Global consequences of climate overshoot pathways

Final report

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CS-NOW

Climate services for a net zero resilient world

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Key messages from this report

1. Most IPCC AR6 scenarios "overshoot" a global surface air temperature rise of 1.5 °C. Global warming could be subsequently reduced to 1.5 °C at a later date (e.g. 2100) but the atmospheric CO_2 removal required would be difficult to achieve.

Atmospheric CO_2 removal is achieved using afforestation, enhanced weathering, storing biomass carbon in soils or underground, or directly capturing atmospheric CO_2. It would be challenging to deliver the required infrastructure or to obtain sufficient sustainable biomass given the competition for land for food production and habitat conservation.

2. Temporarily overshooting 1.5 °C would have a negative global economic impact, particularly for low-income countries.

A benefit-cost analysis of damage and mitigation costs, and co-benefits, shows that overshooting 1.5 °C would likely have higher overall global costs than not overshooting 1.5 °C. Higher overshoots would cause higher global costs. The impacts on low-income countries would be greater than on high-income countries.

3. Even warming of 1.5 °C would have negative impacts. Overshooting 1.5 °C would worsen the impacts.

Even if warming were to reach but not exceed 1.5 °C, sea levels would rise, there would be more frequent and intense droughts and floods, and biodiversity would reduce.

Overshooting 1.5 °C would intensify these changes for the time that the global temperature was above 1.5 °C. Floods and droughts would adversely affect water and sanitation, mortality and morbidity from heat waves would increase and biodiversity losses would be much higher. Adaptation could reduce these impacts, but avoiding these impacts would cost less and be more effective than implementing adaptation measures.

4. Impacts can be minimised by keeping the global temperature as low as possible.

The higher the temperature rise above 1.5 °C, and the longer the duration of high temperatures, the greater the impacts would be. Sea levels would rise faster, and for longer, causing greater flooding. Overshoot impacts would be amplified. The risk of triggering climatic tipping points with deleterious global consequences would be higher.

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, £5.5 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 improves 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)**.

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.

This final report summarises the findings from the study. Six annexes present the technical evidence that underpin this 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.

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Acronyms

AMOC	Atlantic Meridional Overturning Circulation
AR6	IPCC's Sixth Assessment Report (2021-2022)
BECCS	Bioenergy with Carbon Capture and Storage
CDR	Carbon Dioxide Removal
CGE	Computable General Equilibrium
DESNZ	Department for Energy Security and Net Zero
DACCS	Direct Air Carbon Dioxide Capture and Storage
ENGAGE	"Environmental Global Applied General Equilibrium" model at UCL
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GSAT	Global Surface Air Temperature
HO	"High Overshoot" pathway
IAM	Integrated assessment models
IPCC	Intergovernmental Panel on Climate Change
ISIMIP	The Inter-Sectoral Impact Model Intercomparison Project
LO	"Low Overshoot" pathway
NO	"No Overshoot" pathway
RCP	Representative Concentration Pathway
SDG	Sustainable Development Goals
SSP	Shared Socioeconomic Pathway
TIAM-UCL	TIMES Integrated Assessment Model at UCL
UKESM	UK Earth System Model
VHO	"Very High Overshoot" pathway

Executive Summary

Background

There is still a focus on avoiding the most damaging consequences of climate change by limiting the global surface air temperature rise to 1.5 °C above pre-industrial temperatures, in line with the Paris Agreement in 2015. However, this goal is achieved in only a small proportion of the pathways in the IPCC Assessment Report 6 (AR6) scenarios database. Many more pathways overshoot but then return below 1.5 °C by the end of the century. If an overshoot of 1.5 °C were to occur, atmospheric carbon dioxide removal methods could be subsequently deployed to reduce the global temperature to acceptable levels.

This report examines the feasibility of achieving the required atmospheric CO_2 removal in such an overshoot pathway, the economic implications of an overshoot, and the potential consequences for natural and human systems. We compare these with a counterfactual pathway in which the peak temperature does not exceed warming of 1.5 °C. We developed three overshoot pathways with peak temperature increases of 1.6 °C, 1.8 °C and 1.9 °C, respectively, with each returning to 1.5 °C by the year 2100. We focus our impacts analysis on the "Very High Overshoot" pathway with a peak temperature of 1.9 °C.

Is the required level of atmospheric CO_2 removal achievable?

To reduce the global temperature, rise back to 1.5 °C by 2100 in an overshoot pathway, it is necessary to remove substantial amounts of greenhouse gases (GHGs) from the atmosphere – up to 38 $GtCO_2$ per year for the "Very High Overshoot" pathway. Up to 24 $GtCO_2$ per year would be needed for our "No Overshoot" pathway that does not exceed 1.5 °C, but around 15–20 $GtCO_2$ per year is common in IPCC AR6 database scenarios.

Most strategies focus on carbon dioxide removal (CDR) as CO_2 has a long lifetime in the atmosphere. About 2 $GtCO_2$ per year of CDR occurs today by afforestation, but this is offset by emissions from deforestation. Other CDR methods include: (i) changing land management methods to increase carbon in soils; (ii) enhanced weathering; (iii) creating biochar; (iv) generating electricity or fuel using biomass from bioenergy crops with carbon capture and storage (CCS) used to sequester the CO_2 underground; and (v) direct air CO_2 capture with CCS.

It is technically feasible to achieve the level of atmospheric CO_2 removal required for the "Very High Overshoot" pathway, but our analysis suggests that it is unlikely to be achieved in practice for four reasons:

1. The high level of CCS technologies that our analysis indicates would be needed to store atmospheric CO_2 underground would be challenging to deliver.
2. The afforestation and availability of sustainable biomass feedstock that we need to include in our overshoot pathways to reduce warming after an overshoot are probably overly optimistic. Many pathways submitted to the latest Intergovernmental Panel on Climate Change (IPCC) assessment report (AR6) include similarly optimistic levels of afforestation and biomass use.
3. There will be competition for land between food production, habitat conservation and land used for CDR (e.g. afforestation, energy crops for BECCS, peatland restoration). In every region, the most appropriate selection of CDR methods might achieve less carbon removal but meet a broader set of societal objectives (e.g. improved biodiversity, flood alleviation, urban heat adaptation). CDR will not be maximised in many locations as it will be only one of many priorities for land use and other priorities will entail different land uses, with lower CDR.
4. Cost uncertainty for CDR methods leads to large variations in the estimates of the proportion of CDR they might deliver over time and means of securing near term finance is challenging.

Economic implications of an overshoot

The economics of climate change depend on: (i) the costs of damages caused by climate change and adaptation measures; (ii) the costs of mitigating GHG emissions, primarily from the energy system; and (iii) co-benefits realised by mitigating emissions.

Damage costs are highly uncertain. Estimates of damage costs based on observed weather changes as the climate has warmed to date are far higher than previously projected using process models. Moreover, even observed damages could underestimate the substantial damages caused by some earth system tipping points. This means that climate change damage costs are very likely to be higher, and perhaps much higher, than previously thought.

We carried out a benefit-cost analysis of temporarily overshooting that included damage and mitigation costs, and co-benefits. All three of our overshoot pathways have higher overall global costs than keeping the global temperature rise below 1.5 °C. The impact on low-income countries is greater than on high-income countries. The only scenarios in which overshooting is lower cost assume very low damage costs (contradicting observed costs), no co-benefits (assuming reducing urban air pollution has no value) and a high future discount rate (an ethical judgment that future generations are much less important than the current population).

All regions of the world could benefit economically from earlier decarbonisation. Not overshooting 1.5 °C could lead to higher global economic growth over the period 2020–2050 as a result of earlier investment in increased energy and material efficiencies that have positive long-term benefits for economies across the world. The number of people living in extreme poverty is expected to decline substantially from around 700 million in 2020 to around 130–160 million in 2050 in all of our pathways.

Natural system impacts of an overshoot

We examined the potential impacts of overshooting on the Earth system by comparing the "Very High Overshoot" and "No Overshoot" pathways in the UK Earth System Model (UKESM). Widespread increases in land temperature simulated at the middle of the century during the "Very High Overshoot" pathway return to the same levels as in the "No Overshoot" pathway by the end of century in our simulations, giving us confidence that the global surface air temperature would recover from a climate overshoot if the atmospheric CO_2 concentration were sufficiently reduced.

Arctic Sea ice loss is significantly higher in the overshoot pathway but starts to recover by 2100 as the global temperature reduces in our UKESM simulations. An overshoot could reduce long-term precipitation in the tropics, particularly in the Sahel and Indian monsoon regions, but further investigations are required to explore this insight and to understand whether changes are irreversible.

Overshooting 1.5 °C substantially increases the risk of wildfire and biodiversity losses. The risk of catastrophic wildfires could increase, especially in regions already vulnerable to wildfires, if the overshoot were to exceed 1.5 °C of warming for an extended period. Overshooting 1.5 °C could greatly affect biodiversity. There is moderate risk of species loss at 1.5 °C of warming but the risk doubles to high or even very high levels with 2 °C of warming. Insects (which underpin many ecosystem functions) have the lowest tipping point (in many areas at 1.5–2 °C), followed by plants (2–3 °C) and then vertebrates (> 3 °C). However, some parts of Africa and Amazonia have a lower tipping point (< 1.5 °C) than the overall average. Irreversible extinctions would be much more likely in an overshoot.

