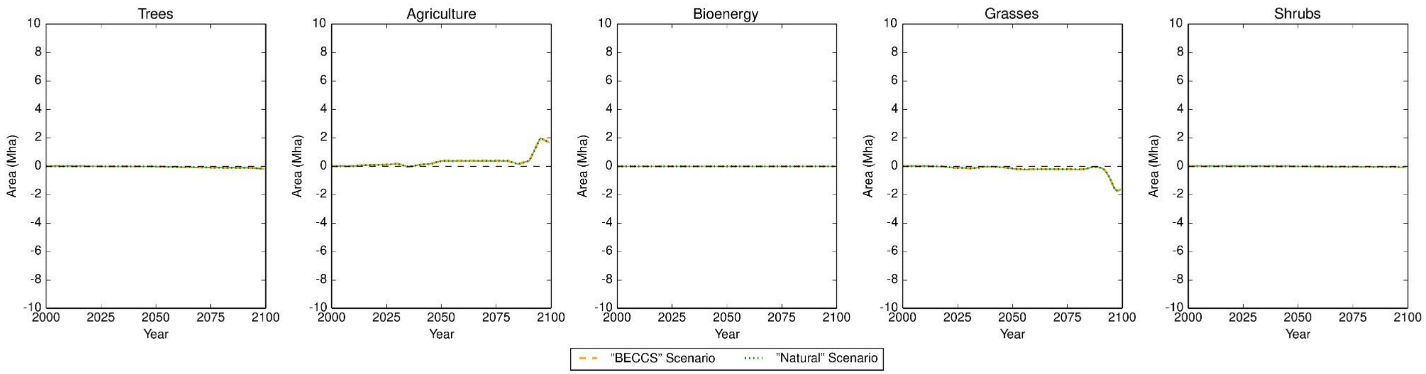

Fig. ~~SI.3~~SI.2o: Ukraine Region

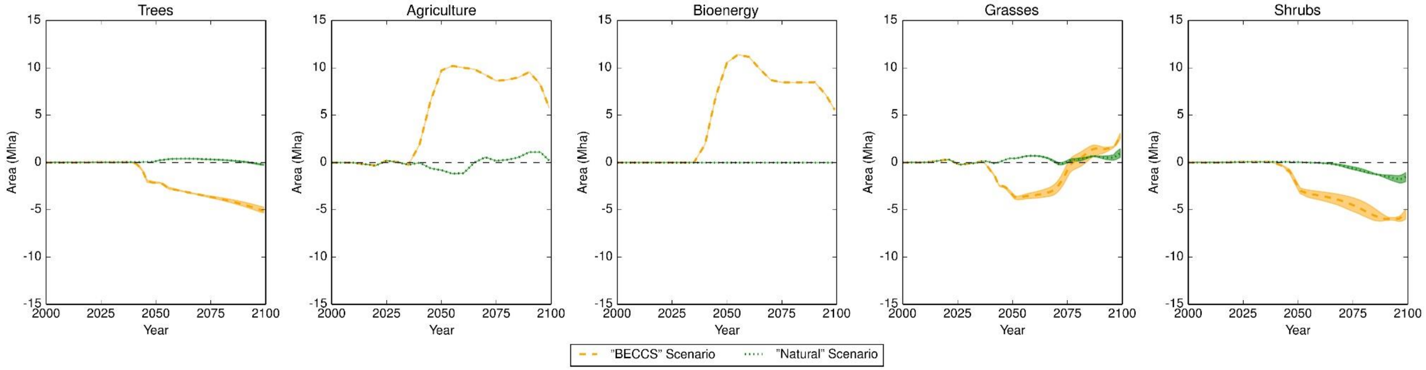

Fig. ~~SI.3~~SI.2p: Central Asia

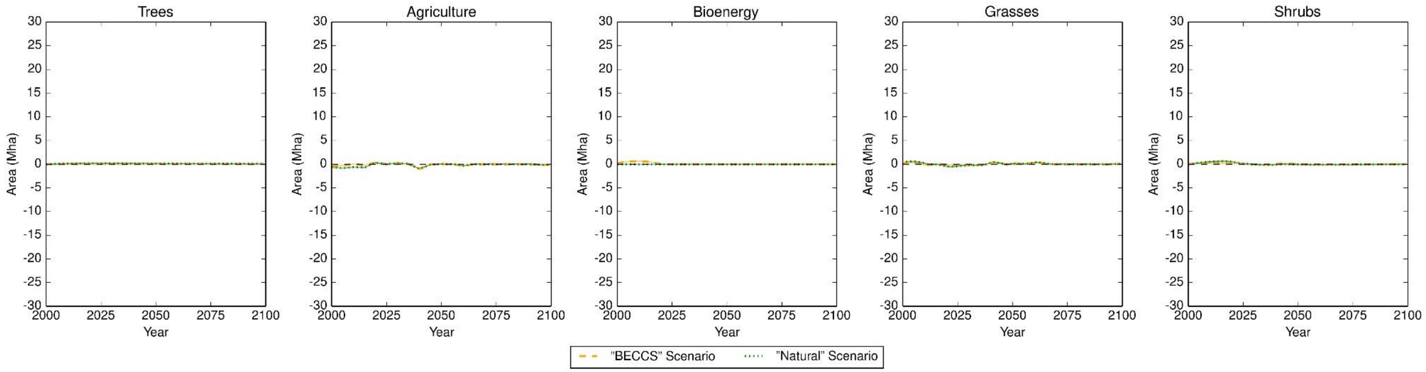

