Development of overshoot pathways

Global consequences of climate overshoot pathways: Annex 1

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CS-NOW

Climate services for a net zero resilient world

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Key messages

1. Three overshoot pathways have been developed for analysis in this study.

Each overshoot pathway has a different peak global surface average temperature in about 2060:

- “Low Overshoot”: 1.6 °C.
- “High Overshoot”: 1.8 °C.
- “Very High Overshoot”: 1.9 °C.

Each overshoot pathway returns to 1.5 °C by 2100 through carbon dioxide removal from the atmosphere.

A counterfactual “No Overshoot” pathway has also been developed in which the peak global surface average temperature does not exceed 1.5 °C.

2. The peak temperature is sensitive to the climate sensitivity and to positive greenhouse gas feedbacks.

The global temperature rise due to doubling pre-industrial carbon dioxide in the atmosphere is estimated by the IPCC AR6 report to be 3 °C, with an uncertainty range of 2.5–4.0 °C. If the climate sensitivity is at the upper end of this range, then the global temperature rise in an overshoot would be higher.

As the global temperature rise exceeds 1.5 °C, melting permafrost will release methane and further reduce the carbon budget, requiring higher carbon dioxide removal to return the global temperature rise to 1.5 °C.

2. The peak temperature is also sensitive to the atmospheric carbon dioxide removal that can be achieved, whose magnitude is very uncertain.

Several carbon dioxide removal methods are being investigated. The feasibility of deploying all of these methods at scale, and hence the feasibility of the two high overshoot pathways in particular, are highly uncertain. Annex 2 examines some of the CDR assumptions in more detail.

About this report

The “Global consequences of climate overshoot pathways” study has examined the natural and human system consequences of the world overshooting 1.5 °C, but then using carbon dioxide removal technologies to return the global temperature to 1.5 °C by 2100.

The final report summarises the findings from the study. Six annexes present the technical evidence that underpin the final report:

- Annex 1: Development of overshoot pathways.
- Annex 2: The feasibility of deploying CDR at the rate required for overshoot pathways.
- Annex 3: Economic implications of climate overshoot.
- Annex 4: Hysteresis and tipping points analysis using the UK Earth System Model.
- Annex 5: Natural system impacts of overshoot pathways.
- Annex 6: Human system impacts of overshoot pathways.

Around 40 scientists have contributed to these annexes and more than 900 literature sources are cited.

This annex, Annex 1, describes how the three overshoot pathways were developed for this project and compares them with pathways in the IPCC AR6 database.

About CS-N0W

Commissioned by the UK Department for Energy Security & Net Zero (DESNZ), Climate Services for a Net Zero Resilient World (CS-N0W) is a 4-year, £5 million research programme, that uses the latest scientific knowledge to inform UK climate policy and help us meet our global decarbonisation and resilience ambitions.

CS-N0W enhances the scientific understanding of climate impacts, decarbonisation and climate action, and improve accessibility to the UK's climate data. It contributes to evidence-based climate policy in the UK and internationally, and strengthens the climate resilience of UK infrastructure, housing and communities.

The programme is delivered by a consortium of world leading research institutions from across the UK, on behalf of DESNZ. The CS-N0W consortium is led by **Ricardo** and includes research **partners Tyndall Centre for Climate Change Research**, including the Universities of East Anglia (UEA), Manchester (UoM) and Newcastle (NU); institutes supported by the **Natural Environment Research Council (NERC)**, including the British Antarctic Survey (BAS), British Geological Survey (BGS), National Centre for Atmospheric Science (NCAS), National Centre for Earth Observation (NCEO), National Oceanography Centre (NOC), Plymouth Marine Laboratory (PML) and UK Centre for Ecology & Hydrology (UKCEH); and **University College London (UCL)**.

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Acronyms

AR5	IPCC's Fifth Assessment Report (2013-2014)
AR6	IPCC's Sixth Assessment Report (2021-2022)
BECCS	Bioenergy with Carbon Capture and Storage
CDR	Carbon Dioxide Removal
CH_4	Methane
CO_2	Carbon Dioxide
DACCS	Direct Air Carbon Capture and Storage
DESNZ	Department for Energy Security and Net Zero
ECS	Equilibrium Climate Sensitivity
ESM	Earth System Model
EW	Enhanced Weathering
FAO	Food and Agricultural Organization
GCP	Global Carbon Project
GHG	Greenhouse Gas
GWP	Global Warming Potential
IAM	Integrated Assessment Model
IIASA	International Institute for Applied Systems Analysis
IPCC	Intergovernmental Panel on Climate Change
LULUCF	Land Use, Land-use Change and Forestry
N_2O	Nitrous Oxide
NDC	Nationally Determined Contribution (emission reduction)
PgC	Petagrams of carbon
RCP	Representative Concentration Pathway
SCS	Soil Carbon Sequestration
SLCP	Short-lived Climate Pollutant
SO_2	Sulphur Dioxide

SSP	Shared Socioeconomic Pathways
TIAM-UCL	TIMES Integrated Assessment Model at University College London
TRL	Technology Readiness Level

Executive Summary

Although there is still a focus on achieving net zero and limiting the global surface average temperature rise to 1.5 °C above pre-industrial temperatures, this goal is achieved in only a small proportion of the pathways in the Intergovernmental Panel on Climate Change (IPCC) Assessment Report 6 (AR6) scenarios database. Many more pathways overshoot but then return below 1.5 °C by the end of the century. This report annex describes the creation of three overshoot pathways characterised by different peak global temperatures for analysis in this study: “Low overshoot” (1.6 °C), “High Overshoot” (1.8 °C) and “Very High Overshoot” (1.9 °C). Each returns to 1.5 °C by the year 2100.

Factors affecting the peak overshoot

The peak temperature of an overshoot depends on global greenhouse gas emissions, the climate sensitivity, the impact of the overshoot on the global carbon budget and the level of carbon dioxide removal (CDR) that is achievable. All of these have substantial uncertainties.

The Equilibrium Climate Sensitivity (ECS) is defined as the change in the global surface temperature when atmospheric carbon dioxide (CO_2) levels are instantaneously doubled and a new stable (i.e. equilibrium) temperature is reached. The ECS is arguably the most fundamental “bulk” parameter that describes how the climate system will alter in response to raised atmospheric Greenhouse Gas (GHG) concentrations. The IPCC AR6 estimate of the “likely” range (66% probability) of ECS remains very large at 2.5–4.0 °C, with a best estimate of 3 °C. One challenge is that many of the most detailed earth system models have a substantially higher ECS and the reasons for this are not well understood (e.g. the UK Earth System Model has an ECS of 5.4 °C).

Much anthropogenic CO_2 released to the atmosphere in the past has been taken up and sequestered by vegetation or in the oceans. However, further global warming will lead to the release of additional carbon from permafrost thaw (as carbon dioxide and methane) and of methane from wetlands. These positive climate feedbacks will reduce the available carbon budgets from anthropogenic sources for a given warming level. Based on recent literature, this study assumed the global anthropogenic carbon budget would reduce by 100 $GtCO_2$ for a "No overshoot" 1.5 °C pathway, and 120 $GtCO_2$ for the overshoot pathways,[1] due to permafrost and wetlands emissions. Other positive feedbacks such as increased fires, causing tree death, biomass and soil carbon loss, were not represented in the model as there were insufficient evidence available.

A wide range of potential CDR methods have been identified, but most have only recently been included in integrated assessment models and several, particularly nature-based solutions, are still not considered. By starting from a landmark study by Fuss et al. (2018) and reviewing literature published since then, potential deployment limits for each CDR method and potential total deployment of all methods were identified. These have considerable uncertainties and feasible deployment is likely to be far lower than the technical potential. Annex 2 of this study investigates feasibility in more detail. Table ES1 summarises the assumptions chosen for the overshoot pathways developed in this study. The "Low Overshoot" pathway used the "Low CDR" assumptions while the "High Overshoot" and "Very High Overshoot" pathways used the "High CDR" assumptions, with different total negative emission limits chosen to distinguish the two high pathways (25 $GtCO_2$/year and 37 $GtCO_2$/year). Bioenergy with carbon capture and storage (BECCS) was limited primarily by global biomass availability. All other methods were limited by their CDR contribution. An "Other CDR" contribution was included in the "High CDR" assumptions to represent other CDR methods that are not commonly included in integrated assessment models.

Development of overshoot pathways for this project

The TIAM-UCL integrated assessment model was used to develop the three overshoot pathways. TIAM-UCL is a global optimisation model that investigates decarbonisation

[1] 120 $GtCO_2$ was derived for the "Very High Overshoot" pathway and used for all three overshoot scenarios created in this project.

of the global E3 (energy-environment-economy) system. It allows us to better understand the global costs and benefits of many different decarbonisation options. The model consists of a bottom-up global energy system optimisation model linked to a climate module that estimates global temperature change as a function of greenhouse gas emissions.

Table ES1. Summary of CDR assumptions in the overshoot pathways.

	Low CDR	High CDR
BECCS	100 EJ biomass	200 EJ biomass
Direct air carbon capture and storage	5 $GtCO_2$	20 $GtCO_2$ in 2050, 30 $GtCO_2$ in 2100 800 $GtCO_2$ for the period 2025–2100
Afforestation and soil carbon	Linear increase from zero in 2025 to 4.9 $GtCO_2$ from 2050.	
Other CDR	None	15 $GtCO_2$ from 2050
Overall limit	None	25 ("High Overshoot" pathway) 37 ("Very High Overshoot" pathway)

TIAM-UCL was calibrated to the IPCC AR6 best estimate of the climate sensitivity of 3 °C and accounted for permafrost melt and wetlands positive feedbacks in each pathway. Each pathway was based on the SSP2 socioeconomic pathway to enable international comparisons of the pathway. "No Overshoot" and "NDC" pathways were created and were consistent with comparable IPCC AR6 scenarios. The TIAM-UCL global emissions budgets were also compared with IPCC AR6 as a further evaluation of the model outputs.

The principal difference between the three overshoot pathways was the availability of CDR. These assumptions are listed in the table above. The "Very High Overshoot" pathway has a higher peak temperature (1.9 °C) than any of the pathways in the IPCC AR6 database. The higher temperature was achieved by assuming global emissions would continue at a high level until 2040 before a substantial reduction, which is later than in most IPCC database pathways. The magnitude of negative emissions in the higher overshoot pathways is higher than for most pathways in the IPCC database, as shown in the graph below. A higher overshoot than 1.9 °C is unlikely to be plausible if the temperature anomaly is to return to 1.5 °C by 2100.

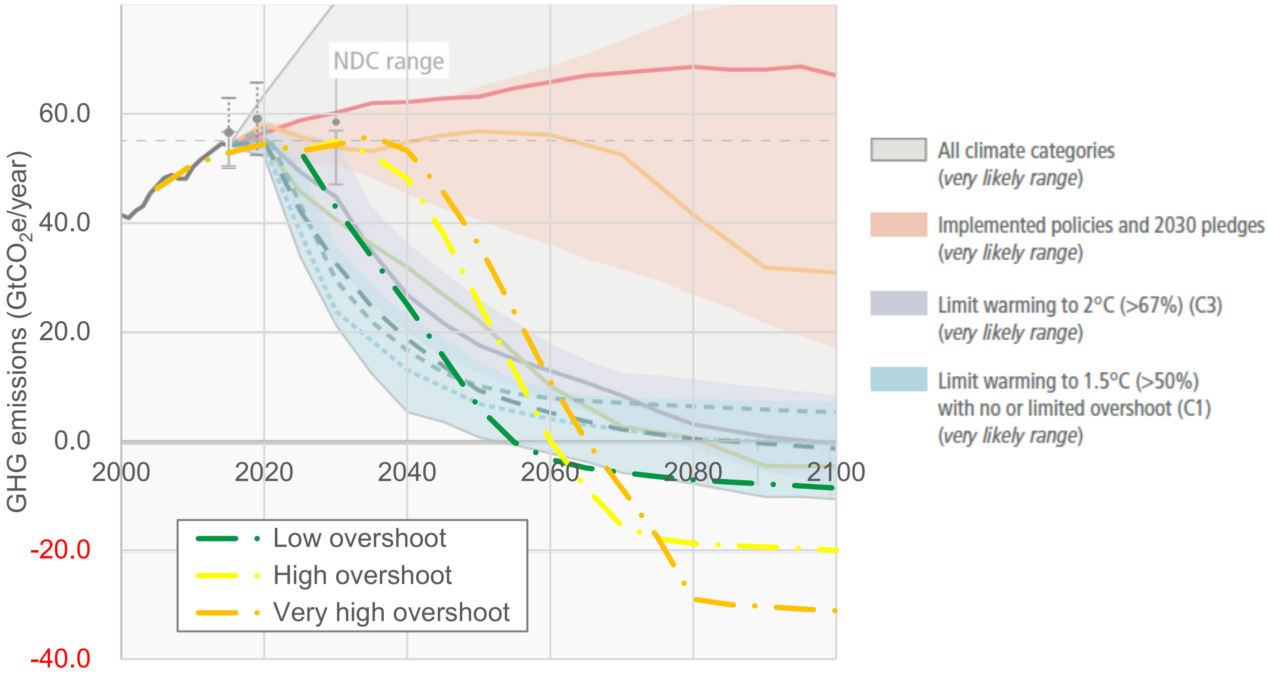

Figure ES1. TIAM-UCL GHG emissions for the three overshoot pathways compared with IPCC AR6 WGIII emission ranges for scenario categories C1–C8 (shaded areas) and Illustrative Pathways (lines). The IPCC part of the graph is based on Figure 3.19 in Riahi *et al.* (2022).