Some natural system tipping elements may have been triggered already, for example the West Antarctic ice sheet. There are early indications that other tipping points for the Greenland ice sheet, the Amazon rainforest, and the Atlantic Meridional Overturning Circulation (AMOC) are being approached. For ocean acidification, sensitive regions such as the Arctic will pass critical chemical thresholds even below 1.5 °C warming.

Other tipping elements might pass their thresholds in an overshoot as global warming approaches 2 °C: warm water corals, boreal permafrost, Barents Sea Ice, Labrador-Irminger seas/Subpolar gyre convection and mountain glaciers. Some important global tipping points such as the AMOC are unlikely to occur if the global temperature rise is kept below 2 °C. The triggering temperature for each tipping point is uncertain so is represented by a temperature range in the literature. It is also unclear whether the risk of causing a tipping point would reduce if the threshold temperature were passed for only a short period during a temporary overshoot, or if the trigger could be a single extreme weather year.

Human system impacts of an overshoot

Human system impacts of overshoot are more difficult to project than natural system impacts, as they depend both on changes to the natural system and the evolution of human systems, so the analyses in this study have substantial uncertainty.

Coastal flooding affects food production through salination while disasters cause infrastructure and livelihood damage, and loss of tourism. Impacts of flooding will increase over the next century as sea levels rise, so would be higher for overshoot pathways.

Terrestrial precipitation is projected to vary in complex ways with global warming. More intense storms, floods and droughts are expected that will affect agriculture, drinking water and sanitation. Even where moderate floods may reduce in magnitude, larger extreme events would likely increase in frequency and magnitude. These would start to reduce in magnitude as the temperature were reduced. Irrigation water needs for agriculture would increase substantially in some key production areas, affecting groundwater. Increased flooding in some areas would damage infrastructure, disrupt water and sanitation services and jeopardise water quality. Drought would affect water supplies and sanitation.

In contrast, impacts on land food production from an overshoot would be relatively smaller, but there would be lower food production and hence GDP in Asia in particular. Changes in ocean temperature would cause a redistribution of consumer fish towards the poles, with a loss of biomass at the equator and to a lesser extent at the poles. Fishing communities in tropical areas in particular would have adverse impacts on their livelihoods.

Overshooting would increase the frequency and intensity of heatwaves, which would increase heat-related mortality and morbidity unless the population were to acclimatise and additional cooling measures such as air conditioning were adopted. Food and water insecurity would increase the risks from heat exposure. There would be economic impacts from the loss of labour due to heat stress. Higher temperatures would expand the spread of many vector-borne diseases to more northerly latitudes.

Mitigating GHG emissions in a "No Overshoot" pathway would reduce air pollution, which would be particularly valuable in Asia where many cities have poor air quality. On the other hand, increased energy demand for cooling including air conditioner use in an overshoot could place considerable strain on the electrical grid infrastructure of middle and even high-income countries, increasing the risk of blackouts and consequent health impacts. This risk would be amplified by lower production from thermal and nuclear power plants due to lower availability of cooling water, potentially lower solar PV generation, reduced transmission capacity in summer and increased distribution infrastructure failure. Higher climate change is expected to increase energy insecurity and access to clean energy services.

Migration has a range of drivers including some made worse by climate change. Flooding is a key driver, but temperature rise and precipitation changes are also important. Most displacement to date has occurred within countries, often from rural to urban areas, rather than across borders. The likelihood of migration depends on the level of investment in adaptation measures, the characteristics of the population, and the strength of local communities and institutions. It is very difficult to assess with any confidence the extent to which climatic changes have caused migration to date. It is even more difficult to project future changes as these depend on both uncertain future weather patterns and socioeconomic, cultural and political factors.

1. Introduction

Although there is still a focus on avoiding the most damaging consequences of climate change by limiting the global surface air temperature (GSAT) rise to 1.5 °C above pre-industrial temperatures, in line with the Paris Agreement in 2015, this goal is achieved in only a small proportion of the pathways in the IPCC Assessment Report 6 (AR6) scenarios database. Many more pathways overshoot but then return below 1.5 °C by the end of the century.

While most governments have committed to the 1.5 °C target, there is scepticism that the global rate of emission reductions that is required can be achieved sufficiently quickly. If an overshoot of 1.5 °C were to occur, atmospheric carbon dioxide removal methods could subsequently be used to reduce the global temperature to acceptable levels.

In this report, we consider the consequences of such a temporary overshoot. We define overshoot pathways, in Section 2, then consider whether the removal of CO_2 from the atmosphere that would be required to reduce the global temperature could feasibly be achieved in Section 3. We quantify the economic consequences of overshooting 1.5 °C in Section 4, including on short-term GDP across world regions. In Sections 5 and 6, we analyse the potential natural and human system impacts of overshooting 1.5 °C in detail. We summarise our principal conclusions in Section 7.

1.1 Evidence annexes

This report is supported by six evidence annex reports:

- Annex 1: Development of overshoot pathways.
- Annex 2: The feasibility of deploying CDR at the required rate in overshoot scenarios.
- 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 almost 900 literature sources are cited. This report summarises the findings from the annexes. Rather than citing the literature in this report, we instead refer to annex sections using the nomenclature "**(§Annex-Section)**", so **(§2-2.3)** refers to Annex 2, Section 2.3.

1.2 Nomenclature in this report

Many studies in the literature are based on scenarios developed to inform IPCC analyses:

- Shared Socioeconomic Pathways (SSPs) are scenarios of projected socioeconomic global changes up to 2100.
- 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}).

The IPCC has a set of representative SSP/RCP combinations that have received detailed analysis **(§1-2)**, and many studies of climate change impacts examine these scenarios.

Throughout this report we specify the GSAT in terms of the increase above the pre-industrial period temperature, in degrees Celsius (°C), in a similar way to the IPCC. We refer to it as the global temperature rise or warming in this report.

2. Definition of temporary overshoot pathways

We have developed four future climate pathways that vary according to the *peak* global temperature rise that is reached:

1. "No Overshoot" (NO), in which the global temperature rise does not exceed **1.5 °C**.
2. "Low Overshoot" (LO), in which the global temperature rise peaks at **1.6 °C** in about 2060 before returning to 1.5 °C by the year 2100.
3. "High Overshoot" (HO), in which the global temperature rise peaks at **1.8 °C** in about 2065 before returning to 1.5 °C by the year 2100.

4. “Very High Overshoot” (VHO), in which the global temperature rise peaks at **1.9 °C** in about 2065 before returning to 1.5 °C by the year 2100.

2.1 Drivers of global temperature rise in an overshoot

The peak temperature of an overshoot pathway depends on: the magnitude of anthropogenic greenhouse emissions; the sensitivity of the climate to those emissions; and whether rising temperature causes additional greenhouse gas emissions (e.g. via permafrost melt). For a temporary overshoot pathway in which the global temperature returns to 1.5 °C, the peak temperature also depends on the achievable rate of carbon dioxide removal (CDR) from the atmosphere. All of these have substantial uncertainties.

The most common metric for climate sensitivity is the Equilibrium Climate Sensitivity (ECS), which 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 **(§1-3)**. The IPCC AR6 estimate of the “likely” range (66% probability) of the Earth’s ECS is very wide at 2.5–4 °C, with a best estimate of 3 °C. Many of the most detailed earth system models have a substantially higher ECS and the reasons for this are not well understood. For example, the UK Earth System Model, which we used to investigate our overshoot pathways in this study, has an ECS of 5.4 °C, so it was necessary to use artificially low CO_2 concentrations to reproduce the VHO and NO pathways in that model (see Section 5.1 for more details). If the climate sensitivity has been underestimated then the peak temperature could be substantially higher than assumed in this study for the same carbon budget.

About half of the anthropogenic CO_2 released to the atmosphere in the past has been sequestered by vegetation or in the oceans. However, further global warming would lead to the release of CO_2 and methane from permafrost thaw and methane from wetlands, and these positive climate feedbacks would accelerate climate change **(§1-4)**. To offset them, a reduction in the global anthropogenic carbon budget of around 100 $GtCO_2$ for the NO pathway and 120 $GtCO_2$ for the VHO pathway would be needed. Other positive climate feedbacks such as increased fires, causing tree death, biomass and soil carbon loss would further reduce the available anthropogenic carbon budget for a temporary overshoot.

2.2 Modelling the overshoot pathways

We developed the three overshoot pathways and the counterfactual NO pathway using the TIAM-UCL integrated assessment model. TIAM-UCL is a global optimisation model that investigates decarbonisation of the global E3 (energy-environment-economy) system. It enables 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 GHG emissions. It minimises the global cost of meeting our energy demands, both now and in the future, subject to meeting our environmental targets.

The principal difference between the three overshoot pathways was the assumed level of carbon dioxide removal (CDR) from the atmosphere **(§1-5)**, which is reviewed in Section 2. We used different limits on CDR interventions for each of our overshoot pathways as summarised in Table 1 **(§1-6)**.

We calibrated TIAM-UCL to the IPCC AR6 best estimate of the climate sensitivity of 3 °C and accounted for permafrost melt and wetlands positive climate feedbacks in each pathway **(§1-7)**. Each pathway was based on the SSP2 "middle-of-the-road" socioeconomic pathway to enable comparisons of the overshoot pathways with other studies. To evaluate our TIAM-UCL simulations, we also created a "Current policy" pathway and we demonstrated that the emission budgets from this and from the NO pathway were consistent with comparable IPCC AR6 pathways **(§1-8)**.