Fig. ~~SI.3~~SI.2q: Russia Region

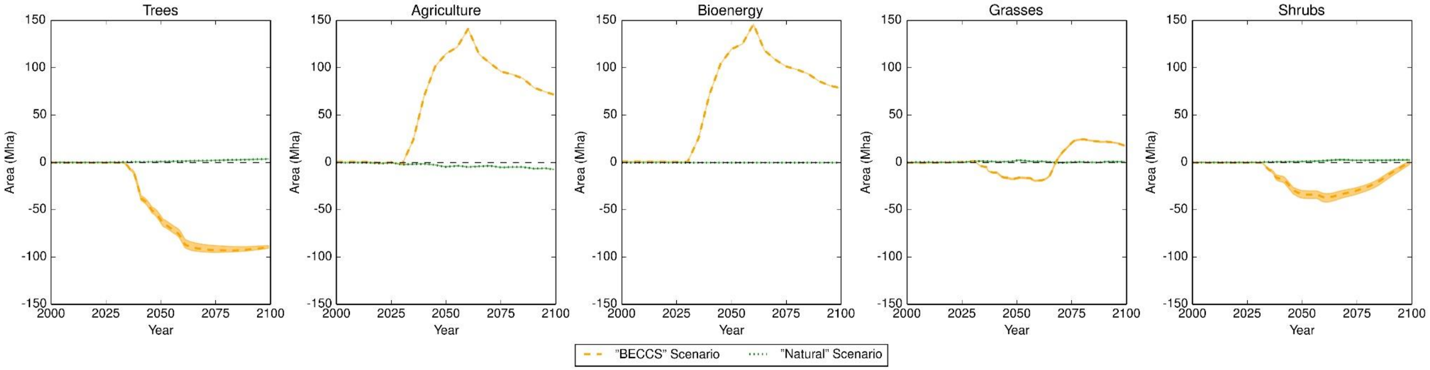

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Fig. ~~SI.3~~SI.2r: Middle East