1. Introduction

The IPCC AR6 scenarios database has 5367 temperature scenarios produced by applying three simple climate models to around 1800 scenarios submitted by the scientific community. The global temperature does not exceed 1.5 °C above pre-industrial[2] in only 12% of these pathways. More than twice as many pathways (23%) temporarily overshoot 1.5 °C but end the century below 1.5 °C, and are referred to "overshoot pathways" in this report. This larger group of overshoot pathways reflects the global failure to reduce global greenhouse gas (GHG) emissions to date and the lack of ambition of current Nationally Determined Contribution (NDC) commitments to meet the global carbon budget required to keep the temperature rise below 1.5 °C. As limiting the global temperature rise to 1.5 °C becomes increasingly difficult, interest in overshoot pathways is growing. For example, the EU-funded PROVIDE project has developed a range of overshoot pathways (Lamboll *et al.*, 2022) and the TerraFIRMA project is examining the earth system implications of overshooting.[3]

Overshoot pathways are characterised by high levels of CO_2 removal (CDR) technologies being deployed towards the end of the century to reduce the global temperature following a mid-century overshoot. In this study, but not always elsewhere, it is assumed that the aim is to return to 1.5 °C above pre-industrial temperatures by 2100.

1.1 Overshoot pathways created in this project

Three representative overshoot pathways were created by this study. These are characterised according to their peak temperature:

- "Low Overshoot" (LO), in which the global temperature peaks at 1.6 °C in about 2060 before returning to 1.5 °C by the year 2100.

[2] Pre-industrial temperature is generally assumed to be the average of the period 1850–1900.
[3] The TerraFIRMA project involves eight UK research centres in partnership with the Met Office and is funded through UKRI-NERC National Capability.

- “High Overshoot” (HO), in which the global temperature peaks at 1.8 °C in about 2065 before returning to 1.5 °C by the year 2100.
- “Very High Overshoot” (VHO), in which the global temperature peaks at 1.9 °C in about 2065 before returning to 1.5 °C by the year 2100.
- Each of these pathways reaches 1.5 °C in the next 25 years. In addition, a counterfactual “No Overshoot” (NO) pathway was created in which the global temperature does not exceed 1.5 °C, and an NDC pathway was created as a current policy scenario.

These pathways were created using the TIAM-UCL integrated assessment model (IAM), with the climate module calibrated to the IPCC AR6 estimate of global climate sensitivity. TIAM-UCL optimises the global energy system transition and CDR in order to limit the temperature rise to the level set by the user. It can be used to identify plausible overshoot pathways.

1.2 Overshoot pathway uncertainty

The magnitude of an overshoot (i.e. the peak temperature) is determined by the GHG emissions profile and the climate system response to those emissions, and is affected by several uncertainties. Each of these uncertainties is examined in this report:

1. The sensitivity of the climate system to emissions varies greatly between models and is uncertain (Section 3). The carbon budget that would enable us to meet the Paris Agreement reduces as the sensitivity increases.
2. Positive feedbacks from natural processes such as permafrost thaw would increase GHG emissions, though often outside of NDCs, and hence increase the required CDRs to bring back an overshoot (Section 3.3).
3. The level of CDR that can be feasibly deployed is uncertain (Section 5). Higher CO_2 removal by CDR later in the century enables higher GHG emissions in the short term. Annex 2 considers whether the CDR assumed for the overshoot pathways in this study is achievable.

Short-lived climate pollutants (SLCPs) – for example, aerosols such as sulphur dioxide (SO_2) – also affect the level of warming and are likely to vary according to the future socioeconomic pathway and the extent of low-carbon interventions (e.g. reductions in coal power generation). These are discussed in detail in Annex 4, which examines earth system modelling.

1.3 Structure of this report

Assumptions about changes in the global economy, and particularly global demand for energy, affect future emissions. To enable international comparability, the overshoot pathways have been developed using assumptions consistent with international socioeconomic pathways (Section 2).

Climate sensitivity, positive feedbacks and CO_2 removal potential, the key uncertainties affecting overshoot pathways, are discussed in Sections 3 to 5, respectively.

TIAM-UCL assumptions are discussed in Section 6 and model calibration and evaluation are discussed in Section 7. An overview of the overshoot pathways developed using TIAM-UCL is presented in Section 8, including a comparison with IPCC AR6 WGIII pathways.

2. Global economic assumptions

Representative Concentration Pathways (RCPs) have been widely used by climate modellers to represent scenarios of GHG emissions in the future. They represent a range of climate forcing levels due to human actions (expressed in terms of W m^{-2}). More recently, a series of Shared Socioeconomic Pathways (SSPs) were developed as scenarios of projected socioeconomic global changes up to 2100. SSPs represent variations in global population projections, economic growth, behaviour and consumption. The emissions from each SSP scenario would be expected to be consistent with a small range of RCPs, based on insights from integrated assessment models (IAMs), as shown in Figure 1, which shows the SSP-RCP combinations examined in the CMIP6 model intercomparison project.

While each SSP can be run for a range of RCPs, not all of these scenarios are plausible. The lowest RCPs are generally used with SSP1 (“Sustainability”). SSP2 (“Middle of the road”) could also be used with RCP1.9 and RCP2.6, but the low level of warming would require greater emission reduction interventions than for SSP1 to counteract the higher economic growth and population assumptions of SSP2. For this reason, the CMIP6 model comparison project examines SSP2 with RCP4.5 (SSP2-4.5). The global surface temperature warming for several SSP-RCP combinations in CMIP6 is shown in Figure 2. The SSP2 scenario has a median temperature rise of 3 °C. The two SSP1 scenarios have temperature rises of 1.4 °C and 2 °C, which cover the range of a high overshoot.

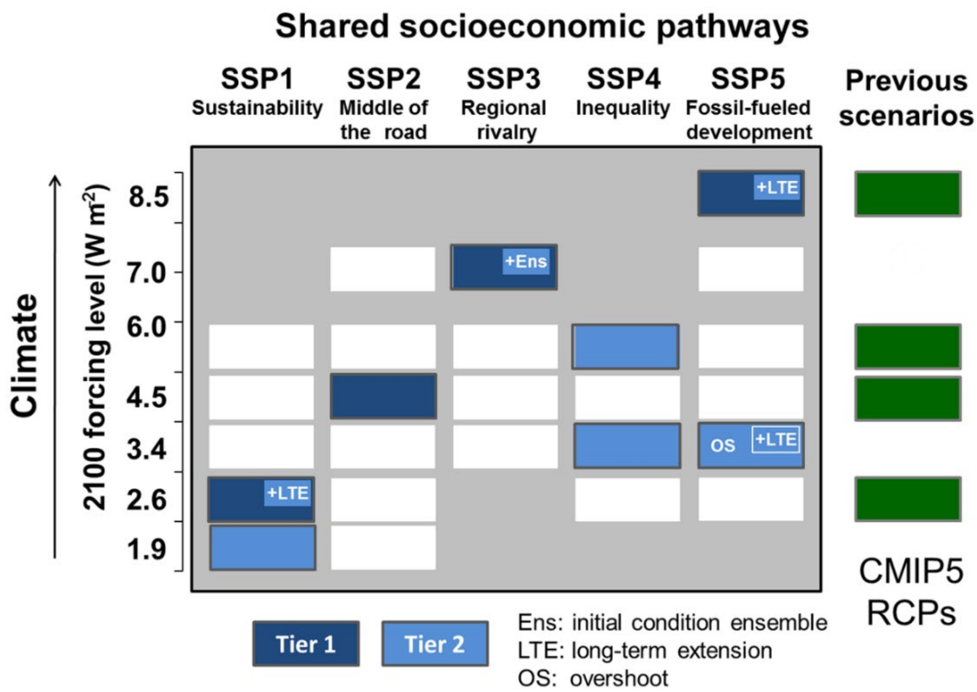

Figure 1. SSP-RCP scenario matrix. Each cell indicates a combination of socioeconomic development pathway (i.e. an SSP) and climate outcome based on a particular forcing pathway that current IAM runs have shown to be feasible (RCP). The highlighted boxes show the pathways that were analysed as part of the Scenario Model Intercomparison Project (ScenarioMIP). These are important because climate projection data are available from several models, including the UK Earth System Model (UKESM). Source: Riahi *et al.* (2017); O'Neill *et al.* (2016), Figure 2, CC BY 4.0.

Either of these SSP scenarios can be used in TIAM-UCL pathways. As SSP2 has higher energy service demands, it is more difficult to decarbonise and the higher levels of low-carbon technologies required are therefore less plausible than for SSP1. On the other hand, SSP2 is considered to be close to existing socioeconomic trends and the behavioural change required for SSP1 might be considered unrealistic by those who advocate primarily technical solutions to climate change. We use SSP2 in this study as that is closest to existing trends.

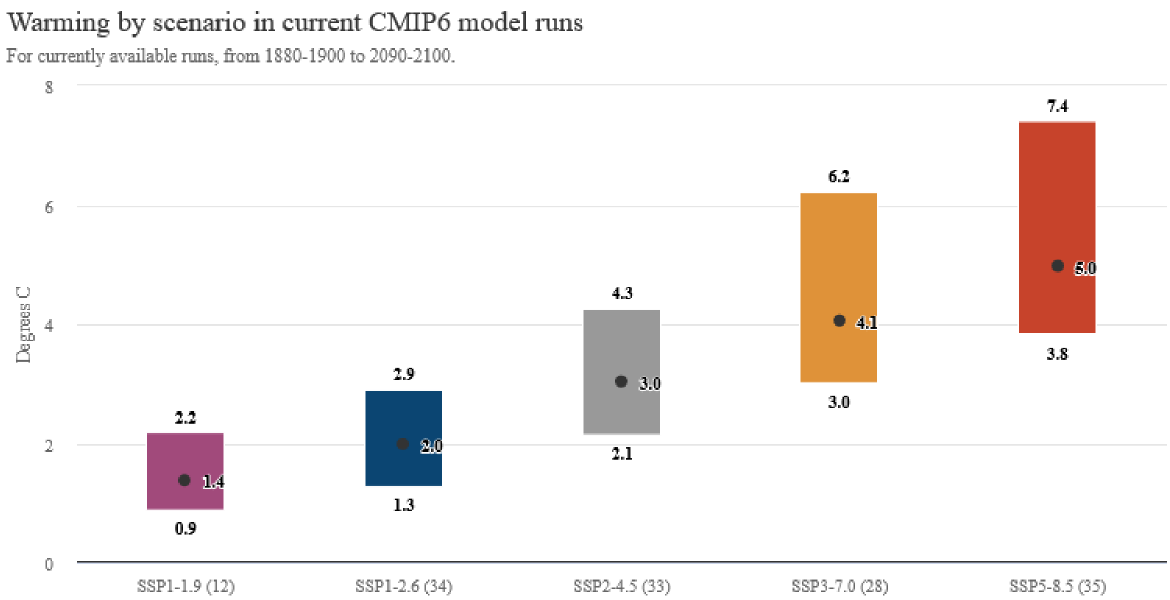

Figure 2. Range of temperatures for each SSP-RCP combination in CMIP6. Source: Carbon Brief (2020).