Table 1. Summary of CDR assumptions in the overshoot scenarios. Source: **(§1-5)**.

	LO pathway	HO and VHO pathways
BECCS	100 EJ biomass/year	200 EJ biomass/year
Direct air carbon capture and storage (DACCS)	5 $GtCO_2$/year	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 $GtCO_2$ in 2050 and subsequent years in all pathways.	
Other CDR	None	15 $GtCO_2$/year from 2050
Overall limit	None	25 $GtCO_2$/year (HO pathway) 37 $GtCO_2$/year (VHO pathway)

The highest achievable temperature rise that could subsequently be reduced back to 1.5 °C by 2100 was 1.9 °C, which defined the VHO pathway. This was achieved by assuming global emissions would continue at a high level until 2040 before a substantial reduction, which Figure 1 shows are later than for pathways in the IPCC AR6 scenarios database. The magnitude of negative emissions in the VHO and HO pathways therefore needs to be higher than for most of those pathways.

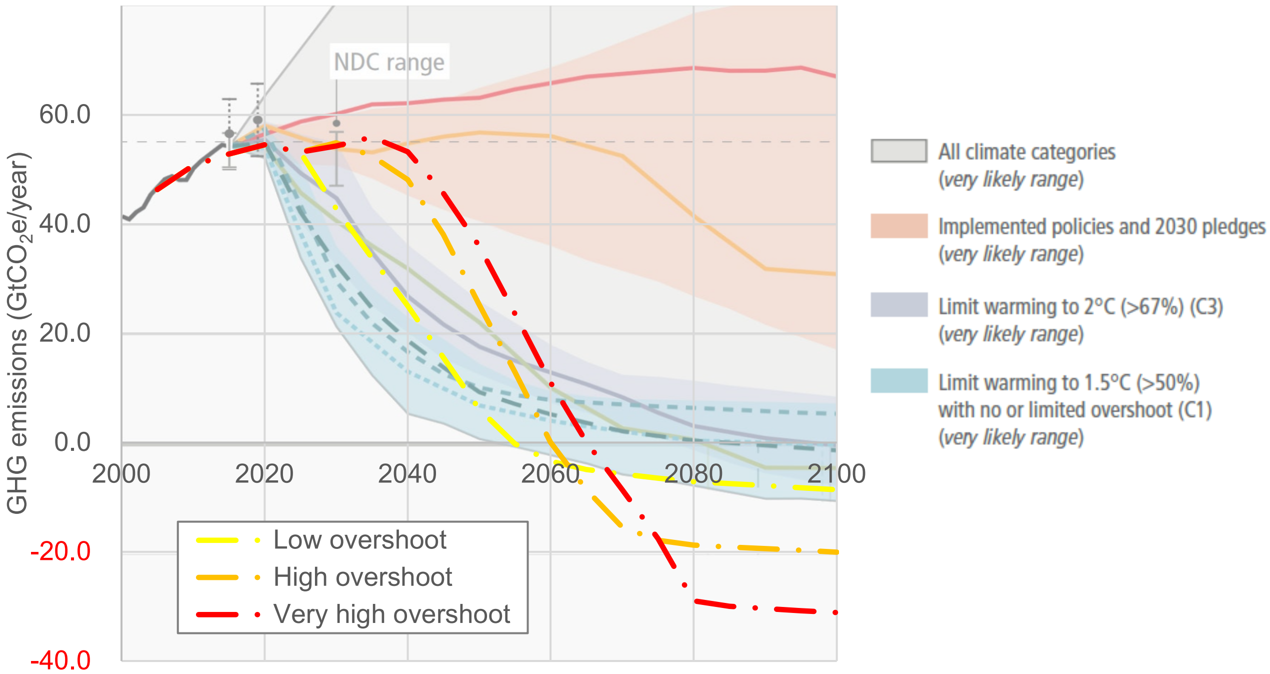

Figure 1. TIAM-UCL GHG emissions for the three overshoot pathways compared with IPCC AR6 WGIII emission ranges for scenario categories C1–C8 (shaded areas) and Illustrative Pathways (lines). The IPCC part of the graph is based on Figure 3.10 in Riahi et al. (2022).[1] Source: **(§1-8)**.

[1] Riahi, K., Schaeffer, R., Arango, J., Calvin, K. *et al.* (2022) Mitigation pathways compatible with long-term goals. *In* P. R. Shukla, J. Skea, R. Slade, A. Al Khourdajie *et al.* (eds.) *IPCC, 2022: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge, UK: Cambridge University Press.

3. Feasibility of removing atmospheric CO_2

Removing CO_2 from the atmosphere through CDR methods would allow us to limit climate change impacts by more than reducing emissions alone. If only a small amount of CDR were feasible, returning the global temperature rise to 1.5 °C might not be possible and a faster rate of decarbonisation would be needed to avoid overshooting 1.5 °C.

About 2 GtCO_2 per year of CDR occurs today by afforestation, but this is offset by emissions from deforestation. Future scenarios that limit global warming to between 1.5 °C and 2 °C have an average of 15 GtCO_2 per year of CDR by 2100 and assume an ambitious decline in global deforestation.

3.1 CDR methods

CDR methods are a group of technologies and land management practices **(§2-1)**. They include enhancements of existing carbon sinks (e.g. afforestation) or can involve chemical engineering with captured CO_2 being stored in geological reservoirs or long-lived materials.

A range of CDR methods have been proposed:

1. Afforestation and agroforestry: planting more trees.
2. Soil carbon sequestration: changing land management methods to increase carbon in soils.
3. Enhanced weathering: spreading finely-ground rock, such as basalt, onto fields to speed up chemical reactions between rocks, water, and air that naturally remove atmospheric CO_2.
4. Biochar: pyrolysis (high-temperature heating in the absence of oxygen) of biomass to produce a substance like charcoal, which is then applied to soils.
5. Biomass Energy with Carbon Capture and Storage (BECCS): combustion or gasification of biomass to produce an energy product with resultant CO_2 captured and stored underground.

6. Direct Air Carbon Capture and Storage (DACCS): removing CO_2 from the air and storing it underground (requiring energy input to capture and separate the CO_2).

There are systems similar to BECCS and DACCS that use the captured CO_2 as a feedstock (e.g. to make synthetic carbon-based fuels) rather than sequestering it. These utilisation systems may have a role in decarbonisation, but they are not CDR methods because the carbon that is captured is not kept out of the atmosphere for decades or more.

3.2 Infrastructure and CDR technology challenges

To deliver CDR that contributes to net zero, the captured CO_2 must be stored for a very long time (e.g. more than 1000 years in underground geological storage or mineral carbonation) **(§2-2)**. For underground geological storage, this would require CO_2 transport and storage infrastructure to be built. This CCS infrastructure would play a role in industrial decarbonisation (reducing net emissions to the atmosphere) as well as providing storage for BECCS and DACCS. If the transport and storage infrastructure were not built sufficiently quickly, then high levels of CDR would be difficult to achieve.

Our experts consider the global capacities of CCS infrastructure and CO_2 storage that our TIAM-UCL simulations suggest would be required for the overshoot pathways to be challenging to be delivery in practice. This means that returning the global surface temperature rise to 1.5 °C by 2100 for a pathway with an overshoot similar to the VHO and HO pathways would be difficult to achieve. The LO pathway has lower CCS requirements and is more likely to be achievable.

There is substantial uncertainty about the costs of deploying and operating BECCS and DACCS **(§2-5)**. A USA National Academies synthesis and Bloomberg forecast costs of 37–407 $/t$CO_2$ for BECCS and DACCS. TIAM-UCL assumes substantially higher future costs, based on older cost projections. If the TIAM-UCL assumptions ultimately were correct then BECCS and DACCS could account for up to 40% of the total energy system costs from 2050, which would likely be economically unsustainable. This would reduce to 20% of the total energy system costs if future DACCS and other CDR costs were assumed in line with the National Academies synthesis.

Given the early stage of BECCS and DACCS, securing finance is a key challenge. High cost and feasibility uncertainty exacerbate investment risks for BECCS and DACCS, making it difficult to access and secure capital. Different investors and types of financing could be deployed at different stages of technology development. Governments could address the early-stage risk investment shortfall, while closer to commercialisation, mainstream investors could provide more capital at scale.

3.3 Land use challenges

To deliver CDR that contributes to net zero, the biomass used for BECCS must be sustainably produced, either through use of a residue (agricultural, forestry or industrial wastes) or through bioenergy crop production with minimisation of direct and indirect land use change emissions **(§2-3)**. The land availability for bioenergy crops or afforestation is difficult to estimate as it would depend on future diets, crop yields and farming improvements, and responses to climate change (e.g. crop yield reductions due to drought or heatwaves) over time. But land for CDR methods would likely be in competition with food production and habitat conservation, as forest residues and marginal land would not provide sufficient biomass resources. This means strong environmental governance would be needed to minimise negative environmental and social impacts and deliver CDR.

In any given location or region, the most appropriate selection of CDR methods might achieve less CO_2 removal but meet a broader set of societal objectives (e.g. improved biodiversity; flood alleviation; urban heat adaptation). For many of the land management forms of CDR, the main implementation driver might be non-CDR objectives **(§2-4)**.