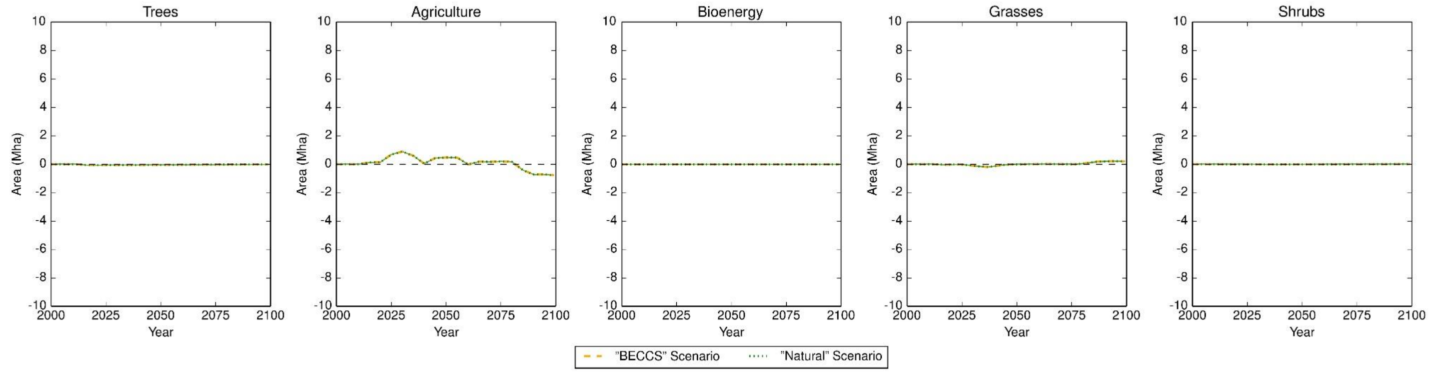


Fig. SI.3SI.2s: India

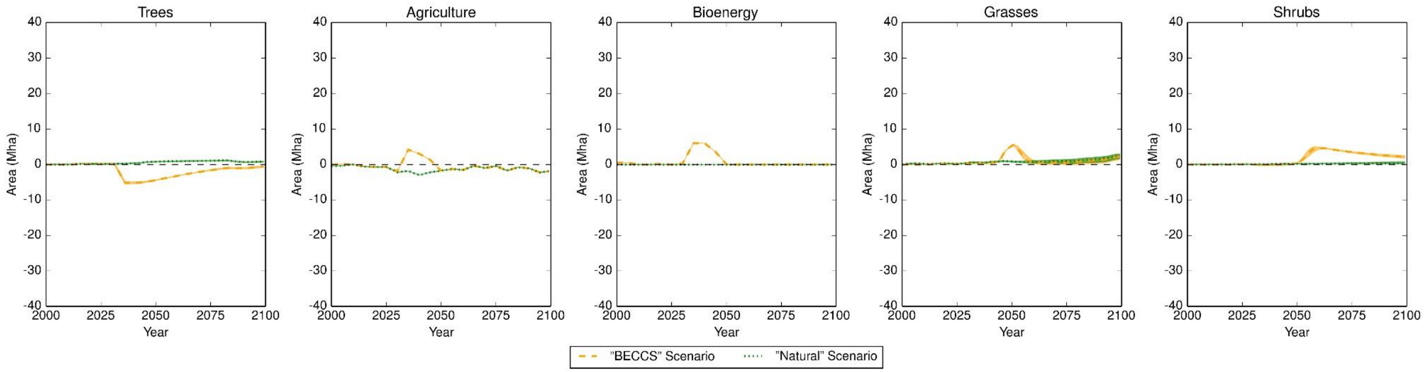


Fig. SI.3SI.2yt: Rest of South Asia

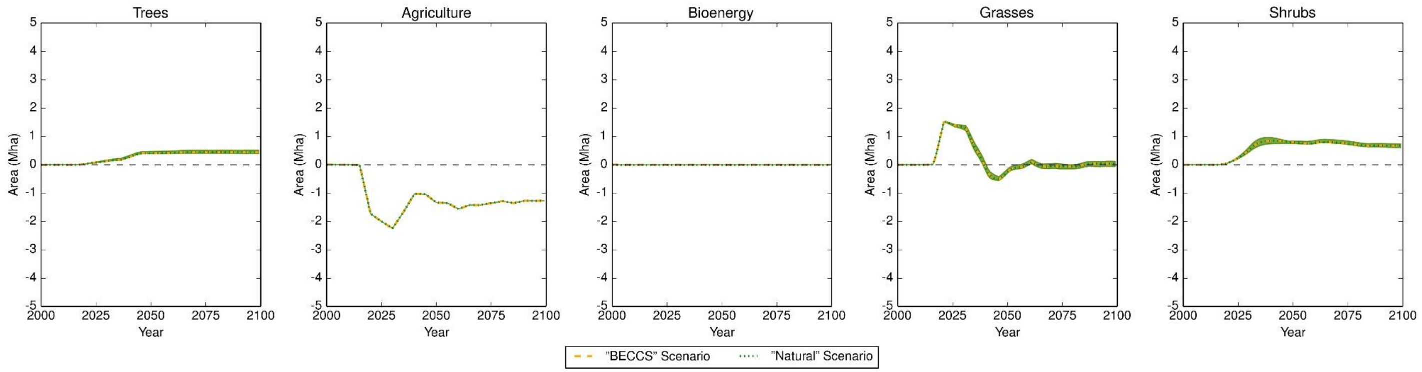