3. Climate system sensitivity to greenhouse gas emissions

The Equilibrium Climate Sensitivity (ECS) is defined as the change in the global surface temperature when atmospheric carbon dioxide (CO_2) levels are instantaneously doubled, and a new stable temperature is reached. The ECS is arguably the most fundamental “bulk” parameter that describes how the climate system will alter in response to raised atmospheric Greenhouse Gas (GHG) concentrations. The metric has been used for 40 years to describe the warming sensitivity to rising atmospheric CO_2 of the planet, and to compare Earth System Models (ESMs). Unfortunately, despite many breakthroughs in climate understanding, the “likely” range (66% probability) of ECS remains very large at 2.5 °C to 4 °C.

Supporting the usefulness of ECS is its versatility. First, it is believed to be invariant, and so can be extrapolated to determine warming for different stable CO_2 levels. Second, an effective CO_2 level (CO_2e) can be used with ECS to project stable warming levels for simultaneous changes to other greenhouse gases (GHGs). CO_2e is calculated by adding the radiative forcings for each GHG, based on their concentration changes and well-established mappings from concentration levels to radiative forcing increases. Third, knowledge of the Earth's ECS is also powerful as it can be used to answer the inverse question: "What CO_2e level is compatible with key temperature targets (e.g. a global temperature rise of 1.5 °C or 2.0 °C)?"

3.1 Estimates of ECS in the literature

Table 1 lists central values and ranges of the ECS from recent assessments (including those from IPCC AR5[4] and AR6) and of the ECS derived from the UK climate and Earth system models contributing to CMIP6. IPCC AR6 estimates a central ECS value of 3 °C, with a likely range of 2.5–4.0 °C. In CMIP6, a significant number of Earth system models exhibit ECS values greater than 4.5 °C, with 5 models suggesting an ECS greater than 5 °C (including the UK models). While such high ECS values are considered highly unlikely, they cannot be ruled out and therefore remain as low probability, high impact futures. Meehl *et al.* (2020) find that cloud feedbacks and cloud-aerosol interactions are the most common contributors to the increase in ECS from CMIP5[5] to CMIP6, although there is no single cause in all cases.

Although the contemporary climate is in a transient phase, some knowledge of oceanic heat draw-down, global temperatures and rising GHG levels should offer some hope of improving estimates of ECS. Unfortunately, one main factor making this difficult is that, although the radiative forcings of different GHGs are known, much less understood is the magnitude of the cooling effect of aerosols. This makes it difficult to differentiate between a high temperature sensitivity world, with high warming presently offset with substantial aerosol cooling, or the opposite (i.e. a world with low ECS, and low cooling by aerosols).

[4] AR5 is the IPCC Assessment Report 5.
[5] CMIP5 was the model intercomparison project that preceded CMIP6, using a previous generation of models.

Table 1. Equilibrium Climate Sensitivities from recent IPCC assessments and for specific models.

Assessment/Study	Central/Model ECS (°C)	ECS Range (°C)	Confidence Interval
IPCC AR5 (Collins *et al.*, 2013, Flato *et al.*, 2013)	3.2	1.5–4.5	Likely (>66% probability)
IPCC AR6 (Forster *et al.*, 2021)	3.0	2.5–4.0	Likely
Sherwood *et al.* (2020)			
WCRP: Baseline		2.6–3.9	Likely
WCRP: Robust		2.3–4.5	Likely
Senior *et al.* (2020)			
CMIP6: HadGEM3-GC3.1-LL	5.5	–	
CMIP6: UKESM1	5.4	–	

3.2 Reducing the ESM uncertainty

There is a need to reduce uncertainty on the value of ECS by determining which ESMs are outliers. The traditional way to weight models is to compare their projections for the contemporary period against measurements. However, this is difficult on two accounts: (i) uncertainty in aerosol forcing described above makes present-day inter-model differentiation difficult; and, (ii) there is always a risk that a model performing poorly at present does have important and accurate features that affect ECS, but only become apparent at GHGs rise.

The only other method currently available to reduce the inter-ESM spread is the technique of Emergent Constraints (ECs). ECs are common relationships (usually a regression) across an ensemble of models, between an aspect of future ES behaviour of interest to policymakers and an observable trend or variation in the contemporary climate (Flato *et al.*, 2013). The constraint then comes from using actual contemporary data for observable quantity ("x"-axis) which then, via the regression, reduces the bounds of uncertainty on the quantity of interest (i.e. "y"-axis). For example, Cox *et al.* (2018) find an EC between contemporary temperature fluctuations and ECS values across ESMs, that when merged with a knowledge of present-day temperature variations, enable a derivation of likely range for the ECS of 2.2–3.5 °C. This range is substantially smaller than the 1.5–4.5 °C bounds. Table 2 in Sherwood *et al.* (2020) provides a list of other ECS ranges derived from a set of alternative ECs. Acknowledging the difficulties in combining the ECS from these different ECs, Sherwood *et al.* (2020) conclude that the emergent constraints from present-day climate system variables suggest that the ECS is greater than 2.8 °C. The EC regression-based method does have some caveats, for instance, where ESMs may not be completely independent of each other. For a full discussion, see Williamson *et al.* (2021).

3.3 Climate sensitivity assumption in this study

In this study, the climate module of TIAM-UCL was calibrated to an ECS of 3 °C following the best estimate from IPCC AR6. This enables a comparison with other international work.

There has been substantial work to reduce the uncertainty in this metric, as described in the sections above. While it is *likely* that the ECS lies in the 2.5–4.0 °C range, the size of the range and substantial influence on the carbon budget means we can at best have medium confidence that the best estimate of 3 °C is appropriate. If the ECS exceeds 3 °C then the carbon budget and hence the maximum overshoot would be lower than assumed in this study.

4. Positive GHG feedbacks in overshoot pathways

Both the release of carbon from permafrost thaw (as carbon dioxide (CO_2) and methane (CH_4)), and the release of methane from wetlands have positive climate feedbacks, thereby reducing the available carbon budgets (i.e. emissions) from anthropogenic sources for a given warming level.[6] Most of the climate and Earth

[6] To enable comparison, Carbon budgets reported in Gt C have been converted to Gt CO_2 using a factor of 44/12.

system models that contributed to CMIP5 and CMIP6 did not represent these processes.

4.1 IPCC Special Report "Warming of 1.5 °C" conclusions

The IPCC Special Report, "Warming of 1.5 °C" (IPCC, 2018) (hereafter denoted IPCC SR1.5), summarised a number of relevant studies in which simpler climate models or climate emulators were used to estimate the magnitude of these feedbacks:

- Lowe and Bernie (2018) use a variant of the MAGICC climate model to estimate that Earth-system feedbacks (such as CO_2 released by permafrost thawing or methane released by wetlands) could reduce carbon budgets for 1.5 °C and 2 °C by ~100 and 150 $GtCO_2$, respectively, on centennial time scales.
- Schädel *et al.* (2014) combine the estimated amounts of carbon thawed by 2050 from Harden *et al.* (2012) with an average aerobic carbon loss of 16.6% for the same timeframe to derive an upper bound of 24.4 PgC (90 $GtCO_2$) carbon released from permafrost thaw for a RCP4.5 scenario. The authors assume that soils would be thawed for only 4 months per year for the next 40 years till 2050 and then stay at a constant temperature of 5 °C.
- Burke *et al.* (2017) use a single model to estimate permafrost emissions between 0.3 and 0.6 $GtCO_2$ yr^{-1} from the point of 1.5 °C stabilization, which would reduce the budget by around 20 $GtCO_2$ by 2100.
- Using an inverse version of the IMOGEN climate emulator including the JULES land surface model, Comyn-Platt *et al.* (2018) investigated the climate-land feedbacks arising from carbon and methane emissions from wetlands and permafrost thaw for three temperature profiles: two of the profiles achieve 1.5 °C or 2 °C of warming by 2100 (without overshoot). The third profiles asymptotes to 1.5 °C of warming after an overshoot to 1.75 °C. The allowable anthropogenic fossil fuel CO_2 emission budgets are reduced by 92–139 $GtCO_2$ (9–15%) for stabilization at 1.5 °C, and 122–189 $GtCO_2$ (6–10%) for 2.0 °C stabilization. In a subsequent paper, Hayman *et al.* (2021) also find that the

inclusion of the natural methane feedbacks from wetlands and permafrost thaw leads to ~10% reduction in anthropogenic carbon budgets to 2100.

IPCC SR1.5 concludes that the additional Earth system feedbacks, taken together, are estimated to reduce the remaining carbon budget to 2100 by ~100 $GtCO_2$ (for warming of 1.5 °C), compared to the budgets without these feedbacks (Chapter 2). With limited evidence and medium agreement, the impacts are assigned a medium level of confidence.

4.2 Insights from studies since IPCC SR1.5

Gasser *et al.* (2018) use the compact Earth system model OSCAR v2.2.1, with parameterizations of permafrost thaw, soil organic matter decomposition and CO_2 and CH_4 emission. They find that permafrost carbon release makes emission budgets path dependent (i.e. the carbon budgets also depend on the pathway followed to reach the target). The median remaining budget for the 2 °C target reduces by 8% (1–25%) if the target is avoided and net negative emissions prove feasible, and by 13% (2–34%) if they do not prove feasible. For an overshoot pathway peaking at 2 °C before falling to meet the 1.5 °C long-term target, emissions from permafrost thaw reduce the net emission budgets by 130 (30–300) $GtCO_2$.

Gedney *et al.* (2019) considered the methane-climate feedback from wetlands. For the RCP2.6 scenario, the allowed anthropogenic emissions reductions are reduced by 79 $GtCO_2e$ (21 GtC), with a likely value (greater than 68% probability) of 45–112 $GtCO_2e$. This is consistent with the wetland methane feedback estimated by Comyn-Platt *et al.* (2018) of 72 $GtCO_2e$ for the comparable 1.5 °C stabilisation threshold.

Natali *et al.* (2021) find that an overshoot of 0.5 °C leads to a twofold increase in permafrost emissions for a 1.5 °C or 2 °C target, and an overshoot of 1.5 °C leads to a fourfold increase. Both Natali *et al.* (2021) and MacDougall (2021) note that no Earth system model to date accounts for abrupt thaw processes in permafrost systems. These processes, including thermokarst production, active hill slope erosion, and coastal erosion, could accelerate thaw processes by 40% over the coming centuries

(Turetsky *et al.*, 2020), resulting in additional release of CO_2 and CH_4 over and above that from gradual permafrost thaw.

4.3 Representing positive feedbacks in TIAM-UCL

Given the considerable uncertainty about the magnitude of future emissions from permafrost thaw and wetlands described above, it was necessary to make assumptions for the TIAM-UCL pathways. It was decided that:

- Global carbon budgets would be reduced by 100 $GtCO_2$ for a pathway reaching 1.5 °C of warming, in line with the IPCC SR1.5.
- A reduction in the carbon budget of 120 $GtCO_2$ would be appropriate for a 1.5 °C overshoot. Initial studies suggest there could be little hysteresis in the climate system for an overshoot pathway reaching 2 °C warming (Comyn-Platt *et al.*, 2018), but there is a possibility of abrupt permafrost thaw and pathway dependence (Gasser *et al.*, 2018) that justifies a slightly higher level of emissions.
- A reduction of 150 $GtCO_2$ would be appropriate for a 2 °C pathway.

Table 2 shows the assumed reduction in the TIAM-UCL global carbon budget caused by permafrost thaw and wetlands methane releases for the period 2015–2100.

Table 2. Assumed reduction in the global carbon budget for the period 2015–2100 due to permafrost thaw and wetlands methane emissions ($GtCO_2e$).

	1.5 °C	1.5 °C overshoot	2 °C
Permafrost thaw	43	48	53
Wetlands methane	57	72	97
Total	**100**	**120**	**150**

Projections of future emissions from permafrost thaw are approximately linear over time and similar for 1.5 °C and 2 °C warming pathways (Comyn-Platt *et al.*, 2018, Figure 2d). These were represented in each TIAM-UCL overshoot pathway as a constant increase in CO_2 each year over the whole time horizon for each pathway. Future emissions from wetlands are much more difficult to represent in TIAM-UCL as they vary between pathways and have a non-linear relationship over time, as shown in Figure 3, and with the magnitude of warming.

Only permafrost thaw and wetlands were represented in TIAM-UCL. Other positive feedbacks such as increased fires, with associated biomass and soil carbon loss, and tree death, were not represented in the model as there was insufficient evidence available. Even the feedbacks for which evidence is available have limited literature and high uncertainty bounds, meaning there is low confidence in the insights. While including permafrost thaw and wetlands feedbacks in TIAM-UCL is an important step that has not yet been taken by many studies, there is low confidence in the assumptions of the impacts of each feedback on the carbon budget. If the assumed feedbacks turn out to be underestimated then the carbon budget and hence the maximum overshoot would be lower.