In practice, CDR methods would be imperfectly applied, subject to compromises and complexities from the sector(s) in which they operated (agriculture, forestry, conservation, mining, power, transport, industry and geologic storage), their geographical contexts (natural resources, economic development, pre-existing technologies, infrastructure and institutions), competing societal objectives (e.g. energy access, health, biodiversity, adaptations to climate impacts) and how each of these would change over the remainder of the century **(§2-ES)**.

3.4 Is the level of CDR required for overshoot scenarios feasible?

Estimates of the feasibility of global CDR in overshoot pathways from 2030 to 2100 cannot be given a feasible quantity or likelihood **(§2-ES)**. The levels of CDR required are likely to be technically feasible, but at the upper end of what is considered feasible when considering the economic, institutional, environmental and social challenges described above. It would be highly challenging for global society to achieve the CDR required for the VHO pathway.

4. Economic implications of an overshoot

The atmosphere is a global public good. Cooperation between world governments is required to protect public goods, and many governments use benefit-cost analyses to inform decisions. For this reason, the IPCC has estimated the economic implications of climate change, and of mitigating climate change, since the first assessment report.

Many studies have focused on mitigation costs with the aim of understanding the potential negative economic impacts of mitigating climate change, particularly on GDP **(§3-1.1)**. Other studies have used climate change benefit-cost analyses that compare mitigation and damage costs to assess appropriate decarbonisation rates and targets. Few studies have attempted to include co-benefits of mitigation, such as improved health from better air quality and diet, in benefit-cost analyses.

4.1 Economic damage from climate change is substantial but with uncertain magnitude

Estimates of climate change damages vary widely. At least part of the variation stems from the methods used. Future projections of damages based on econometric analyses of the impact of climate change to date are substantially higher than projections from detailed sectoral models that have traditionally been used:

- The lowest estimates from empirical econometric studies are for a 1%–3% reduction in global GDP when the global surface air temperature increases by 1 °C **(§3-2.1)**. Yet several studies project GDP reductions in 2100 in an RCP8.5 scenario of 7%–23%, and 60% in one study. Projected impacts are higher for studies than consider changes in extreme weather and that assume that GDP losses will compound over time.

- Integrated Assessment Models (IAMs) using insights from detailed sectoral-based models (e.g. biophysical crop yield models) project a lower decline in global GDP of -1%–1% of GDP for a temperature increase of 1.5–2 °C **(§3-2.3)**.

Given the wide variation in projected damage costs from different sources, we examined two quite different damage cost functions for each overshoot pathway in our benefit-cost analysis. The first based was on process models (denoted "PAGE09") and the second was based on an econometric synthesis study that assumes compound reductions to GDP growth from climate damages with a 23% reduction in global GDP in 2100 in an RCP8.5 scenario (denoted "Burke").

4.2 Benefit-cost analysis of overshooting 1.5 °C

We carried out a benefit-cost analysis of the implications of overshooting 1.5 °C that accounted for climate change damage and adaptation costs, mitigation costs and co-benefits. Both the PAGE09 and Burke damage cost functions were implemented in the PAGE model for each of the pathways created in TIAM-UCL **(§3-3.2)**. We estimated mitigation costs using the TIAM-UCL integrated assessment model directly **(§3-3.3)**. Finally, we incorporated co-benefits from improved air quality, improved diet and greater active travel into the analysis **(§3-3.4)**. As co-benefits are difficult to assess and have high uncertainty, we considered scenarios both with and without these co-benefits.

The choice of the future global discount rate (the extent to which we believe future benefits and costs, and hence future generations, are less important than those today) is an ethical judgment that has been a key parameter affecting previous benefit-cost analyses. It is important because a low discount rate gives future damages and mitigation actions a much greater weight compared to mitigation investments today than a high discount rate. Overshoot pathways have delayed mitigation actions followed by higher CO_2 removal later in the century, so have lower relative mitigation costs at higher discount rates and might be expected to have a more favourable economic case at higher discount rates. For this reason, our benefit-cost analysis considered a range of future discount rates **(§3-3.5)**.

Energy system costs from the TIAM-UCL integrated assessment model for each pathway were much larger than damage costs or co-benefits, as illustrated in Figure 2. Costs rise steadily over the century primarily due to population and economic growth, with both increasing demands for energy services worldwide over the time horizon **(§3-3.3)**. Mitigation costs, defined as the difference in energy system costs between a low-carbon and counterfactual case with no emission limits, account for around $9tn of the $53tn NO pathway energy system costs in 2100. As both pathways have the same population and economic growth assumptions, the differences in energy system costs between the NO and VHO pathways in Figure 2 are the differences in mitigation costs, and are small compared to co-benefits until 2050 **(§3-3.5)**.

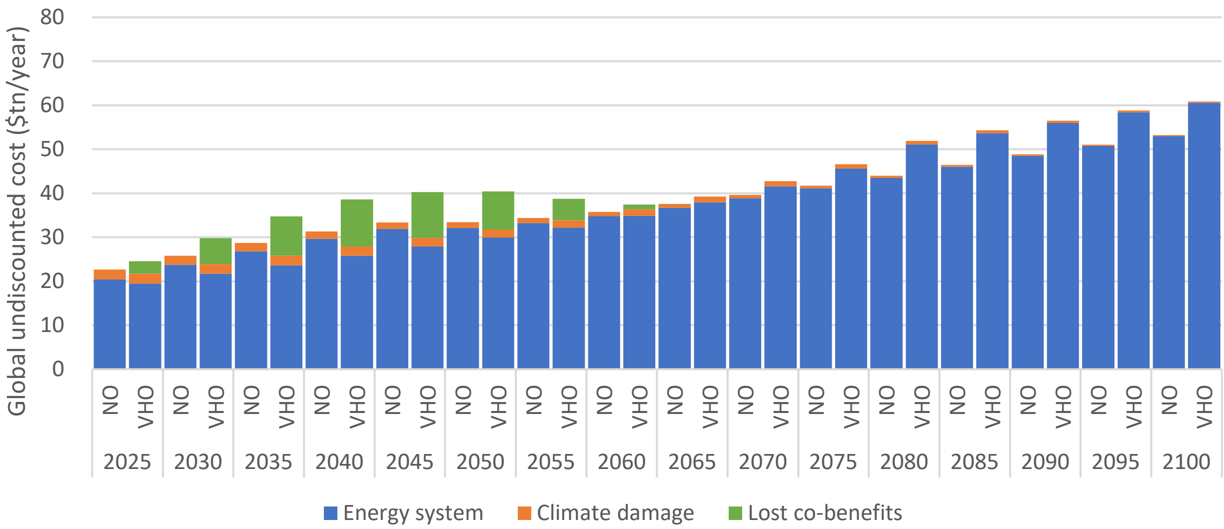

Figure 2. Global undiscounted costs assuming PAGE09 climate damage costs for the NO and VHO pathways. Source: **(§3-3.5)**.

Combining the damage costs, mitigation costs and co-benefits suggests that overshooting would have much higher overall costs than the NO pathway **(§3-3.5)**. Figure 3 shows that the costs increase as the magnitude of the overshoot increase. Figure 4 shows that for overshooting to be lower cost, it would be necessary to assume very low (PAGE09) damage costs, no co-benefits and to use a high future discount rate (4% or higher). In reality, studies of damages from weather events over recent decades as the planet has warmed suggest that damage costs will be higher than suggested by process models.

Moreover, there are likely to be at least some co-benefits from reduced air pollution. Based on this analysis, claims that overshooting might be lower-cost are not credible. Overshooting could be considerably more expensive than not overshooting. Early mitigation action is more cost-effective strategy than relying on CDR later in the century, particularly if climate damages and mitigation co-benefits are taken into account.

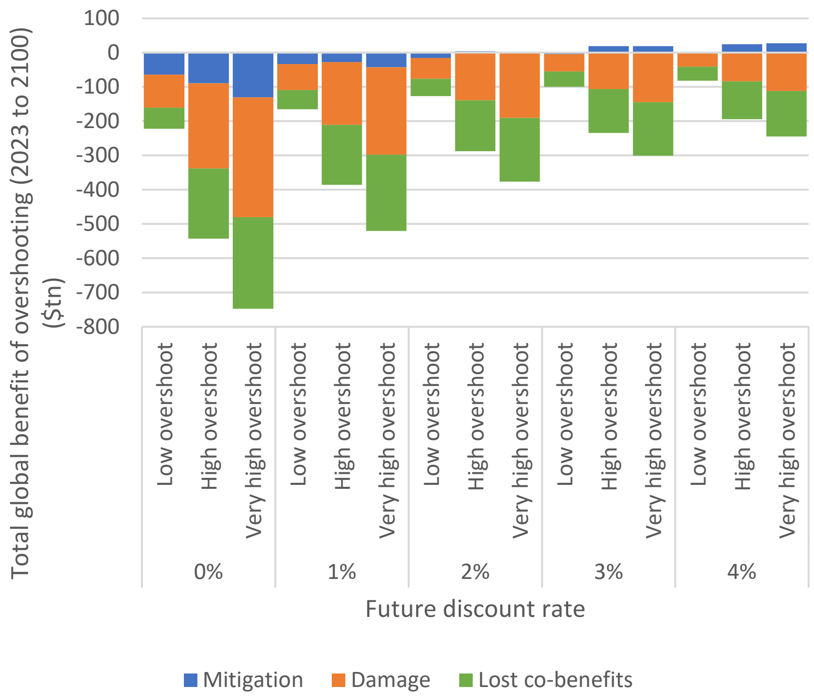

Figure 3. Total global economic benefits of the three overshoot pathways compared to the NO pathway, for the Burke damage cost function with several discount rates. Negative values represent a negative impact on global economies. Source: **(§3-3.5)**.