Fig. ~~SI.3~~SI.2u: China

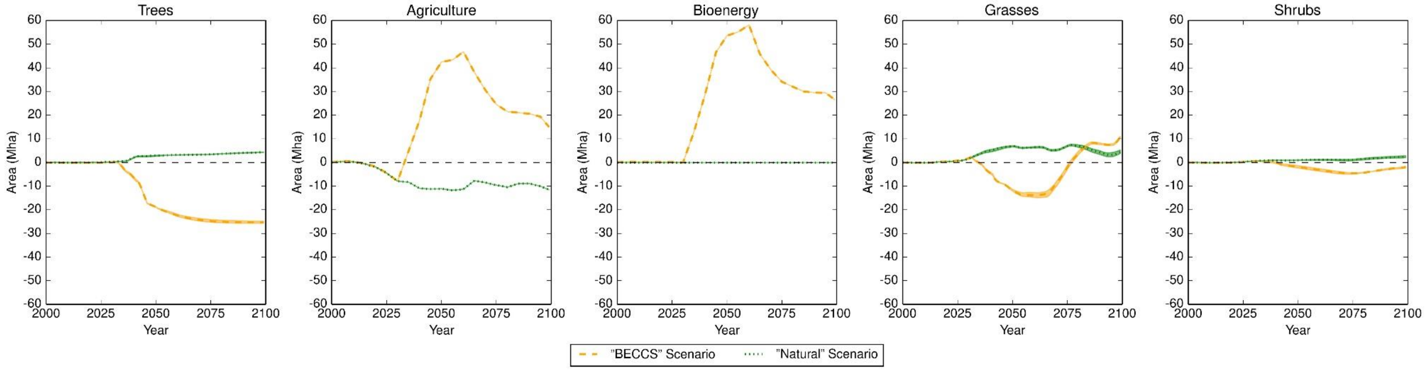


Fig. ~~SI.3~~SI.2v: Korea Region

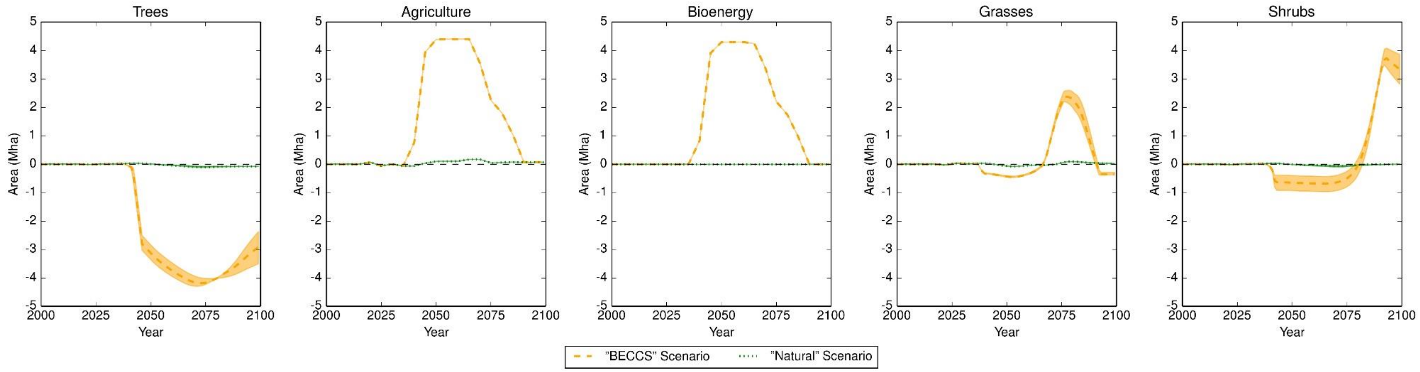


Fig. SI.2w: Japan