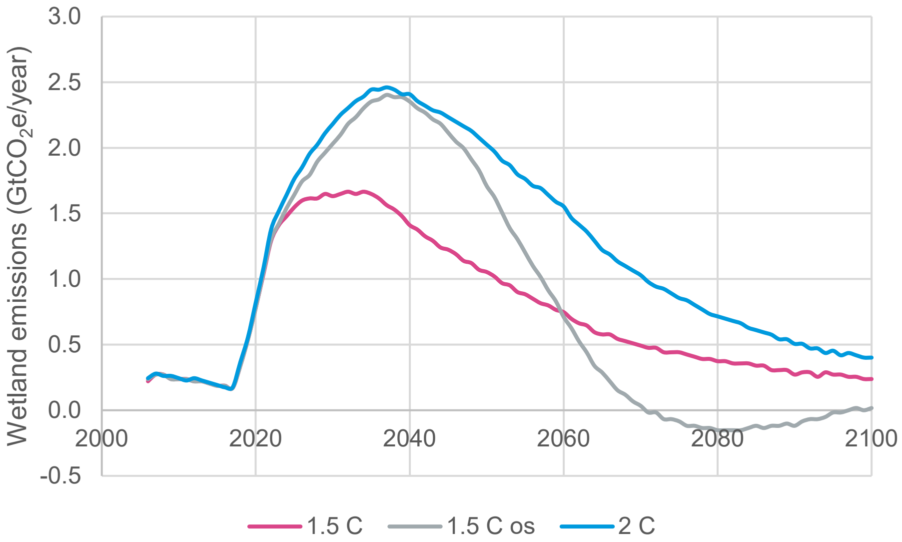

Figure 3. Wetland emissions over time for warming pathways. Adapted from Figure 3c in Comyn-Platt *et al.* (2018). Reproduced with permission from Springer Nature.

5. CO_2 removal potential in the overshoot pathways

The most important difference in the development of the three overshoot pathways in TIAM-UCL is the CDR assumptions.

In IPCC AR5, the only CDR technologies represented in IAMs were afforestation and bioenergy with carbon capture and storage (BECCS) (Fuss *et al.*, 2014, Minx *et al.*, 2018). In IPCC SR1.5, BECCS and afforestation dominate, but some IAMs included direct air carbon capture and storage (DACCS) (e.g. Strefler *et al.*, 2018). Analysis of IAM pathways that reach 2 °C and 1.5 °C show that substantial CDR is used in almost all pathways, ranging from -1 to -27 $GtCO_2$/yr with a mean of -15 $GtCO_2$/yr (IPCC, 2018, Roe *et al.*, 2019). Land management-based CDR approaches are poorly captured within most IAMs(IPCC, 2018).

5.1 Potential CO_2 removal rates for CDR technologies and impacts

Table 3 presents the values for potential global CO_2 removal rates for CDR technologies from Fuss *et al.* (2018), which is a seminal literature assessment of CDR technology potentials in 2050 that forms the core information within the relevant sections of the IPCC SR1.5. Some estimates of global potential CO_2 removal rates include life cycle emissions (i.e. embedded energy emissions, land use change), while others do not. Fuss *et al.* (2018) present the full range of values in the literature alongside an assessment of potential that includes numerous limiting factors. Key updates from more recent literature have also been added in Table 3 but make no significant change to the overall ranges or feasible potentials presented by Fuss *et al.* (2018).

The total potential found by summing the Fuss *et al.* (2018) estimates is 25 $GtCO_2$ yr^{-1}, while the maximum from the literature is 222 $GtCO_2$ yr^{-1}. BECCS and DACCS, the two most well understood technologies, each have potentials of 5 $GtCO_2$ yr^{-1} in Fuss *et al.* (2018) but 40 and 20 $GtCO_2$ yr^{-1} in the wider literature. Both have a low Technology Readiness Level (TRL) and neither have been deployed at scale, reflecting the lack of market support mechanisms, so there are substantial uncertainties in their potential contribution. For example, the development of an affordable and efficient solid sorbent for DACCS would greatly reduce both capital and operating costs, and could underpin a much higher deployment (NAS, 2019).

The large uncertainty ranges are in some cases, such as enhanced weathering, due to limited knowledge (e.g. where only theoretical studies, modelling or lab experiments have been conducted). For others (e.g. BECCS and DACCS), the difference between upper estimates and Fuss *et al.* (2018)'s feasible potentials are due to inclusion or omission of social, political or sustainability factors such as land availability, fertiliser input, political leadership needed to incentivise and support emerging technologies and finance structures to pay for the removal of carbon. Annex 2 examines these issues and their implications for the magnitude of CDR that could be achieved in the future.

Table 3 Estimates of global CDR rates. Adapted from Table 2 in Fuss *et al.* (2018). Data is also presented in IPCC SR1.5 (2018). These are potential estimates for the year 2050.

CDR method	(Fuss *et al.*, 2018) ($GtCO_2\ yr^{-1}$)		Key updates in literature (2018 to 2021) - note these are often maximum estimates with limited consideration of sustainability or other feasibility factors.
	Potential	Literature	
Afforestation & reforestation	0.5–3.6	0.5–7	Tropical reforestation: 0.078–1.84 $GtCO_2$/yr in 2050 (Busch *et al.*, 2019). If all 350 Mha degraded land identified under the Bonn Challenge would be converted to natural forests, these would store 42 PgC (154 $GtCO_2$) by 2100 (Lewis *et al.*, 2019). The extent and severity of degraded land is poorly constrained (IPCC, 2019). Under a global program of forest restoration, Bastin *et al.* (2019) identified 900 Mha which could naturally support woodlands and forests, with a potential of storing 133.2 to 276.2 GtC (488–1,012 $GtCO_2$). In direct response to Bastin *et al.* (2019), Taylor and Marconi (2020) argue the 900 Mha would give only 71.7–75.7 GtC (263–278 $GtCO_2$) (critiquing two assumptions about pre-existing carbon and accumulation rates of soil organic carbon). The Taylor and Marconi (2020) estimate does not account for albedo response or socio-economic factors.

CDR method	(Fuss *et al.*, 2018) ($GtCO_2\ yr^{-1}$)		Key updates in literature (2018 to 2021) - note these are often maximum estimates with limited consideration of sustainability or other feasibility factors.
	Potential	Literature	
			These estimates assume a return to natural forest and that the pressures that have led to degradation are removed, but realistically the timing of recovery and the socio-economic consequences mean these numbers are very much upper bound and would require urgent highly resourced action for reality to approach these levels of removal.
Biochar	0.5–2	1–35	No new insights.
Soil carbon sequestration	2–5	0.5–11	Bossio *et al.* (2020) estimate the contribution of increased soil carbon in all natural climate solutions (NCSs) (based on Griscom *et al.* (2017)) – restoring actions gives 3.3 $GtCO_2e$/yr for 2030.
Enhanced weathering (EW)	2–4	0–100	Goll *et al.* (2021) consider applying basalt dust to hinterland soils and assume increased soil carbon due to phosphate input. Limited by low carbon energy requirement of mining, crushing, transport of basalt. Max scenario: 2.5 $GtCO_2$/yr. On land for afforestation and bioenergy crops, de Oliveira Garcia *et al.* (2020) estimate EW at 12 (0.2–27) GtC [44 (0.7–99) $GtCO_2$] by 2100.

CDR method	(Fuss *et al.*, 2018) ($GtCO_2\ yr^{-1}$)		Key updates in literature (2018 to 2021) - note these are often maximum estimates with limited consideration of sustainability or other feasibility factors.
	Potential	Literature	
			Beerling *et al.* (2020) estimate basalt on agricultural land at 2 $GtCO_2$/yr, aggregating to 25–100 $GtCO_2$ removed over 50 years. Need further laboratory research and long-term field trials to determine consistent of these estimates with real world C removal. Assumed transport method and grain size key for $kgCO_2\ ton^{-1}$ rock (Rinder and von Hagke, 2021). Their results are lower than Strefler *et al.* (2018).
Bioenergy with carbon capture and storage (BECCS)	0.5–5	1–85	Creutzig *et al.* (2021) review BECCS in IAM 1.5 °C and 2 °C scenarios (IPCC SR1.5C). Find deployment of 3–30 $GtCO_2$/yr in 2100. 33% of all scenarios exceed the Fuss *et al.* (2018) upper sustainable limit of 5 $GtCO_2$/yr. Muratori *et al.* (2020) find 8–28 $GtCO_2$/yr in 2100 across the EMF-33 scenarios. Range reflects interactions between bioenergy, CCS and carbon prices (Muratori *et al.*, 2020). Hanssen *et al.* (2020) propose BECCS for electricity in 2050 at 2.5 $GtCO_2$/yr, and 40 $GtCO_2$/yr in 2100. For liquid transport fuels they propose negligible penetration in 2050 and 4.8 GtCO2/yr in 2100. Larger estimates in 2100 as initial LUC emissions and foregone sequestration are offset over the longer time horizon with annual removals from BECCS.
Direct Air Carbon Capture	0.5–5	Limited by upscaling, cost	Max 20 $GtCO_2$/yr in 2050, 570–840 $GtCO_2$ cumulative over the period 2025–2100 (Hanna *et al.*, 2021).

CDR method	(Fuss *et al.*, 2018) ($GtCO_2$ yr^{-1})		Key updates in literature (2018 to 2021) - note these are often maximum estimates with limited consideration of sustainability or other feasibility factors.
	Potential	Literature	
and storage (DACCS)		& energy demand	Max 30 $GtCO_2$/yr by 2100, cumulative ~800 $GtCO_2$ up to 2100 (Realmonte *et al.*, 2019). The max is "in line with past CDR potential assessments (Chen and Tavoni, 2013, Tavoni and Socolow, 2013, Marcucci *et al.*, 2017, Strefler *et al.*, 2018)". Limit is the rate that DACCS can be ramped up (Realmonte *et al.*, 2019). Optimistic rates seem focused on capture units and not location issues (power, heat) or transport and storage infrastructure. Smith *et al.* (2019a) suggest an upscaling limit of 1.5 $GtCO_2$/yr. Lifecycle assessments highlight DACCS design differences and the need for a low-carbon power and heat supply (Sabatino *et al.*, 2021, Terlouw *et al.*, 2021).
Ocean fertilisation	Extremely limited	0.5–44	A key scientific uncertainty is the need for verification that a significant fraction of the increase in carbon uptake resulting from a stimulated phytoplankton bloom is exported out of the surface waters to deep waters. Legal constraints: International Maritime Organisation, LC/LP, Marine geoengineering amendments.[7]

[7] https://www.imo.org/en/OurWork/Environment/Pages/geoengineering-Default.aspx

5.2 Portfolios of CDR technologies

In practice, 222 $GtCO_2$ yr^{-1} could not be achieved as individual practices can overlap and so are not always additive (Smith *et al.*, 2019b). For example, land dedicated to afforestation would produce a much lower biomass yield for BECCS than dedicated energy crops. Since AR5 and Fuss *et al.* (2018), there have been more assessments of CDR technologies used in combination (Table 4). In recent years, IAMs are including DACCS and EW (e.g. Strefler *et al.*, 2021), however detailed analysis of the trade-offs between technologies within these portfolios is, to our knowledge, not yet available. Recent papers on enhanced weathering include the concurrent increase in soil organic carbon that arises as a side effect of the application of basalt (due to phosphate input) (de Oliveira Garcia *et al.*, 2020, Goll *et al.*, 2021).[8] Analysis of land-based CDR methods are often conducted together with other land management practices that seek to restore or reduce emissions from land rather than remove CO_2 from the atmosphere – this can lead to larger estimates of carbon potential than other CDR-only assessments (e.g. Griscom *et al.*, 2017, Lal *et al.*, 2018, Smith *et al.*, 2019b).

5.3 Limitations on modelling CDR

The representations of technologies and practices within modelling tools are rational and adhere to internally consistent rules. The application of CDR in the real world will be imperfect, subject to compromises and complexities from the sector(s) within which they operate (i.e. agriculture, forestry, conservation, mining, power, transport, industry, and geologic storage) and geographical contexts (i.e. natural resources, economic development, pre-existing technologies, and infrastructures) (Forster *et al.*, 2020, Clery *et al.*, 2021).