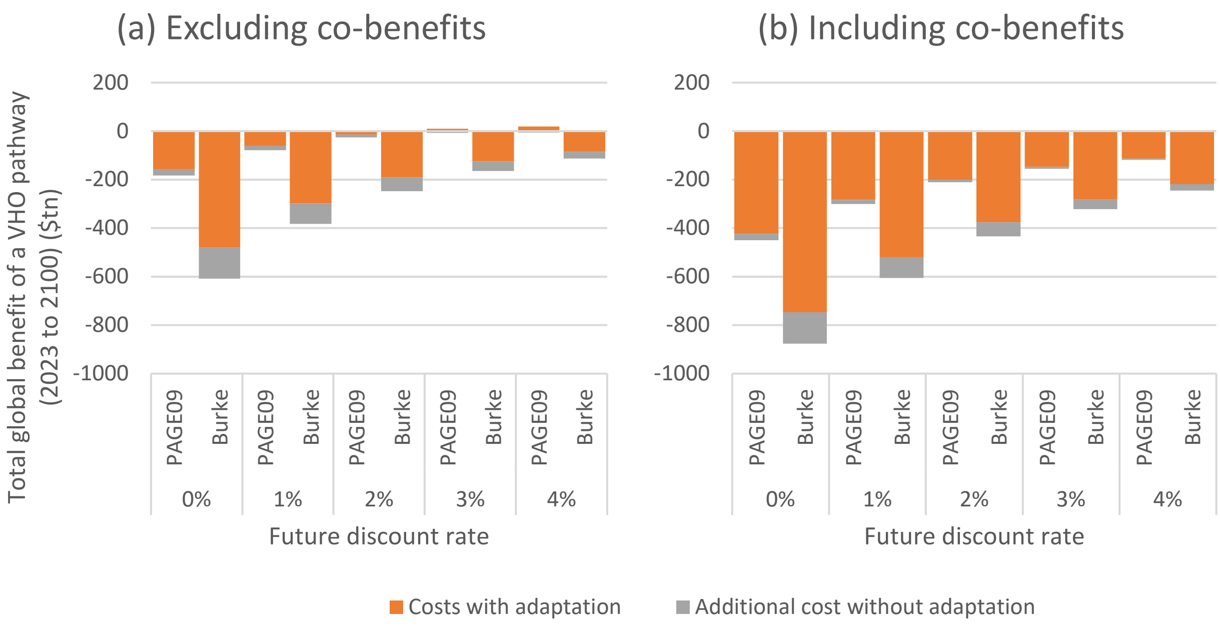

Figure 4. Total global economic benefits of the VHO pathway compared to the NO pathway, as a function of the damage cost function (PAGE09 and Burke), impact of adaptation actions and the future discount rate. Negative values represent a negative impact on global economies. Source: **(§3-3.5)**.

Damage and mitigation costs and co-benefits all have high uncertainty **(§3-3.6)**:

1. Damage costs from econometric studies are based on historic weather events so include extreme events such as storms, floods and droughts. These suggest that damage projections from process models (such as those informing PAGE09) have been underestimated. It is likely that damages are higher than projected by PAGE09, possibly much higher. The discrepancy could widen in the future as the frequency and intensity of extreme events is expected to increase as the global temperature rises.

2. Mitigation cost uncertainties primarily derive from future energy demand uncertainties. We did not assume a contribution from behavioural change, so any energy demand reduction could make the NO pathway even lower cost relative to the overshoot pathways.

3. Co-benefits are uncertain in terms of magnitude but are likely to be substantially more than zero, even if they are lower than the upper amount we examined.

Hence it is very unlikely that the assumptions required for the VHO pathway to be lower cost than the NO pathway would occur in reality. Most of the uncertainty lies on the side of the overshoot pathways being substantially more costly.

It would be insightful to compare our temporary overshoot pathways against pathways that do not return to global warming of 1.5 °C, for example those reaching an equilibrium of 2 °C, 3 °C and 4 °C.

4.3 Regional economic impacts of overshooting 1.5 °C

There are substantial social, economic and technological challenges to address to avoid overshooting 1.5 °C. It would require a pronounced acceleration of the transformation of the whole economy towards net zero emissions by 2050. Using a global economy-wide CGE model (ENGAGE), we estimated the economic impacts of overshooting 1.5 °C across a range of sectors and regions in the period to the year 2050 **(§3-4.1)**. ENGAGE primarily considers mitigation costs but does represent some agricultural and heat stress damages.

ENGAGE projects higher global economic growth over the period to 2050 through not overshooting 1.5 °C, as a result of earlier investment to increase energy and material efficiencies that have positive long-term economic benefits **(§3-4.2)**. In contrast, TIAM-UCL projected a higher cost of mitigation for the period 2020–2050 for the NO pathway. The discrepancy is likely due to TIAM-UCL assuming constant energy service demands in all pathways and only accounting for the impacts of improved energy efficiencies in the energy system rather than across the whole economy.

This second analysis with a different type of economic model provides further evidence that not overshooting would likely have better economic outcomes worldwide than following an overshoot pathway. All global regions benefit economically from earlier decarbonisation in the ENGAGE analysis **(§3-4.2)**. While the optimum rates of decarbonisation in each region vary over time, similar overall increases in GDP occur in each region by 2050 in the NO pathway compared to the VHO pathway.

5. Natural system impacts of an overshoot

The Earth system comprises the physical climate system (atmosphere, ocean, land, sea and land ice), the varying composition of trace gases and air pollutants in the air and oceans, and the varying biogeochemical cycles present on land and in water.

In this section, we examine the impacts of overshooting on five parts of the Earth system:

1. Atmosphere: (i) changes in the West African and Indian monsoon; (ii) changes in the frequency and reversibility of extreme events (e.g. heatwaves, intense precipitation).
2. Ecosystems: (i) loss of boreal forests (fires and pests); (ii) loss of the Amazon and other Tropical Rainforests (fire and drought); (iii) greening of the Sahel region of West Africa; (iv) lock into dust-bowl conditions.
3. Biodiversity: (i) loss of biodiversity, including insects; (ii) changes in ranges, phenology, physiology and morphology of terrestrial and freshwater species.
4. Oceans and coastal regions: (i) collapse of the Atlantic Meridional Overturning Circulation (AMOC); (ii) cooling of the subpolar gyre; (iii) frequency and intensity of ocean heatwaves; (iv) frequency and intensity of ocean deoxygenation and hypoxic events; (v) change in the rate of ocean acidification; (vi) loss of coral reefs.
5. Cryosphere: committed loss to the ocean of the ice stored within (i) the Greenland Ice Sheet, (ii) Antarctic ice sheets, and (iii) mountain glaciers; (iv) loss of perennial Arctic Sea ice; (v) permafrost thaw.

We were particularly interested in four types of Earth system changes that might occur in an overshoot:

1. Changes to the system that reverse as the temperature falls following a temporary overshoot.
2. Changes that are reversible but on much longer timescales – for example, sea level rise.

3. Hysteresis, when a change to the system caused by rising temperatures remains if the temperature is subsequently reduced back to the system change trigger temperature. However, if the temperature were reduced sufficiently below the trigger temperature, the change would eventually reverse **(§5-1.2)**.
4. Tipping points, which refer to critical thresholds that can be passed in response to human-induced climate change, and lead to changes in components of the Earth system ("tipping elements") that are abrupt, high-impact (on human societies or the natural world), and often irreversible **(§5-1.1)**.

The IPCC AR6 assessment concluded that the tipping point temperatures of some tipping elements are lower than previously considered. There is concern that exceeding a tipping point in one tipping element could possibly trigger tipping points in other tipping elements, often referred to as a "cascading transition".

5.1 Methods

We examined the potential impacts of overshooting on each part of the Earth system. We took particular interest in whether tipping elements or hysteresis might occur to parts of the system in the overshoot pathway **(§5-1)**. The overall approach we adopted for this research was:

1. To review existing literature for a 1.5 °C rise and a 2 °C rise in global temperature, particularly material used in recent IPCC reports.
2. To supplement this literature review with an analysis of whether overshooting might pass tipping point thresholds or cause hysteresis using the UK Earth System Model (UKESM).

Earth system models such as the UKESM are used to represent the numerous complex interconnections and consider how GHG emissions might affect natural systems in the future.

We recreated the VHO and NO pathways in the UKESM and compared the outputs. As the UKESM has a higher climate sensitivity than the IPCC best estimate, we artificially reduced the atmospheric CO_2 concentration in the model to produce the same global temperature rise as TIAM-UCL **(§4-3)**. This approach assumed that most natural system impacts are driven by temperature rather than by CO_2 concentration. It would have caused the growth of some vegetation in the model to be lower than would be expected in reality as the benefits of "carbon fertilisation" was underestimated in the model due to using lower atmospheric CO_2 concentrations. Through consultations with experts, we determined this would not significantly affect atmospheric responses to changing temperatures. We simulated each pathway four times to try to understand the implications of natural variability in the Earth system.[2]

5.2 Atmosphere

By mid-century (defined here as 2056–2065), the VHO pathway has 0.5–1.0 °C extra warming over most land areas and even larger warming (2.5–4.5 °C) over the Arctic region compared with the NO pathway in our UKESM simulations **(§4-4)**. This "Arctic amplification" is well-documented in the literature and is the result of a number of complex Earth system mechanisms. The oceans are simulated to have little surface air temperature warming.