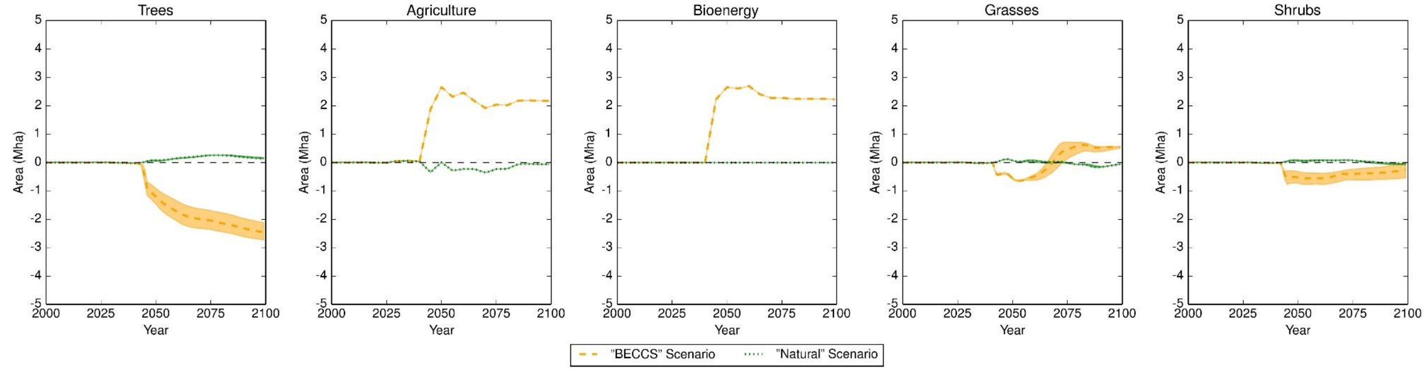


Fig. ~~SI.3v~~SI.2x: South East Asia

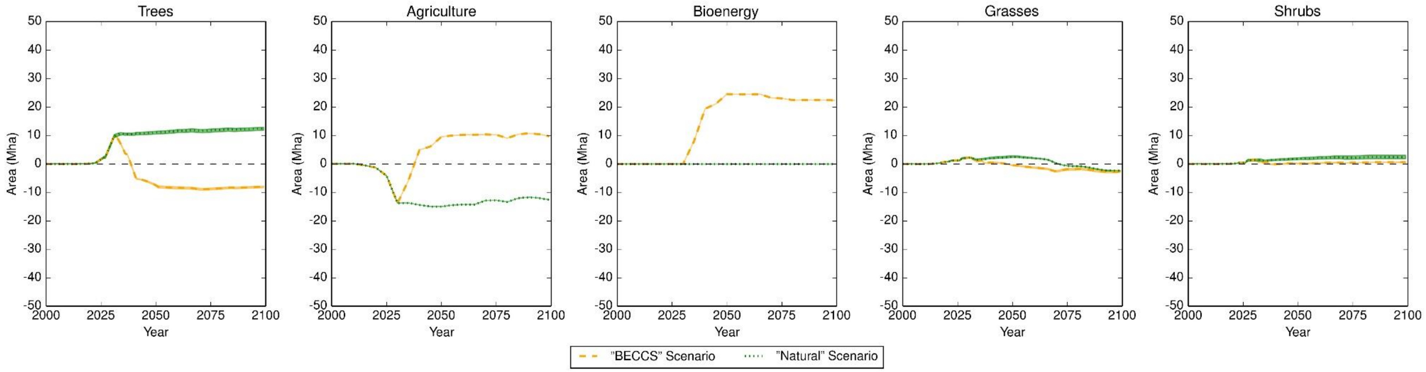
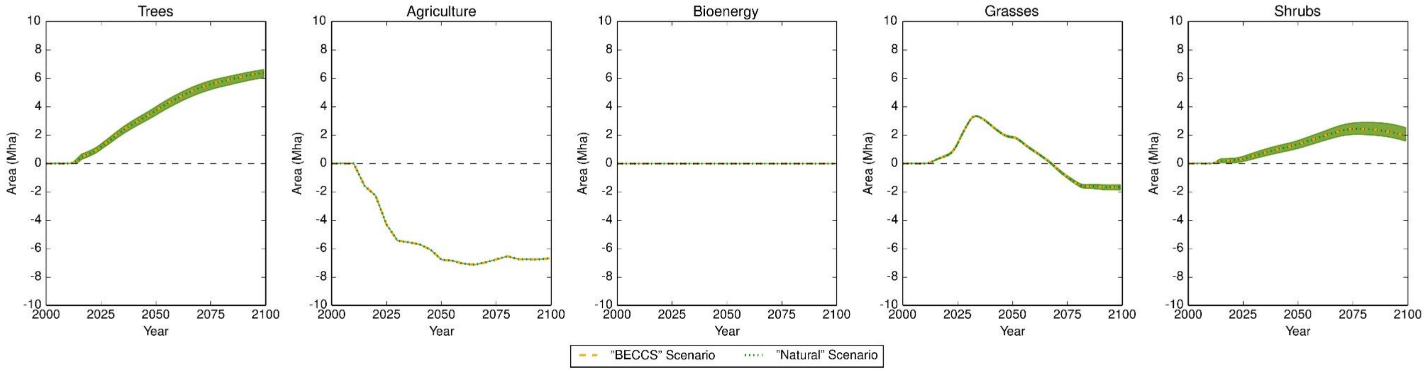
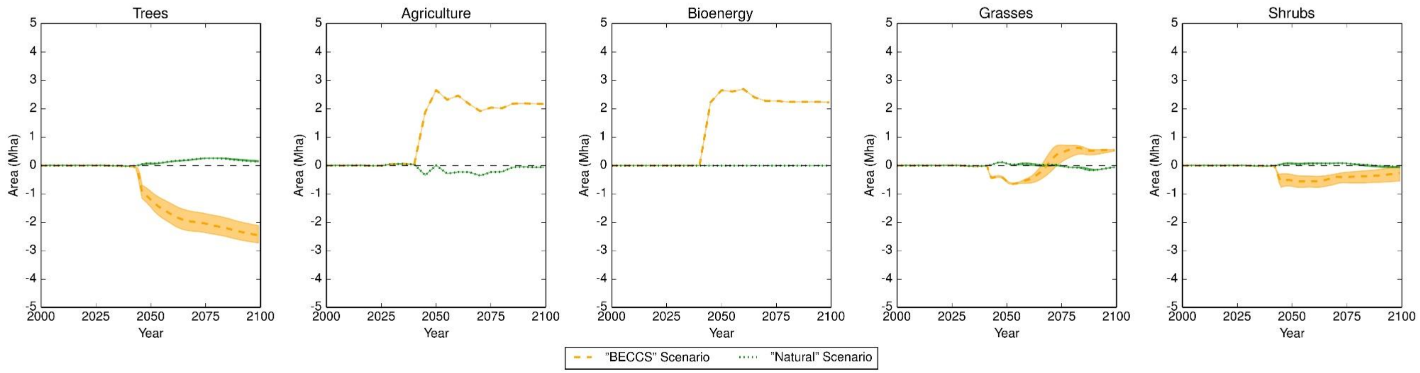