[8] Experimental data is needed to confirm the computer simulations of enhanced weathering from these studies. The benefit is only realised when enhanced weathering is carried out in tandem with land uses that enable vegetation growth, ideally with a deep rooting plant to maximise the effect of root exudates. Longer-lived energy crops tend to meet these criteria better than food crops.

Table 4. Assessments of combinations of CDR methods.

Paper	Analysis	CDR methods included	Key findings
Roe *et al.* (2019)	Synthesis of recent literature	Afforestation & Reforestation, Coastal wetlands, SCS, biochar, BECCS	Portfolio without BECCS: Median value 7 $GtCO_2$/yr, range 1.11–22.71. Portfolio with BECCS: Median value 11.3 $GtCO_2$/yr, range 1.51–36.52 (Fig 4).
Lal *et al.* (2018)	Literature review	Afforestation, Agroforestry, Peatlands, Biochar, SCS. Also includes non-CDR land management. No BECCS.	23.8 $GtCO_2$/yr, range 13.6–34.1. Notes caution of double counting (not clear how this is factored into this assessment).
Smith *et al.* (2019a)	Analysis of ecosystem function, Nature's Contribution to People and SDGs	BECCS, Afforestation & Reforestation, EW, SCS, Biochar, wetland restoration	No assessment of combinations of CDR methods. Assessment is for each approach in turn used a standardised qualitative method.
Smith *et al.* (2019b)	Literature review and assessment against land challenges (mitigation, adaptation, desertification, land degradation and food security).	SCS, Biochar, EW, peatland and coastal restoration, BECCS and bioenergy. Also includes non-CDR land management.	No assessment of combinations of CDR methods. Agroforestry and SCS have medium to large benefits across all land challenges. SCS has a large mitigation potential, agroforestry and forest management have a medium mitigation potential, all without adverse effects on other land challenges.
Asibor *et al.* (2021)	Literature based assessment of operational factors (climate, vegetation, soil, water, energy, costs, land, biomass)	BECCS, DACCS, Afforestation, EW, SCS, Biochar	No assessment of combinations of CDR methods. Identifies operational factors to optimise performance of each method, individually. Not spatially explicit (e.g. only three climatic zones) and no synthesis.

Policy design and implementation will determine the potential of CDR. For example, poor environmental governance of biomass production for BECCS could lead to a net emission of carbon to the atmosphere from a BECCS supply chain (Fajardy and Mac Dowell, 2017, Harper *et al.*, 2018). The fate of the captured CO_2 – utilisation in a <50-year lifetime end-product compared to long term storage in suitable geological structures – is critical to the delivery of a net removal of CO_2 from the atmosphere of BECCS and DACCS supply chains (Hepburn *et al.*, 2019). Social, political and institutional barriers to ramping up BECCS are identified as important in case studies in Sweden (Fuss and Johnsson, 2021) and the UK (Forster *et al.*, 2020, Clery *et al.*, 2021) and are often poorly represented in IAMs (Butnar *et al.*, 2020, Forster *et al.*, 2020).

Improvements in scientific understanding of the earth system (for CDR that enhances land and ocean carbon sinks, of broader climate feedback process that may constrain carbon budgets) and of technological innovation (for CDR that includes engineered and/or technical components) would reduce the uncertainty in the maximum potential estimates. The high uncertainty at present is reflected in the breadth of estimated costs per ton of CO_2 removed in the literature. At present, there is limited evidence in the literature with low agreement, meaning we can have only low confidence in the estimates of CDR potential and deliverability. CDR potential substantially impacts the carbon budget and hence the maximum overshoot.

5.4 CDR assumptions in the overshoot pathways

The limits on each type of CDR in each overshoot pathway are summarised in Table 5.

Limits to BECCS should account for other uses of biomass in the energy system. It is therefore appropriate to limit total biomass availability rather than BECCS deployment. A lower bound of 100 EJ biomass would be consistent with conservative pathways identified by Slade *et al.* (2011), while an upper bound of 200 EJ would be consistent with SSP2. The total global supply of sustainable biomass is constrained rather than the level of BECCS, as there are many potential uses of biomass across the energy system (e.g. for low-carbon chemicals and transport fuels). In addition, a dynamic growth constraint limits the BECCS capacity growth in each region to 10%/yr. Emissions associated with dedicated biocrops (e.g. farm carbon losses) are assumed to be 15 gCO_2/MJ.

A lower limit to DACCS of 5 GtCO_2 yr^{-1} would be consistent with the assumptions of Fuss *et al.* (2018), while an upper limit of 20 GtCO_2 yr^{-1} in 2050 and 30 GtCO_2 yr^{-1} in 2100, combined with a cumulative limit of 800 GtCO_2 for the period 2025–2100, would be consistent with the wider literature cited in Table 4. "Low CDR" therefore has much tighter limit on DACCS than "High CDR".

Afforestation and soil carbon sequestration are assumed the same in both CDR pathways. Other land-based approaches are more speculative but could make a substantial contribution and should not be discounted. For "High CDR", an undefined technology ("Other") is assumed to contribute up to 15 GtCO_2/year at a cost of \$500/tCO_2.[9] This technology represents CDR methods whose potentials are less well understood, for example biochar and enhanced weathering. This undefined technology is assumed to be not available in the "Low CDR" assumptions.

Dynamic growth constraints, which limit new capacity as a function of existing capacity, are applied to DACCS and the undefined technology to ensure that growth rates are plausible.

Finally, two overall limits on CDR are applied for the HO and VHO pathways. For the HO pathway, total CDR emission reductions are limited to 25 GtCO_2/year, which is the upper end of the range identified by Fuss *et al.* (2018). For the VHO pathway, total CDR emission reductions are limited to 37 GtCO_2/year, which is the upper end of the range identified by Roe *et al.* (2019).

6. TIAM-UCL assumptions

TIAM-UCL is a global optimisation model that investigates decarbonisation of the global E3 (energy-environment-economy) system.[10] TIAM-UCL allows us to better understand the global costs and benefits of many different decarbonisation options. It also allows us to

[9] All TIAM-UCL costs are in USD in 2005. \$500/tCO_2 in 2005 is equivalent to around \$650/tCO_2 in 2019.
[10] TIAM-UCL documentation is available at: https://www.ucl.ac.uk/drupal/site_energy-models/sites/energy-models/files/tiam-ucl-manual.pdf.

investigate international climate change policies, such as Kyoto, and international issues such as aviation and shipping, which are not possible with a UK model. The model consists of:

- A bottom-up global energy system optimisation model that represents energy service demands across the economy, in the period to 2100 or even further, and calculates the cheapest way to meet these demands while also meeting any emission constraints. Energy service demands are different for each SSP, and SSPs 1, 2 and 5 can be represented at present. The world is split into 16 regions that trade with each other (e.g. USA; Western Europe; UK & Ireland). The evolution of the world's energy system is calculated for 5-year periods until mid-century and 10-year periods after then.
- A climate module that links emissions to global temperature using a number of assumptions about climate sensitivity (the temperature response to both increasing and reducing the atmospheric CO_2 concentration). These assumptions are currently calibrated using outputs from the MAGICC model for RCPs 2.6, 6 and 8.5, but can be changed as appropriate.

Table 5. Summary of global negative emission technology assumptions in TIAM-UCL. All figures are annual resources/emission reductions except where stated otherwise.

	Low CDR	High CDR
BECCS	100 EJ biomass	200 EJ biomass
DACCS	5 $GtCO_2$	20 $GtCO_2$ in 2050, 30 $GtCO_2$ in 2100 800 $GtCO_2$ for the period 2025–2100
Afforestation and soil carbon	Linear increase from zero in 2025 to 4.9 $GtCO_2$ from 2050.	
Other CDR	None	15 $GtCO_2$ from 2050
Overall limit	None	25 (HO pathway) 37 (VHO pathway)

A schematic of data flows is shown in Figure 4. Mitigation efforts can be represented either by constraining GHG emissions or by constraining the temperature rise. Constraints can be applied only in individual periods or across all periods. For example, to prevent the global temperature rise relative to pre-industrial exceeding 1.5 °C, a constraint would be applied in each period, but for an overshoot pathway, the constraint might only be applied in the period for the year 2100.

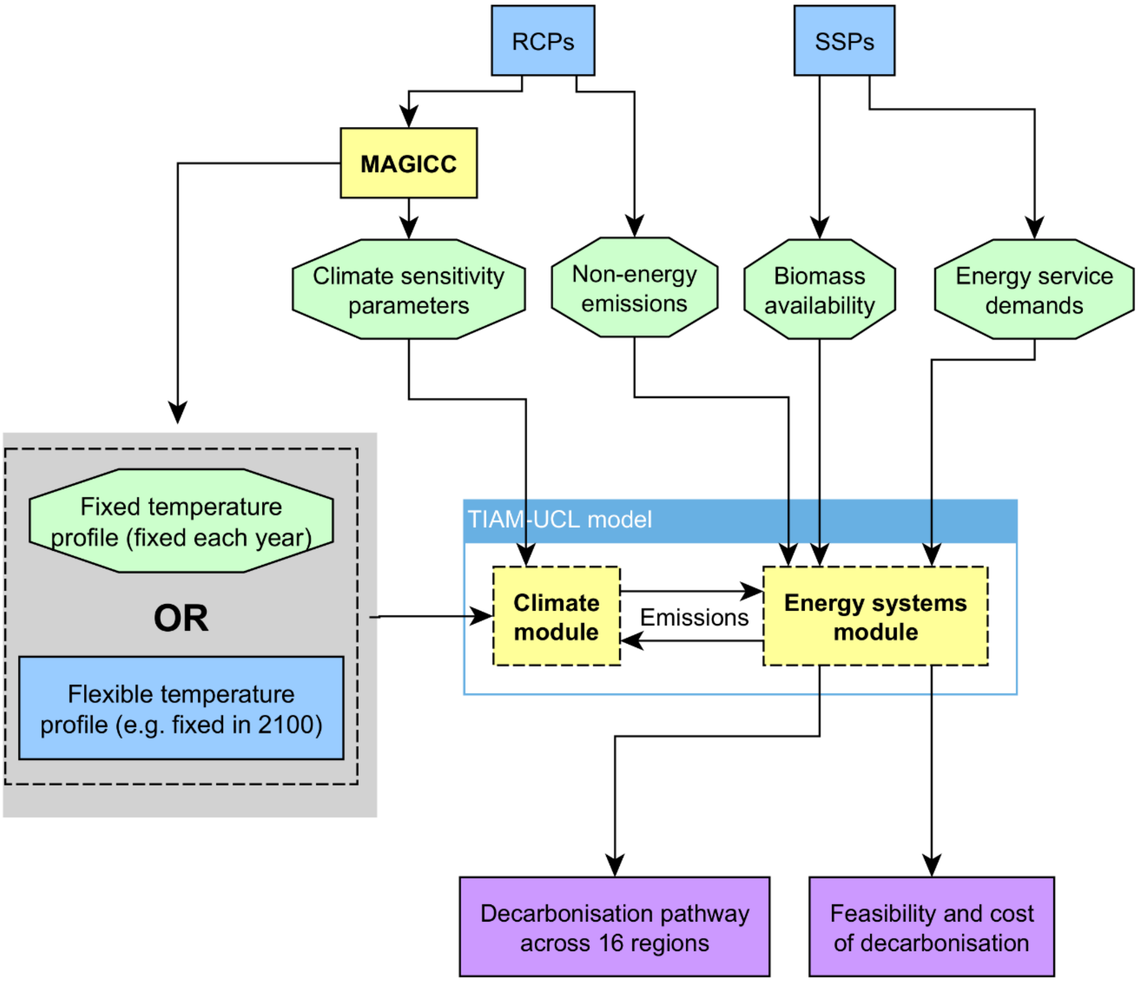

Figure 4. Modelling future climate pathways using RCPs and SSPs in TIAM-UCL.

Total greenhouse gas emissions in TIAM-UCL are estimated using global warming potentials from IPCC AR6 WG1 (Forster *et al.*, 2021) for a 100-year time period (GWP-100), and are summarised in Table 6.[11] These have wide uncertainty bounds. F-gases, indirect

[11] Global Warming Potential (GWP) enables a comparison of the global warming impacts of different gases. It is a measure of the energy the emissions of 1 tonne of a gas will absorb in the atmosphere over a given period of time relative to the emissions of 1 tCO_2.

GHGs (e.g. water vapour; hydrogen) and other SLCPs are not represented in TIAM-UCL except as a constant exogenous climate forcing (see Section 7.1).