By end-century (defined here as 2090–2100), land temperatures for the VHO pathway reduce to a similar level to the NO pathway except at high northern latitudes, where there continue to be differences despite the global temperature rise being approximately the same **(§4-4)**. These differences are particularly large in the Arctic region, where temperatures remain substantially higher than for the NO pathway.

Differences in precipitation of up to ±20% occur at end-century between the pathways, primarily in low-latitude areas **(§4-7)**. The Sahel monsoon and the early months of the Indian monsoon have substantially lower precipitation, which is important because tropical monsoon systems have a large impact on human and natural systems. However, these precipitation changes were not statistically significant. For the West African Monsoon, current literature suggests a tipping point occurs at a threshold of ~2.8 °C (2–3.5 °C) (low

[2] In climate science terms, we created an ensemble for each of the two pathways, each containing four members.

confidence), over a timescale of 50 years (10–500 years) (low confidence), with uncertain Earth system impacts **(§5-2.1)**.

The IPCC AR6 assessment contains new evidence which strengthens previous conclusions that even relatively small incremental increases in global warming (e.g. +0.5 °C) cause statistically significant changes in temperature and precipitation extremes (high confidence) **(§5-2.3)**. Even for the NO pathway scenarios, it remains an active area of research whether the whole temperature distribution increases or the high-temperature end of the distribution expands with global warming.

Running only four simulations of each pathway meant that it was not possible to identify statistically significant changes in extreme temperature or long-term precipitation, as the natural variability in these was similar to the differences between the simulated pathways. Further investigations with a larger number of runs or advanced machine learning techniques would be required to determine the significance of differences in these areas.

5.3 Ecosystems

The tipping point on Amazon rainforest dieback has a proposed threshold of ~3.5 °C (2–6 °C), notwithstanding deforestation (which would likely lower the threshold) (low confidence), with timescales of 100 years (50–200 years) (low confidence) **(§5-3.1)**.

Boreal forests are considered to be a regional impact tipping element with two potential climate tipping points as vegetation moves towards the poles **(§5-3.2)**:

1. Abrupt dieback at the southern edge with a threshold of ~4 °C (1.4–5 °C) (low confidence).
2. Abrupt expansion at its northern edge (referred to as tundra greening) with a threshold of ~4 °C (1.5–7.2 °C) (low confidence).

Climate change is already causing substantial shifts in fire regimes over much of the world's ecosystems **(§5-3.3)**. The extent of the changes increases with the level of global warming. In some regions, such as the Arctic, the increase in the frequency and intensity of wildfires may still be substantial even with a 1.5 °C warming because of the susceptible nature of this region. In other regions, such as the Mediterranean and particularly tropical forests, more extreme temperature changes could increase the frequency of extreme wildfires. The impacts on wildfires could become more severe if an overshoot above 1.5 °C of warming is prolonged. While there is little research available on hysteresis in the context of overshoots, research on the warming and speed of forest losses suggest they can respond quickly and early. Although the version of the UKESM used for the pathway runs did not include a representation of vegetation fires, UKESM outputs are able to reproduce the trends in the bioclimatic variables relevant to fire. We analysed the outputs for the VHO and NO pathways and they were qualitatively consistent with the literature.

Even at current levels of warming, there are significant losses in carbon from forest fires, which could reduce the allowable anthropogenic emissions to achieve 1.5 °C of warming by 20% **(§5-3.3)**. An additional 40 $GtCO_2$ might need to be removed should there be an overshoot.

5.4 Biodiversity

The typical response of species to climatic changes over time has been to change their range. However, this usually takes a long time, even in species with rapid population cycling. The IPCC AR6 assessment concluded that there are now very high confidence that poleward and upward movements of species is attributable to climate change, across a large number of species types and across the globe **(§5-4.1)**. Such adaptation is only possible if the rate of change matches the ability of the species to track its suitable climate. If the rate is too fast, or the magnitude of the change too great, then local extinctions are likely to occur, becoming overall extinctions if the change is great enough or a species has a very small range.

Although an extensive literature has been published on the potential impacts of climate change on species, few of the publications consider overshoot pathways. The global risk of biodiversity loss is moderate at 1.5 °C (NO pathway) but between high and very high at 2 °C (VHO pathway) **(§5-4.2)**. For Africa and for Arctic Sea ice ecosystems, overshooting increases the risks to biodiversity and ecosystems from high to very high. For coral reef ecosystems, loss and degradation are already very high even for the NO pathway.

Globally, range losses exceeding 50% are projected for 18% of insects at 2 °C (VHO pathway) but only 6% at 1.5 °C (NO pathway) **(§5-4.3)**. For plants, range losses similarly increase from 8% to 16% in an overshoot. Hence avoiding overshooting reduces the risks by at least half for insects and plants. A key issue is that the models used, like most species distribution models, are based on long-term changes in the mean climate and do not take into account extreme events that increasingly occur. Incorporating changes in the frequency of extreme events in large-scale species modelling is an active area of current research.

One of the biggest risks of overshooting on biodiversity is the degree to which ecological communities may potentially transform over time **(§5-4.4)**. As climate changes, regions will gain some species and lose others. This mixing is likely to be underestimated for an overshoot scenario because the dispersal rates of some species may not keep pace with the temperature increase and subsequent temperature reduction. The regions showing the greatest potential risk are in Southern Amazonia/Cerrado (South America), Miombo Woodlands (Africa), Southern Europe, India, parts of Australia, and the Kamchatka Peninsula and surrounding areas in Russia.

Some pollinators can disperse to track climatic changes while flowering plants generally cannot. Overshooting is projected to potentially impact pollinator and flowering plants (including insect-pollinated crops) in Amazonia, Southern Africa and much of Europe **(§5-4.4)**.

5.5 Oceans and coastal regions

Oceans play a critical role in the Earth's climate system by storing large amounts of heat and carbon, transporting heat from warm to cold regions, and regulating the global climate.

The Atlantic Meridional Overturning Circulation (AMOC) is a core global tipping element (medium confidence) with a best estimate threshold of ~4 °C (1.4–8 °C) on timescales of ~50 years (15–300 years) **(§5-5.1)**. The few available studies suggest that there is no evidence that the weakening of the AMOC will be significantly different for 1.5 °C or 2 °C of global warming. There is a dearth of scientific literature about the AMOC response to overshoot scenarios. There are many uncertainties arising from: (i) missing processes in both models and measurements used for evaluation of AMOC trends and variability; (ii) a lack of understanding of how ocean circulation is changing with warming, especially the role of vertical mixing, deep ocean processes, currents, and their impact on weather patterns on a regional scale; and (iii) any potential hysteresis.

There are few studies focusing on sea level rise for warming of 1.5 °C or 2 °C, including a small overshoot, leading to a lack of consensus between reported ranges of global mean sea level rise **(§5-5.3)**. Nevertheless, there is agreement that the median of global mean sea level in 2100 would be 0.1 m higher in a 2 °C warmer world compared to a 1.5 °C world. The magnitude and frequency of extreme sea level events in coastal regions would increase for both the NO and VHO pathways compared to the present day.

Since the 1980s, marine heatwaves have approximately doubled in frequency (high confidence) and have become more intense and longer (medium confidence) **(§5-5.2)**. They are projected to further increase in duration, intensity, frequency and spatial extent with global warming, so would be higher in a VHO pathway than a NO pathway. This is important because they cause mass mortalities of coastal species and large-scale bleaching of coral reefs, as well as shifting fish stocks with reduced fisheries.

The global ocean has become about 40% more acidic since pre-industrial times **(§5-5.4)**. Although few studies focus on acidification differences between 1.5 °C and 2 °C warming, studies have shown that acidification is directly related to CO_2 concentration and uptake into the ocean and will continue as emissions rise. Even as CO_2 concentrations decline again, there will be a decadal to centennial level delay in the recovery of the ocean carbonate system. Even under 1.5 °C warming, sensitive regions, such as the Arctic, will pass critical chemical thresholds for acidity (or pH), causing the breakdown of calcium carbonate minerals such as aragonite, which are used by many marine calcifying organisms such as calcifying plankton, corals, molluscs and crustaceans.

Warm water coral reef ecosystems are considered to be a regional tipping element (high confidence) **(§5-5.5)**. Evidence indicates the transition from high to very high risk occurs at a temperature threshold consistent with overshooting (1.5–2.0 °C of warming).

5.6 Cryosphere

Observations have revealed that the Greenland Ice Sheet and parts of the West Antarctic Ice Sheet may have already passed a tipping point **(§5-6.1)**. An increase in warming from 1.5 °C to 2 °C increases the likelihood of the collapse of these ice sheets. As the ice sheet response timescale is long, passing of this tipping point could be avoided with post-overshoot cooling to 1.5 °C by 2100, provided that the uncertain critical threshold beyond which the Greenland ice sheet would tip lies at the upper end of the estimated temperature range of 1.5–3 °C.