Fig. ~~SI.3w~~SI2.y: Indonesia



~~Fig. SI.3SI.2x: Japan~~



~~Fig. SI.3~~SI.2~~y: Rest of South Asia~~

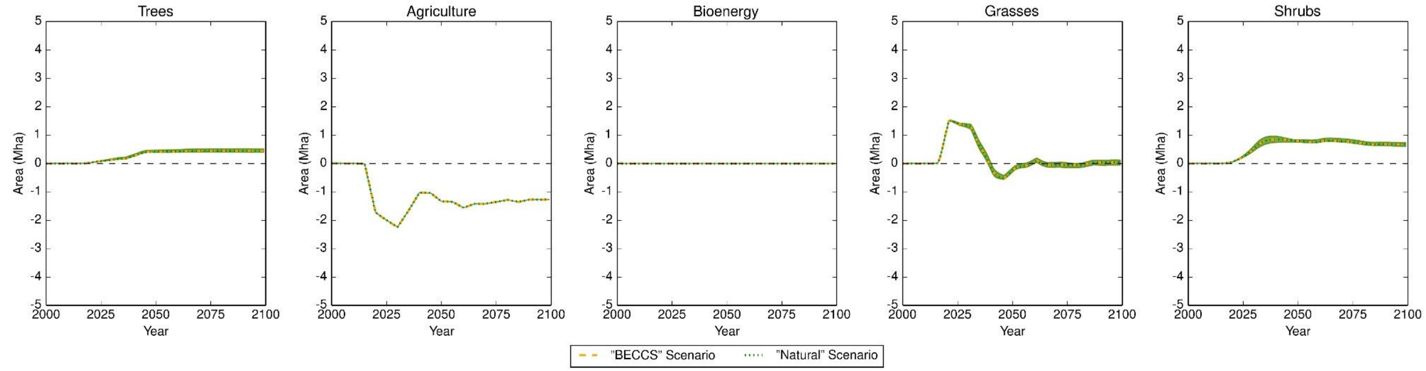
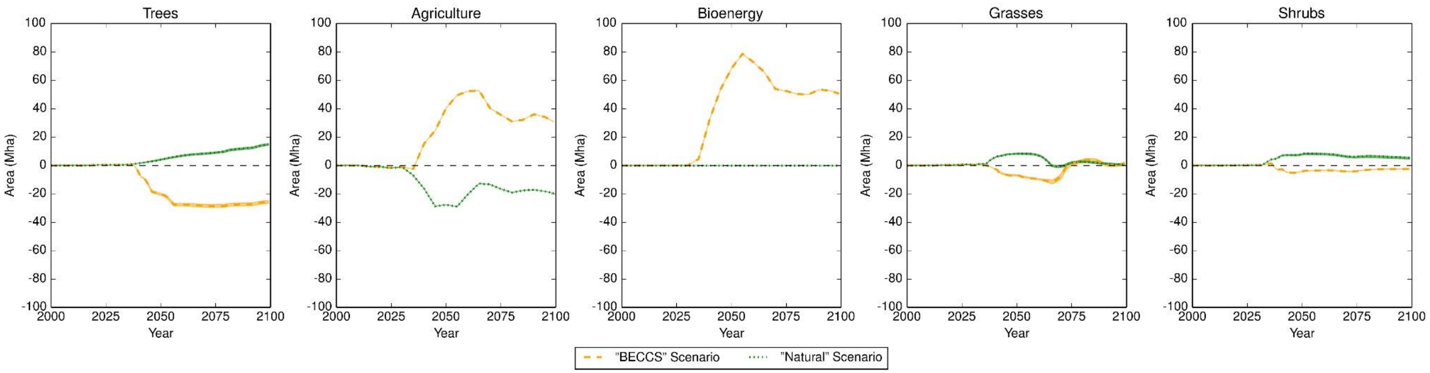
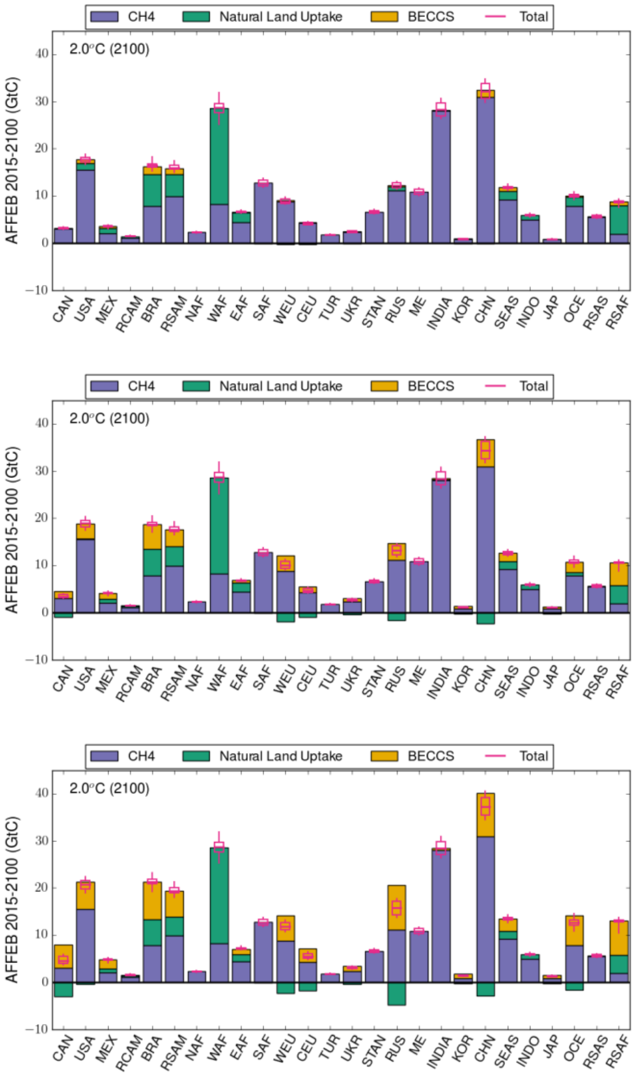