Table 6. Global warming potentials for a 100-year time period (GWP-100) used in TIAM-UCL, from IPCC AR6 WGI. Source: Forster *et al.* (2021, Table 7.15).

Species	GWP-100
CO_2	1
CH_4 from fossil fuels	29.8±11
CH_4 from non-fossil sources	27.2±11
N_2O	273±130

6.1 Land use emission assumptions

There is considerable uncertainty regarding the level of global agriculture, land use and forestry emissions. The Global Carbon Project (GCP) has coordinated a cooperative community effort for the annual publication of global carbon budgets since the year 2005.[12] The most recent report from the GCP is the Global Carbon Budget 2020 (Friedlingstein *et al.*, 2020). There are three broad methods to estimate land use emissions:

1. Bookkeeping models. Friedlingstein *et al.* (2020) use three models that track carbon stored in vegetation and soils during land use changes using literature-based response curves.
2. Dynamic global vegetation models (DGVMs). Friedlingstein *et al.* (2020) examine an ensemble of 17 DGVM simulations that account for deforestation and regrowth, vegetation growth, mortality and organic matter decomposition, but do not represent all the impacts of human activities on land.
3. Aggregating national assessments of emissions from managed land. For example, the Food and Agricultural Organization (FAO) records national estimates of land use emissions in its FAOSTAT database.

[12] https://www.globalcarbonproject.org

The global CO_2 budget has been examined in each IPCC assessment report. The IPCC AR6 WGIII land use emission estimate is the average of the three bookkeeping models reviewed in Friedlingstein *et al.* (2020). Global land use, land use change and forestry (LULUCF) CO_2 emissions in 2019 are estimated with a 90% confidence interval to be 6.6±4.6 $GtCO_2$ (IPCC, 2022, p5). For comparison, the DGVM ensemble mean in 2019 is 8 $GtCO_2$, while the FAO estimate is only 1.4 $GtCO_2$ (Dhakal *et al.*, 2022, p223).[13] Note that DGVMs aren't directly comparable to bookkeeping models due to underlying assumptions on carbon stocks.

TIAM-UCL has been calibrated to use LULUCF emissions from the IMAGE model for SSP2-RCP2.6 and SSP2-RCP6 (Riahi *et al.*, 2017). For the period 2000–2020, LULUCF emissions are assumed to be around 3.8 $GtCO_2$, which is substantially lower than but within the error range of the most recent IPCC AR6 estimate.

Regional emissions data from the bookkeeping models are not available to compare with IMAGE data in order to understand the discrepancy. For the overshoot pathways, IMAGE estimates were therefore used under the assumption that the regional share of emissions is correct. IMAGE estimates for SSP2-RCP2.6 were used as that has a similar trend over time to the IPCC AR6 assessment (i.e. little change between 2000 and 2019) (IPCC, 2022). The overall magnitude of LULUCF emissions was not changed to match IPCC AR6 because the assumption lies within the AR6 error range and because the cause of the discrepancy between the estimates, and whether they will continue in the future, is not understood. The land use discrepancy of 3 $GtCO_2$/yr is only around 10% of the 37 $GtCO_2$/yr maximum CDR in the VHO pathway so is not a substantial potential error.

6.2 Afforestation and soil carbon sequestration

Contributions of afforestation and soil carbon sequestration to reducing LULUCF emissions are represented in TIAM-UCL as an exogenous, uncosted reduction in LULUCF emissions in each region. These negative emissions are based on afforestation assumptions in the

[13] China, Russia and the Middle East in particular report much lower emissions to the FAO than are estimated by land use models.

IMAGE SSP2 pathway. Measures are assumed to be implemented from the 2025 period. The magnitude is pathway-dependent:

- NDC pathway: as this has only existing commitments, no future negative emissions are assumed.
- No Overshoot pathway: negative LULUCF emissions increase linearly from zero in 2020 to 4.9 $GtCO_2$/yr from 2040.
- Overshoot pathways: negative LULUCF emissions are delayed by 10 years compared to the NO pathway, with negative emissions increasing linearly from zero in 2030 to 4.9 $GtCO_2$/yr from 2050.

This is consistent with the potential emissions of 2.5–8.6 $GtCO_2$/yr in the year 2050 identified by Fuss *et al.* (2018), and substantially lower than the potential in the wider literature of up to 18 $GtCO_2$/yr.

7. Calibration and evaluation of TIAM-UCL

TIAM-UCL is calibrated to a base year of 2005. This means the modelled energy system in each region is calibrated to actual energy flows in that year and the GHG emissions should be similar to reality. The evolution of the energy system and the resulting emissions after 2005 are calculated by the model and are not calibrated directly. For the period 2005–2020, the climate module atmospheric concentration of CO_2 to 2020 is calibrated to the Mauna Loa annual mean (NOAA, 2022), and the surface temperature to 2020 is calibrated to the IPCC AR6 WG1 best estimate of historical human-caused warming (IPCC, 2021, Fig. SPM.10).

7.1 Climate module calibration

The climate module in TIAM-UCL contains equati ons that model the concentrations of CO_2, CH_4 and N_2O in three steps:

1. It tracks the accumulation of anthropogenic emissions in the atmosphere.
2. It calculates the resulting change in radiative forcing due to emissions accumulation.

3. Temperature changes are calculated from the change in radiative forcing, accounting for transfers of heat between two reservoirs (atmosphere and ocean respectively).

The carbon cycle is represented by a three-reservoir model: (i) atmosphere; (ii) biosphere and upper ocean; and, (iii) lower ocean. There are 4 fluxes between the 3 reservoirs (up and down between atmosphere and biosphere/upper ocean, and up and down between upper and lower ocean). The carbon cycle can handle negative emissions. CH_4 and N_2O are represented using single reservoirs.

The three radiative forcings (CO_2, CH_4 and N_2O) are summed together with an external radiative forcing that represents other greenhouse gases (F-gases, ozone, etc.) and aerosols and cloud impacts that are not explicitly represented in TIAM-UCL. This external forcing is supplied by the user for each year. It can vary by pathway because, for example, pathways with faster decarbonisation are likely to have lower aerosol emissions.

The representation of the temperature change caused by radiative forcing in the climate module of TIAM uses a two-reservoir model for balancing the achieved temperature. One reservoir represents faster processes, such as the surface response and the atmosphere, and a second reservoir represents slower processes, and in particular the deep oceans. The atmospheric temperature changes are calculated by applying the equilibrium climate sensitivity to the radiative forcing and fluxes of heat between the two reservoirs that are calibrated using three coefficients using the equations in Box 1.

Box 1. TIAM-UCL climate module equations to calculate temperature changes

Fast temperature changes: $\Delta T_s(y) = \Delta T_s(y-1) + \sigma_1 (\Delta F(y) - \lambda \Delta T_s(y-1) - \sigma_2 [\Delta T_s(y-1) - \Delta T_L(y-1)])$

Slow temperature changes: $\Delta T_L(y) = \Delta T_L(y-1) + \sigma_3 [\Delta Ts(y-1) - \Delta T_L(y-1)]$

where:

ΔT_s is the globally averaged surface temperature increase above pre-industrial level.

ΔT_L is the deep-ocean temperature increase above pre-industrial level.

σ_1 is the speed of adjustment parameter for atmospheric temperature (or lag parameter).

σ_2 is the coefficient of heat loss from atmosphere to deep oceans.

σ_3 is the coefficient of heat gain by deep oceans.

λ is the feedback parameter.

ΔF is the radiative forcing.

y is the year (and y-1 the previous year).

These relatively simple equations are calibrated to represent the many complex processes in the climate system. To justify this approximation, we need to keep the results of these simplified equations as close as possible to the results obtained by more complex climate models. In order to calibrate the climate module, we can use the results of specific climate models or the ensemble mean resulting from models intercomparison project such as CMIP. The calibration of the module is made offline by minimising over the 2020–2100 period the difference between the TIAM-UCL climate module results and the corresponding results we want to emulate. The optimisation is conducted by sampling a set of parameters included in the equations of the TIAM-UCL climate module. These parameters consist, for example, in fluxes between reservoirs (as presented above), N_2O CH_4 radiative forcing overlap or climate sensitivity. The calibration is conducted for each of the three steps (calculation of atmospheric concentrations, radiative forcing and temperature change). The first two steps (concentrations and radiative forcing) are calibrated to results from the RCP (namely

RCP1.9, 2.6 and 4.5 from the IIASA database) and the global surface temperature change to the AR6 global surface temperature change estimate for the same RCPs.

To be more precise, the λ and the three σ coefficients are calibrated to represent the climate sensitivity obtained from the IPCC AR6 assessment ("AR6") – these are calibrated to the results of AR6 best estimations with a climate sensitivity at 3 °C. Through these parameters, the climate module represents both the strength and the speed of the temperature responses to radiative changes over the 2020 to 2100 period.

The TIAM-UCL representations for the three RCPs are compared with the IPCC AR6 temperature increases in the graphs below. There is very close agreement with the RCP1.9 and RCP2.6 scenarios but poorer agreement at RCP4.5 after 2050.

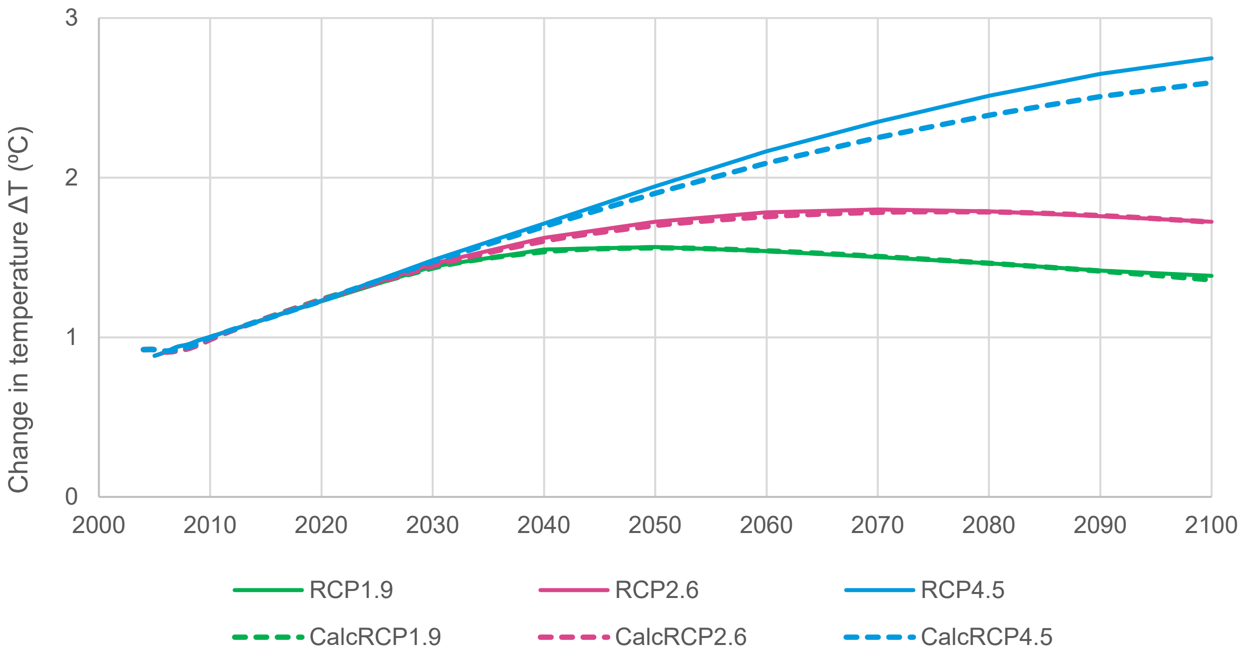

Figure 5. Comparison of TIAM-UCL global surface temperature rise calibration with IPCC AR6. The dashed lines are the simulations from TIAM-UCL.

7.2 Evaluation of TIAM-UCL emission projections

An NDC pathway in which only existing NDCs are assumed to be implemented was used to define the pathways for the period 2005–2020. In this pathway, emissions are not mitigated and warming of almost 3 °C occurs by 2100. The decarbonisation pathways use the NDC pathway to 2020 then diverge according to the pathway assumptions.

The historic greenhouse emissions in the TIAM-UCL NDC pathway are compared to the literature in Table 7. CO_2 emissions are consistent with other studies. CH_4 emissions are lower throughout the period, while N_2O emissions are consistent. Overall, TIAM-UCL emissions are up to 5% lower but close to broadly consistent with estimates from the literature, and well within the uncertainty bound for 2019 in IPCC AR6 of ±12.4 $GtCO_2$.