Perennial sea ice in the Arctic is likely to be lost under sustained warming exceeding 1.5 °C **(§5-6.1)**. The Arctic summer sea ice system as a whole exhibits no hysteresis and no tipping point, with losses reversible 'within years to decades' under a cooling climate. An exception is sea ice in the Barents Sea, for which there are early warning signs about a regional-scale tipping point for the loss of ice at ~1.6 °C (1.5–1.7 °C) (medium confidence) warming. Our UKESM simulations are broadly consistent with the literature, with Arctic ice loss at the end of the century projected to be 30% for the NO pathway and 40% for the VHO pathway, with particularly large differences in winter and spring **(§4-5)**. In contrast, while the seas around Antarctica lose ice mid-century in the VHO pathway, they have higher sea ice by 2100 than for the NO pathway. This increase in sea ice in Antarctica is driven by atmospheric circulation changes and has also been documented in the past few decades in observations.

Loss of permafrost carbon due to thaw is irreversible at centennial time scales (high confidence). Permafrost abrupt thaw has been identified as a potential tipping point as a 'regional impact' (but not global) with the risk increasing as the temperature rises beyond 1.5 °C **(§5-6.1)**.

The likelihood of triggering the loss of more than 50% of extra-polar glacier ice is non-negligible as the temperature exceeds 1.5 °C **(§5-6.3)**. Loss becomes likely by ~2 °C. Mountain glaciers are considered to be potentially susceptible to tipping under all of the overshoot pathways. Given the lack of information, uncertainties and regional variability in feedback mechanisms, such tipping points are described as potentially avoidable and probably reversible with subsequent cooling.

6. Human system impacts of an overshoot

We investigated the potential impacts of overshooting on human systems in general and on the UN Sustainable Development Goals (SDGs) in particular. We focused on the areas covered by SDGs that are likely to be directly affected by climate change (SDG1 –poverty; SDG2 – hunger; SDG3 – good health and wellbeing; SDG6 – clean water and sanitation; SDG7 – affordable and clean energy; SDG 10 – inequality; SDG14 – marine resources). In this section, we examine flooding, water and sanitation, food production, health, energy, poverty and migration.

Most evidence in the literature focuses on the impacts of a 2 °C temperature or higher rise, although evidence for a 1.5 °C rise was collected to inform the IPCC Special Report on Global Warming of 1.5 ºC that was published in 2018. Virtually no literature analyses the impacts of temporary overshoot pathways similar to those analysed in this study. We have reviewed the literature and have augmented this with our own analyses where possible. But for many areas, only a qualitative analysis is possible. While the general direction of change (i.e. better or worse) can be assessed, the magnitude of impacts cannot be assessed with any level of confidence as they depend as much on societal actions (e.g. adaptation investments and the resilience of infrastructure) as climatic influences.

6.1 Coastal and inland flooding

Several SDGs are affected by coastal flooding. For example, salinisation affects food production, while disasters cause infrastructure and livelihood damage and loss of tourism.

Coastal flooding is likely to increase in many areas as sea levels rise due to climate change **(§6-2.1)**. A time lag exists between global temperature rise and subsequent sea-level rise, meaning that the impacts of today's emissions may not be seen for decades. Rates of rise are expected to accelerate this century for both overshoot and no overshoot pathways, but an overshoot would cause a higher overall rise. Particularly vulnerable regions include polar regions (due to sea-ice free summers and permafrost melting), Eastern Central and North American coasts (due to more extreme El Niño events affecting storms and beach erosion), low-lying atoll islands in the Indian and Pacific Oceans, and coastal zones sensitive to inland processes **(§6-2.2)**.

We also examined inland flooding arising from rivers **(§6-3.1)**. Rising global temperatures are expected to increase the intensity of river floods, even where moderate floods reduce, but there are no studies addressing the impact of an overshoot scenario on inland flooding from rivers so these conclusions are uncertain **(§6-3.2)**.

Overshooting 1.5 °C would strengthen these trends, though this might be modulated by regional temperature variations. This effect does not translate directly to flood risk. As global warming subsequently reduces in a temporary overshoot, areas with an increased flood risk would begin to see a reduction and areas with a declining flood risk might begin to see an increase towards 2100. However, there could be a time lag in the recovery, and changes in land use and glacial melt in the intervening decades would likely change the flood risk. Overall, there is much uncertainty about the impacts of overshooting on inland floods **(§6-3.3)**. An adaptive approach in which planned actions were implemented in stages, when they were deemed necessary given the latest information available, could avoid over-engineering assets by providing flexibility, given the uncertainties of future climate change.

6.2 Water consumption

Terrestrial precipitation is projected to vary in complex ways with global warming, with increases in some regions and reductions in others. More intense storms, floods and droughts are expected that will affect agriculture, drinking water and sanitation **(§6-4.1)**.

Changes in water requirements and agricultural water deficit vary substantially between regions. We examined changes in water requirements in case studies for wheat and barley in an overshoot **(§6-4.2)**. Both crops could require between two and six times more water under a 2 °C scenario in key growing regions such as Mexico and Kenya for wheat and the USA and China for barley. Groundwater would deplete more quickly during an overshoot within these regions.

Wetter conditions in some areas, and more frequent and intense precipitation events more generally, will damage infrastructure, disrupt water and sanitation services and jeopardise water quality **(§6-4.3)**. Meeting ‘safely managed’ targets for drinking water and sanitation will become more difficult under overshoot scenarios in areas experiencing wetter conditions due to increased flooding, especially in fast-growing informal settlements where climate risk and poverty increasingly coincide.

Aridity, drought and/or water scarcity will increase in some areas, challenging those water supply and sanitation technologies unable to draw on safe storage **(§6-4.3)**. Meeting 'safely managed' targets for drinking water, in particular, will become more difficult under overshoot scenarios in areas experiencing drier conditions, especially where overall water demands are increasing, and where supplies become more variable and of lower quality.

SDG 6 sets ambitious targets for clean water and sanitation that are not currently on track to be met. One reason is that water resources have already been affected by climate change in many regions, particularly through extreme drought and floods happening more often and with greater intensity. For example, in Eastern and Southern Africa, precipitation has already become more variable and extremes more common, and these impacts would be amplified during an overshoot **(§6-4.5, §6-4.6)**. In South Asia, Bangladesh would suffer further from higher sea level rise, sooner, in an overshoot pathway **(§6-4.7)**. Overshooting would also increase the rate of glacier loss that feeds the Indus and Ganges **(§6-4.8)**. The impact of higher temperatures on the monsoon are uncertain and hence precipitation that feeds river flow in the upper Indus could reduce.

6.3 Food system

We examined the relationships between temperature and precipitation patterns and crop productivity using economic models for four cereals grown worldwide in different climates: wheat, rice, soybean and barley **(§6-5.1)**. A global temperature rise to 2 °C, in an overshoot pathway, would cause small reductions of cereal yields, but a greater increase in the interannual yield variability. Increasing variability could lead to shortages in some years and require additional risk management to secure farmer livelihoods. As temperature increased beyond 2 °C, wheat, rice and soybean yields would reduce.

We examined the potential impacts of overshooting on food production in the year 2050 using the ENGAGE CGE model (see Section 0 for an overview of the model) **(§6-5.2)**. The global temperature difference between the VHO and the NO pathways is only 0.27 °C in 2050 so the global reduction in food production is small. There are regional variations, however, with higher yields causing an increase in GDP of up to 0.6% in high-latitude regions but with higher localised impacts in low-latitude regions, for example higher food prices and GDP reductions of up to 6% in South and Southeast Asia.

Changes in ocean temperature will cause a redistribution of consumer fish towards the poles, with a loss of biomass at the equator and to a lesser extent at the poles **(§6-5.3)**. The overall loss of biomass is likely to be small for the overshoot pathways but will be greater than for the NO pathway due to higher oceanic temperatures for an extended period. The redistribution of fish would vary by species and could lead to fishing communities needing to adapt their approach to fishing.

6.4 Health

Overshooting will increase the frequency and intensity of heatwaves **(§6-6.1)**. This would increase heat-related mortality and morbidity by 2050. The largest increases are projected for sub-Saharan Africa, but the lack of epidemiological data means that estimates of heat-related mortality and morbidity are not possible. In all regions, however, declines in population susceptibility due to physiological acclimatisation and additional cooling measures such as air conditioning may result in a lower-than-expected health burden in an overshoot. Such adaptations are not always considered in current epidemiological models but consistently emerge in historical data. Additional cooling could place considerable strain on the electrical grid infrastructure of middle and even high-income countries, increasing the risk of blackouts and consequent health impacts.

Indirect effects from locally higher levels of food insecurity in an overshoot pathway may lead to malnutrition and diet-related non-communicable morbidity and mortality, and may exceed health risks from population exposure to heat **(§6-6.2)**. An overshoot would expand the spread of many vector-borne diseases to more northerly latitudes, but could decrease incidence in areas where vectors are already endemic.

Mitigating GHG emissions could result in several co-benefits that substantially reduce mortality and morbidity **(§6-6.3)**. Improving diet has the largest potential benefit. Lower air pollution would be particularly valuable in Asia, where many cities have poor air quality. Physical activity by contrast has smaller potential benefits for morbidity and mortality.

Indoor and outdoor workers are exposed to high temperatures and humidity in workplaces, particularly in low and middle-income countries. The loss of labour capacity, supply and productivity in moderate outdoor work due to heat stress is projected to range from 2%–14%, depending on the location and indicator **(§6-6.4)**. Our analysis using the ENGAGE CGE model showed that changes in the frequency and intensity of extreme temperatures due to an overshoot would increase heat stress and reduce productivity, and hence GDP, in some regions.