Fig. ~~SI.3~~SI.2z: Oceania



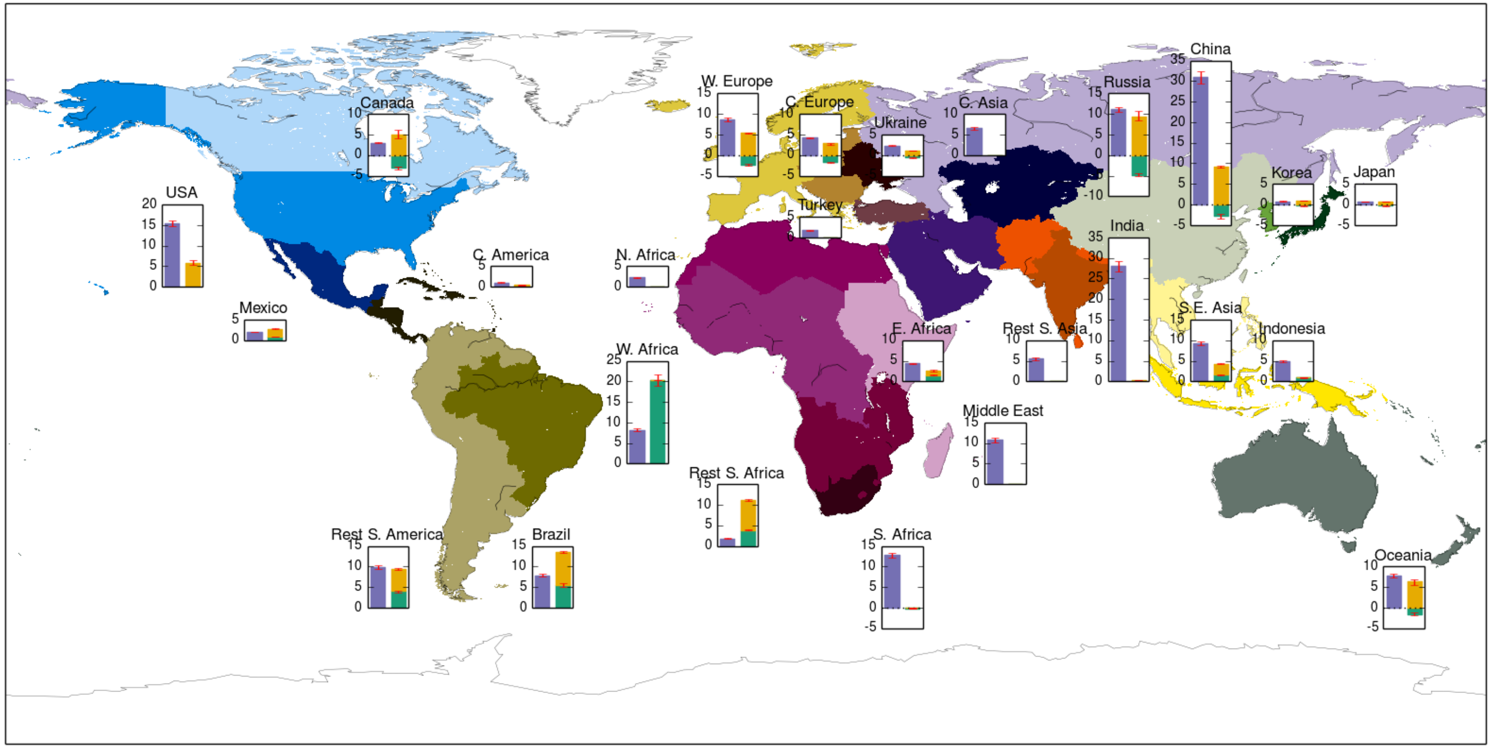


(a)

(b)

(c)

Fig. SI.2 3 | Contribution of different mitigation options to the increase in allowable anthropogenic fossil fuel emission budgets by IMAGE region to meet the 2°C target. The stacked bars represent the median methane mitigation potential (purple bars) and median land-based mitigation potential (natural land uptake, green; BECCS, brown). Panel (a) is based on a BECCS scaling factor of unity, (b) a BECCS scaling factor of 2 and (c) a BECCS scaling factor of 3. The total (pink) shows the median and interquartile range for the 34 GCMs emulated and 4 factorial sensitivity simulations.



Canada
USA
Mexico
C. America
Rest S. America
Brazil
W. Europe
C. Europe
Ukraine
Turkey
N. Africa
W. Africa
Rest S. Africa
E. Africa
S. Africa
Middle East
C. Asia
Russia
China
India
Rest S. Asia
S.E. Asia
Indonesia
Korea
Japan
Oceania