Table 7. Comparison of TIAM-UCL greenhouse emissions with estimates from the literature. All figures have units $GtCO_2e$. IPCC AR6 data are from Dhakal *et al.* (2022) and Global Carbon Project data are from Friedlingstein *et al.* (2022).

GHG	Year	IPCC AR6	Global Carbon Project	Minx *et al.* (2021)	TIAM-UCL
CO_2 FFI	2010	34	33	34	33
	2015		36	36	35
	2019	38	37	38	37
CO_2 LULUCF	2010	5	4		4
	2015		5		5
	2019	7	4		5
CH_4	2010	9		10	9
	2015			10	9
	2019	11		11	8
N_2O	2010	3		2	4
	2015			3	4
	2019	3		3	3
Total (averaging literature estimates)	2010	51			50
	2015	54			52
	2019	56			53

The NO pathway, in which the global temperature does not exceed 1.5 °C, was created in TIAM-UCL as a counterfactual to the overshoot pathways. CO_2 emissions for the NDC and NO pathways are compared with IPCC emission pathways in Figure 6. As would be expected, the NDC pathway is consistent with the IPCC Current Policies range, and the NO pathway is at the lower end of the IPCC C1 category range. TIAM-UCL has higher negative emissions in the NO pathway than most pathways in the IPCC scenarios database.

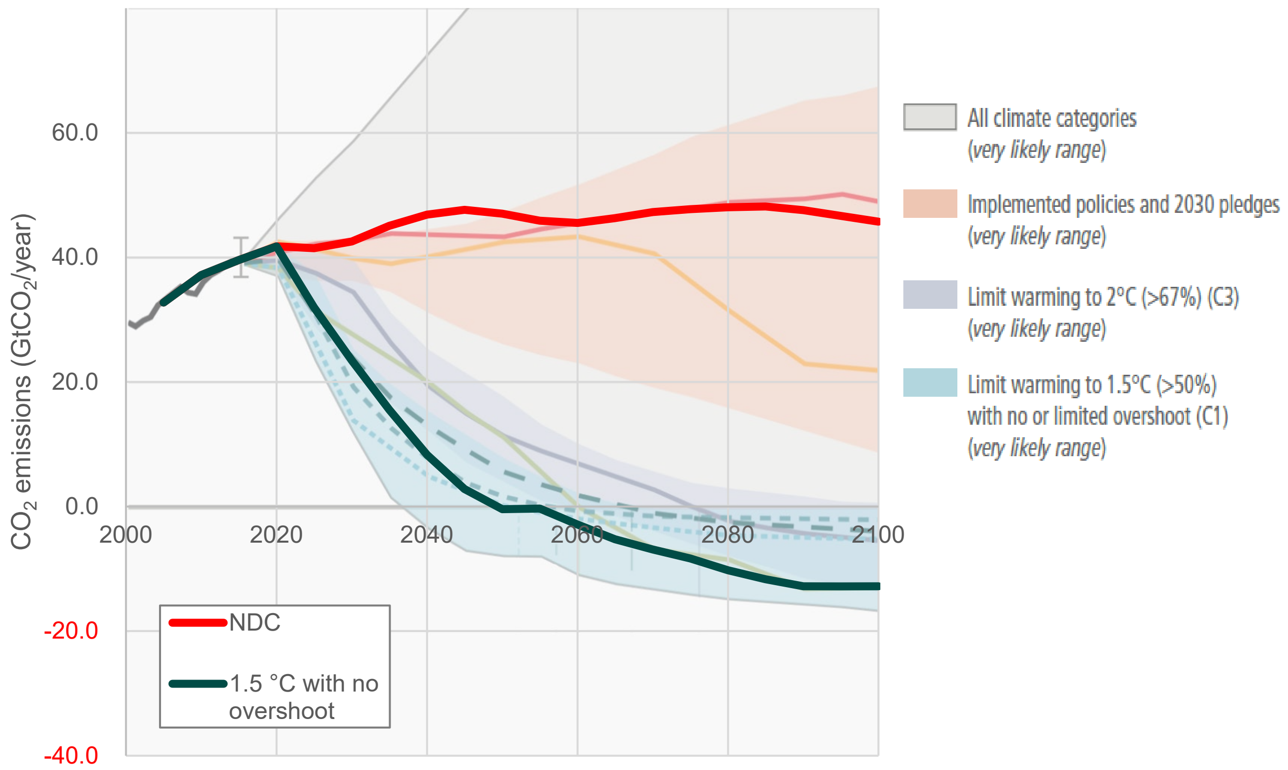

Figure 6. TIAM-UCL CO_2 emissions for the NDC and 1.5 °C pathways compared with IPCC AR6 WGIII CO_2 emission projections emission ranges for scenario categories C1–C8 (shaded areas) and Illustrative Pathways (lines). The IPCC part of the graph is based on Figure 3.6 Panel (b) in Riahi *et al.* (2022).

The IPCC AR6 report defines carbon and total greenhouse gas budgets as the remaining cumulative emissions from the year 2020 until negative emissions are achieved. The budgets for the NDC and NO pathways from TIAM-UCL are compared with IPCC AR6 budgets in Table 8. The NO pathway TIAM-UCL budget is slightly higher, but balanced by substantially larger negative emissions after net zero CO_2 is achieved. This reflects that the

TIAM-UCL budget is for a no overshoot pathway, while the IPCC budget also includes some pathways with a small overshoot. The NDC pathway sits between IPCC categories C6 and C7, which limit warming to between 3 °C and 4 °C, respectively. The NDC pathway is similar to the IPCC "Current Policy" scenario as it examines the consequences of no emission reduction policies beyond those currently announced; "Current Policy" is within IPCC category C7. As the budgets for both NDC and NO pathways are broadly consistent with IPCC budgets for equivalent scenarios, this suggests that the pathways produced by TIAM-UCL are consistent with those from the international community.

Table 8. Comparison of TIAM-UCL CO_2 budget and net-negative emissions with IPCC budget estimates. The CO_2 budget is from 2020 until net-zero CO_2 is achieved (1.5 °C) or 2100 (NDC). The net-negative emissions are from the year when net-zero CO_2 is achieved. The NO pathway is consistent with IPCC category C1, while the NDC pathway is between IPCC categories C6 and C7.

Pathway	CO_2 budget to net zero CO_2		Net-negative CO_2 emissions after net zero	
	IPCC AR6	TIAM-UCL	IPCC AR6	TIAM-UCL
NO	510	536	-200	-397
NDC	2790/4220	3732	n/a	n/a

8. Developing the overshoot pathways in TIAM-UCL

Each overshoot pathway follows the NDC pathway until 2030 and then diverges before returning to 1.5 °C warming in 2100:

- **Low Overshoot**: a cost-optimal pathway using the "Low CDR" assumptions, in which a maximum temperature of 1.6 °C is reached at about 2050.
- **High Overshoot**: a cost-optimal pathway using "High CDR" assumptions, in which a maximum temperature of 1.8 °C is reached later, at about 2060.
- **Very High Overshoot**: a higher overshoot using the "High CDR" assumptions that is achieved by: (i) heavily discounting the future, at a range of 10%, to minimise the cost of CDR in the second half of the century; then, (ii) running the same pathway with the

normal discount assumptions and with CO_2, CH_4 and N_2O emissions fixed to the pathway developed in (i). A maximum temperature of 1.9 °C is reached at about 2065.

The temperature profiles of these pathways are compared with the IPCC AR6 scenario database pathways in Figure 7. In the period to 2040, they are consistent with the IPCC pathways. The two High Overshoot pathways do not fit well into any of the IPCC AR6 categories as they have high emissions in the period to 2050 and high negative emissions afterwards.

8.1 Comparison with IPCC overshoot pathways

Of the 5367 temperature pathways in the IPCC AR6 database, only 24 are "high" overshoot pathways in which the global temperature exceeds 1.8 °C before returning to 1.5 °C by 2100, and only 3 of these exceed 1.9 °C. These are compared with the three overshoot pathways from this study in Figure 8. Global temperature tends to rise for longer in the VHO pathway than in the IPCC studies due to a longer delay in reducing global emissions. While most pathways peak in 2050–2060, the VHO pathway does not peak until about 2065.

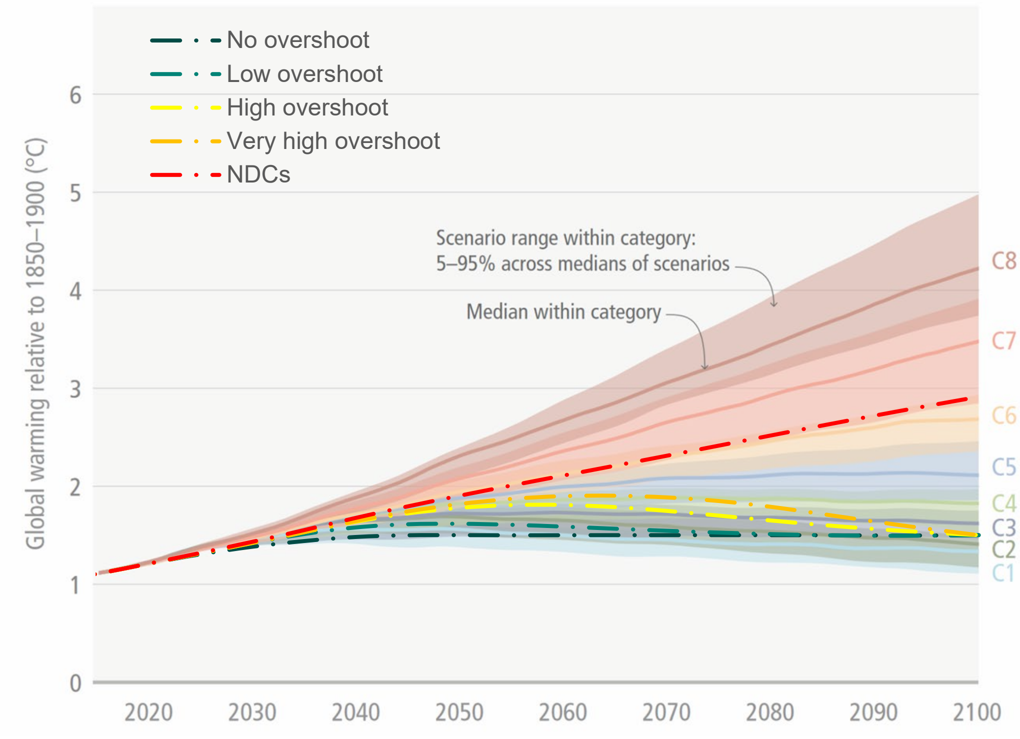

Figure 7. Temperature profiles of the TIAM-UCL AR6 pathways compared with IPCC AR6 categories and pathways from Figure 3.11 in Riahi *et al.* (2022).

The IPCC vetted these pathways and identified only 1202 that met quality criteria (coherence with historic emission trends, near-term plausibility and sufficient data to be classified according to temperature) (Riahi *et al.*, 2022). Of these remaining pathways, only 8 are high overshoot pathways and none exceed 1.85 °C, which is lower than the VHO pathway in this study. In each of these pathways, 1.5 °C is exceeded for at least 60 years, and 1.7 °C for at least 30 years. High overshoot is not a short-term phenomenon.

The overall greenhouse gas emission profiles are compared to the IPCC AR6 WGIII pathways in Figure 9. The three overshoot pathways assume global decarbonisation efforts are generally unsuccessful until 2030 (2040 in the Very High Overshoot pathway), but that a rapid global decarbonisation effort then reduces emissions and invests heavily in CDR technologies in the second half of the century. All three overshoot pathways lie outside of the IPCC scenario categories. Even the IPCC C3 category (below 2 °C) assumes that decarbonisation will occur after 2020 at a constant but slower rate than for the three overshoot pathways. Near-term global failure followed by long-term success is not considered by IPCC AR6 WGIII.

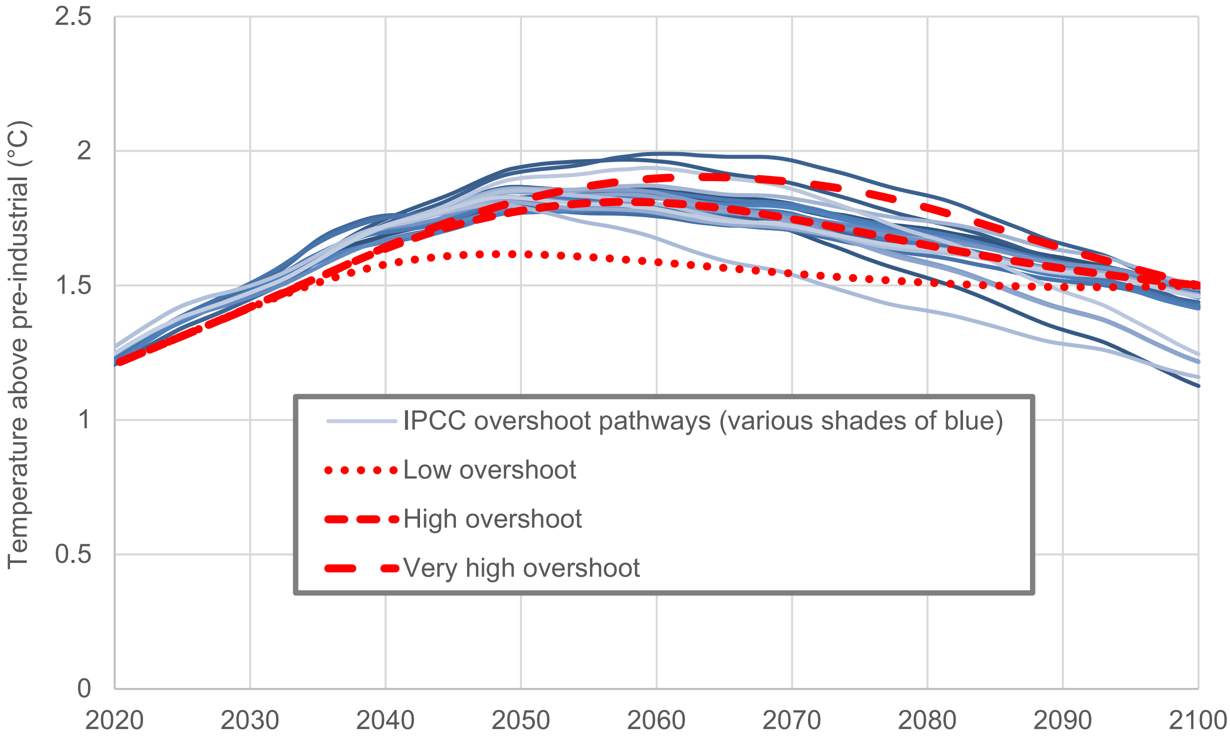

Figure 8. Comparison of high overshoot pathways (>1.8 °C) in the IPCC AR6 scenarios database with the three overshoot pathways developed in this study. IPCC pathways are blue and the pathways in this project are red.

8.2 Emission profiles in the overshoot pathways

The global reduction in GHG emissions is an aggregate of emissions reductions across world regions and economic sectors. Figure 10 shows that reductions occur at a relatively even pace in all regions in the Very High Overshoot pathway, with divergence primarily occurring as a result of varying contributions to negative emissions after 2060. Emissions in all regions are stable after 2080.

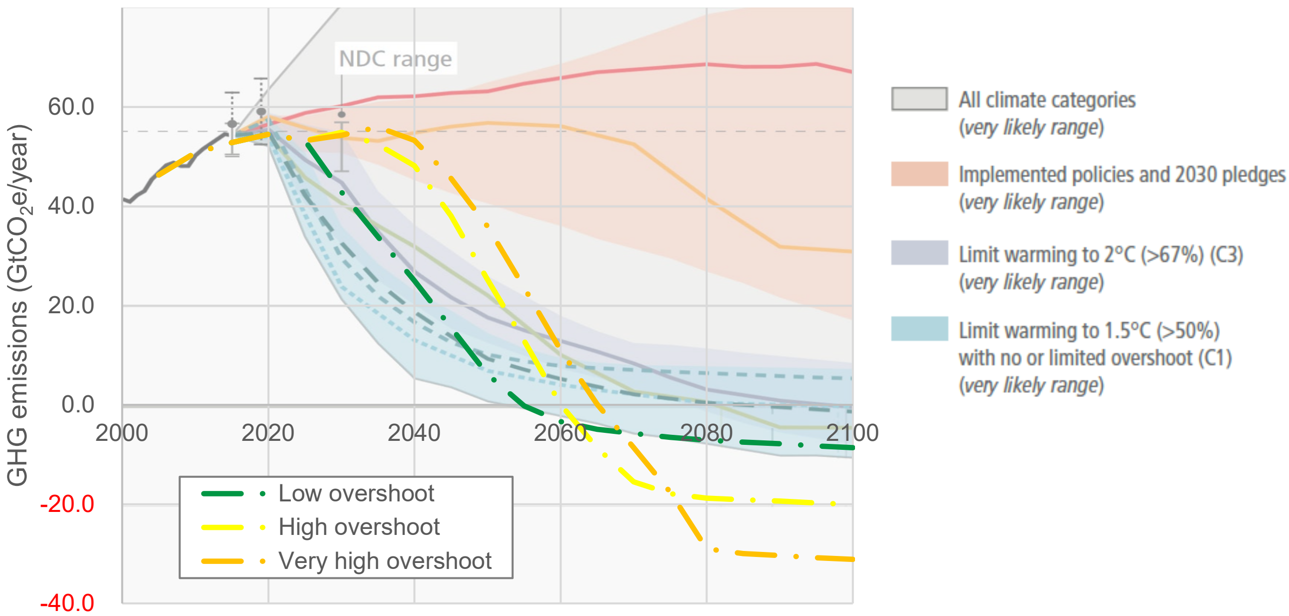

Figure 9. TIAM-UCL GHG emissions for the three overshoot pathways compared with IPCC AR6 WGIII emission ranges for scenario categories C1–C8 (shaded areas) and Illustrative Pathways (lines). The IPCC part of the graph is based on Riahi *et al.* (2022, Figure 3.10).

Table 9 compares CDR in each of the overshoot pathways with suggested limits from the literature. The LO pathway is conservatively within upper literature projections for all technologies except BECCS, for which TIAM-UCL uses a 100 EJ biomass limit rather than a direct limit on BECCS. The two High Overshoot pathways peak at 25 and 37 $GtCO_2$/year negative emissions, which are substantially lower than the limits on individual technologies in the wider literature. The technical potential for CDR is very high but a judgement must be made of the extent to which economic, environmental and regulatory barriers will restrict the overall potential, which was the aim of the three cited studies in Table 9. The level of CDR in the overshoot pathways developed for this report are consistent with these three studies. Annex 2 explores whether these levels might be achievable in practice. If an overshoot were to occur and the required levels of CDR were not achieved, then the global temperature would stay above 1.5 °C in the long term and might even continue rising.

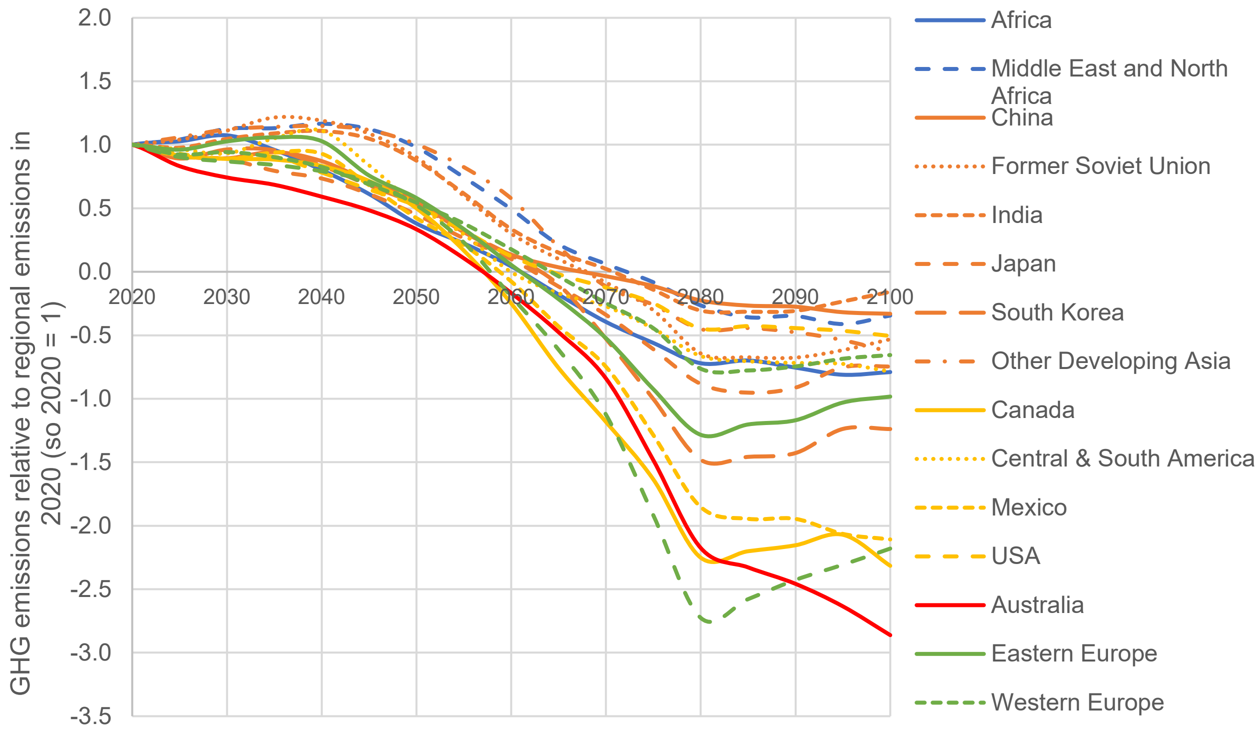

Figure 10. Evolution of GHG emissions by world region in the VHO pathway, normalised to the emissions in 2020 in each region.

Table 9. Comparison of TIAM-UCL emission reductions from CDR in the three overshoot pathways, in the year that they peak, with the literature. Units: $GtCO_2$/yr.

Literature sources: Fuss *et al.* (2018) suggested limits are upper values from Table 3. Wider literature limits are also documented in Table 3. The Roe *et al.* (2019) and Lal *et al.* (2018) combined ranges are documented in Table 4.

	BECCS	Afforestation	DACCS	Other	Total
Low Overshoot	6.2	4.9	5.0	0.0	16
High Overshoot	4.4	4.9	0.7	15.0	25
Very High Overshoot	7.8	4.9	9.3	15.0	37
Fuss suggested limits	5.0	8.6	5.0	6.0	25
Wider literature limits	85	18	30	179	312
Roe combined range					2–37
Lal combined range					14–34

9. Conclusions

The global surface temperature rise is kept below 1.5 °C in only a small proportion of the pathways in the IPCC AR6 scenarios database. Many more pathways overshoot but then return below 1.5 °C by the end of the century.

This annex describes the creation of three overshoot pathways characterised by different peak temperatures: LO (1.6 °C), HO (1.8 °C) and VHO (1.9 °C). The magnitude of an overshoot (i.e. the peak temperature) depends on the climate sensitivity and the availability of CDR technologies. Each pathway was based on SSP2 and assumed the IPCC AR6 best estimate of the climate sensitivity but had quite different CDR technology availability. The potential for CDR is very uncertain and examined in detail in Annex 2.

The overshoot pathways were created using the TIAM-UCL integrated assessment model. The model was calibrated to the IPCC AR6 climate sensitivity and accounted for positive feedbacks such as permafrost melt in each overshoot pathway. The historic emissions projected by TIAM-UCL were broadly consistent with actual emissions to 2019, and the NO and NDC pathways produced by the model were consistent with their respective IPCC AR6 pathways, giving confidence in the quality of the overshoot pathways.

The VHO has a higher peak temperature than any of the pathways in the IPCC AR6 database. The higher temperature is achieved by assuming global emissions continue at a high level until 2040 before substantial reductions commence, which is later than in most IPCC database pathways. A higher overshoot is unlikely to be plausible. The natural and human system impacts of the VHO pathway should be more substantial than for most overshoot pathways, so it is an appropriate pathway for detailed analysis in this study.

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Quality assurance

Each part of the work was reviewed by a member of the CS-N0W consortium. The implementation of the modelling was reviewed by Paul Dodds (UCL). The climate sensitivity and positive feedbacks reviews were reviewed by Garry Hayman (UKCEH) and Chris Huntingford (UKCEH), respectively. Isabela Butnar (UCL) reviewed the CO_2 removal potential. All of the insights were additionally reviewed in internal workshops with UK Government stakeholders and a range of consortium experts.

UK Government

CS-NOW

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