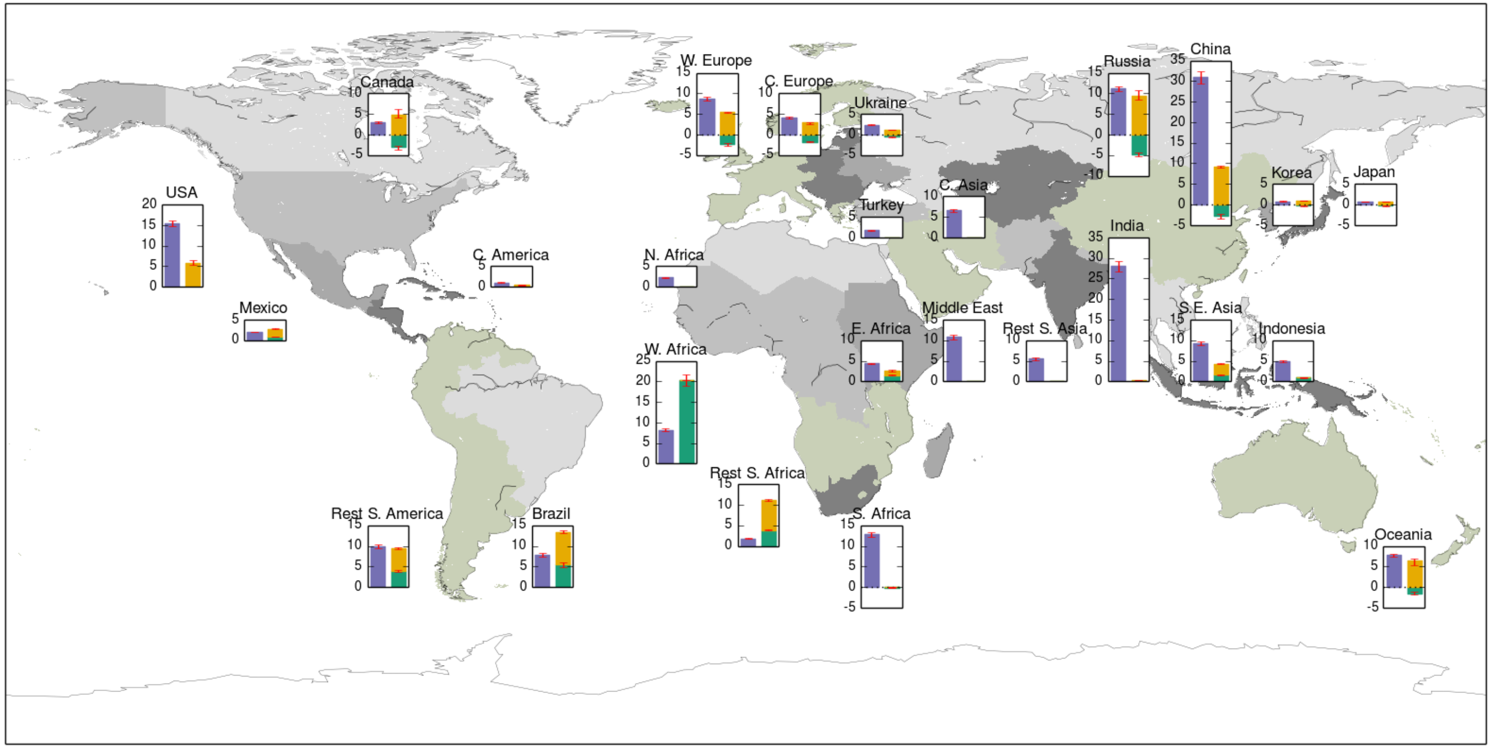


Fig. SI.4 | Contribution of different mitigation options to the allowable anthropogenic carbon emission budgets by region. The contribution to the allowable carbon emission budgets (GtC) between 2015 and 2100 for each of the 26 IMAGE IAM regions from methane mitigation (purple bars) and land-based mitigation options (green: natural land uptake; yellow: BECCS with κ = 3), for the temperature pathway stabilising at 2°C warming without overshoot. The bars and error bars respectively show the median and the interquartile range, from the 34 GCMs emulated and 4 factorial runs.

Table SI.1 | Mitigation options, estimated maximum reduction potential and the accompanying marginal price for mitigation of different anthropogenic methane source sectors for 2050 and 2100 [based on Lucas et al., 2007].

Source Sector	**Mitigation option(s)**	**Max. possible reduction relative to baseline (%)**	**Marginal price of max. reduction (1995 US$/$tC_{eq}$)**
Coal production	Maximising methane recovery from underground mining of hard coal	90 (2050) 90 (2100)	500 (2050) 500 (2100)
Oil/gas production & distribution	Control of fugitive emissions from equipment and pipeline leaks, and from venting during maintenance and repair.	75 (2050) 90 (2100)	300 (2050) 500 (2100)
Enteric fermentation	Change of animal diet and use of more productive animal types.	50 (2050) 60 (2100)	1000 (2050) 1000 (2100)
Animal waste	Capture and use of methane emissions through anaerobic digesters.	50 (2050) 60 (2100)	1000 (2050) 1000 (2100)
Wetland rice production	Changes to (1) the water management regime to reduce the period of anaerobic conditions in flooded fields; (2) the soils to reduce methanogenesis.	80 (2050) 90 (2100)	1000 (2050) 1000 (2100)
Landfills	(1) Reduced amount of organic material deposited in landfills; (2) capture of methane	90 (2050) 90 (2100)	500 (2050) 500 (2100)
Sewage and wastewater	(1) More wastewater treatment plants and also recovery of the methane from the plants; (2) More aerobic wastewater treatment.	80 (2050) 90 (2100)	500 (2050) 500 (2100)
Other anthropogenic sources	Note 1	-	-

Note: (1) These sources are either difficult to abate (e.g., land clearing for agricultural extension, and the use of traditional biomass for energy production and cooking) or are too small (e.g., methane emissions from industry, iron and steel production and the chemical sector).

Reference: Lucas, P. L., van Vuuren, D. P., Olivier, J. G. J. & den Elzen, M. G. J., 2007: Long-term reduction potential of non-CO_2 greenhouse gases. *Environmental Science & Policy* **10**, 85-103, doi: https://doi.org/10.1016/j.envsci.2006.10.007.