6.5 Energy

We examined the implications of overshooting for energy in terms of the changes in the energy system needed to avoid overshooting and the potential impacts of overshooting on electricity generation, system resilience and energy access and affordability.

To avoid overshooting, our TIAM-UCL energy systems analysis shows that substantial investments to decarbonise the energy system are required over the next 30 years **(§6-7.2)**. Global fossil fuel production would need to reduce more quickly in the short term for the NO pathway, but greater reductions would be required for the VHO pathway after 2060 to achieve the required level of "negative" emissions (Section 3). Electrification of many processes in industry, buildings and transport would be necessary **(§6-7.3)**, powered by a massive expansion of renewable generation **(§6-7.4)**.

Overshooting could reduce production from thermal and nuclear power plants by 7% in 2050 **(§6-7.5)**. These plants require large quantities of water at a sufficiently low temperature. Many plants use (and hence heat) river water and would need to shut if the water temperature were to exceed a threshold to avoid damaging aquatic organisms.

Changes in hydropower potential would vary across the world according to changes in precipitation, but the aggregated global hydropower potential would be similar. Changes in wind power speeds would similarly vary between regions; for example, Northern Europe is projected to have higher speeds and Southern Europe to have lower speeds.

Overshooting could have several adverse impacts on solar PV generation **(§6-7.5)**. Reducing fossil fuel use early for the NO pathway would decrease atmospheric aerosol and therefore increase solar PV generation. Moreover, overshooting could increase both cloud cover and temperature, which would reduce solar PV outputs. These various consequences of overshooting would reduce overall generation capacity during summer when demand for cooling would peak. Overshooting would also reduce transmission capacity in summer and could increase distribution infrastructure failure due to faster decay and stronger storms **(§6-7.6)**.

It is estimated that there were 675 million people who lacked access to electricity in 2021 and a further 2.3 billion people without access to clean cooking fuels and technologies **(§6-7.7)**. SDG 7.1 aims to ensure universal access to affordable, reliable, and modern energy services by 2030. Although climate change mitigation could have short-term costs that increase energy prices, efficiency improvements from global climate policy (SDG 7.2) could offset the additional electricity generation needed to achieve universal access, and climate policies could stimulate the expansion of renewable off-grid systems. In contrast, climate change, including overshooting, is projected to increase energy insecurity worldwide. It could also indirectly hinder efforts to achieve universal access to clean cooking **(§6-7.8)**.

6.6 Poverty, inequality and migration

The number of people leaving in extreme poverty is expected to decline substantially from around 700 million in 2020 to around 130–160 million in 2050 **(§6-8.1)**. Following either the NO or VHO pathway makes little difference to the number of people in poverty in 2050. Most of the differences between the two scenarios for the period to 2050 are for people in Africa.

Migration has a range of drivers, including some made worse by climate change **(§6-8.2)**. Flooding is a key driver, but temperature rise and precipitation changes are also important. Most displacement to date has occurred within countries, often from rural to urban areas, rather than across borders. The likelihood of migration depends on the level of investment in adaptation measures, the characteristics of the population and the strength of local communities and institutions.

It is very difficult to assess with any confidence the extent to which climatic changes have caused migration to date. It is even more difficult to project future changes as these depend on both uncertain future weather patterns and socioeconomic, cultural and political factors. Overshooting is expected to lead to greater flooding, more frequent and deeper droughts and more powerful storms for a period of 50 years, compared with not overshooting. It is therefore likely that migration in a VHO pathway would be higher than for a NO pathway, but the magnitude of the increase is difficult to project.

7. Conclusions

We have developed three temporary overshoot pathways with peak temperatures of 1.6 °C, 1.8 °C and 1.9 °C, respectively, with each returning to 1.5 °C by the year 2100. We have also developed a counterfactual NO pathway in which the global temperature does not exceed 1.5 °C. We have examined the feasibility of achieving the required atmospheric CO_2 removal in such an overshoot pathway, the economic implications of following an overshoot pathway, and the potential consequences of overshooting for natural and human systems.

7.1 Feasibility of removing enough atmospheric CO_2

To reduce the global temperature rise back to 1.5 °C by 2100 in an overshoot pathway, it is necessary to remove substantial amounts of GHGs from the atmosphere – up to 38 $GtCO_2$ per year for the VHO pathway. A much lower amount would be needed for a NO pathway. About 2 $GtCO_2$ per year of CDR occurs today by afforestation, but this is offset by emissions from deforestation.

It is unlikely that the level of atmospheric CO_2 removal required for the VHO pathway could be achieved in practice. It would be challenging to deliver the high level of CCS technologies that we assume would be needed to store atmospheric CO_2 underground in practice. The afforestation and availability of sustainable biomass feedstock that we assume in our overshoot pathways, and in many pathways submitted to the latest IPCC assessment report, are probably overly optimistic. One reason is the competition for land between food production, habitat conservation and land used for CDR. Moreover, the cost of CDR is highly uncertain.

7.2 Economic implications of an overshoot

We carried out a benefit-cost analysis of overshooting that included damage and mitigation costs and co-benefits. Overshooting 1.5 °C is likely to have much higher overall global costs than keeping the global temperature below 1.5 °C. The impact on poorer countries is greater than on richer countries.

All regions of the world could benefit economically from earlier decarbonisation. Not overshooting 1.5 °C could lead to higher global economic growth over the period 2020–2050 as a result of earlier investment in increased energy and material efficiencies that have positive long-term benefits for economies across the world. The number of people living in extreme poverty is expected to decline substantially from around 700 million in 2020 to around 130–160 million in 2050, and would be little affected by following an overshoot pathway.

7.3 Natural and human system impacts of an overshoot

Even if warming is kept below 1.5 °C, sea levels will rise, increasing coastal flooding. Precipitation patterns will change and extreme weather will be more frequent and stronger, affecting water and sanitation through stronger droughts and floods, and reducing agricultural productivity in some areas. Biodiversity will reduce. Moreover, some natural system tipping elements may already have been triggered. Observations indicate that parts of the West Antarctic ice sheet may have already passed a tipping point. There are early indications about the Greenland ice sheet, the Amazon rainforest and the Atlantic Meridional Overturning Circulation.

In an overshoot, floods, droughts and extreme weather events would become stronger. The risk of fire would increase substantially. Biodiversity losses would more than double to very high levels, particularly for insects, with tipping points reached in tropical areas of Africa and Amazonia. Other tipping elements might pass their thresholds: warm water corals, boreal permafrost, Barents Sea Ice, Labrador-Irminger seas/Subpolar gyre convection and mountain glaciers. More frequent, hotter heat waves would occur. Water and sanitation infrastructure and energy infrastructure would need to be more resilient to weather damage and energy system losses would be higher. Adaptation could reduce these impacts but would have negative economic consequences.

Although the global surface air temperature would likely recover quickly from a climate overshoot if the atmospheric CO_2 concentration were sufficiently reduced, sea levels would rise higher, Arctic ice would take decades to recover and precipitation patterns might also change, particularly in tropical areas such as the Sahel and Indian monsoon regions. Negative impacts on human systems would continue for decades into the twenty-second century.

7.4 Future research priorities

Each annex describes future research priorities in detail. There are numerous areas for further research:

1. **Overshoot pathway definitions:** exploring a much wider range of overshoot pathways, particularly those that investigate uncertainty in key parameters such as climate sensitivity and positive emission feedbacks, and scenarios with alternative future global socioeconomic and population assumptions.
2. **CDR:** narrowing the uncertainty in our understanding of the feasibility of delivering CDR. In particular, further research into understanding local conditions and consequences of scaling-up CDR is required.
3. **Climate damage costs:** are highly uncertain, particularly the extent to which growth impacts are likely to persist and further reduce long-term GDP levels. They greatly influence the benefit-cost analysis so narrowing the uncertainty would be valuable. Adaptation options, benefits and costs are also not well understood.
4. **Economics of overshoot:** comparing the economics of our temporary overshoot pathways against pathways that do not return to global warming of 1.5 °C, for example those reaching an equilibrium of 2 °C, 3 °C and 4 °C. We could also explore alternative methods to benefit-cost, for example risk-opportunity.
5. **CGE modelling:** in our global CGE model, we only simulated our pathways to the year 2050 as there is a need to represent CDR in CGE models in general and to understand why ENGAGE in particular becomes unstable later in the century.

6. **Extending our earth system modelling:** extending the simulations of our overshoot pathways in the UK Earth System Model into the twenty-second century to explore potential hysteresis, particularly for Arctic ice, and to run additional versions of the same simulations to better understand how precipitation patterns might change in an overshoot.
7. **Additional earth system scenarios:** exploring other "real world" overshoot pathways scenarios in earth system models. The NERC-funded TerraFIRMA project is investigating some idealised overshoot pathways in the UK Earth System Model but there is a need to also examine scenarios with greenhouse and aerosol emissions linked to real-world decarbonisation strategies.
8. **Earth system impacts:** there are few dedicated analyses of the natural system impacts of overshoot pathways. For ocean and coastal systems, the cryosphere and biodiversity, we relied on comparing impacts at 1.5 °C and 2 °C. There is a need to carry out bespoke analyses for these systems.
9. **Earth system tipping points:** although we have a good understanding of tipping points that might occur if warming were to exceed 1.5 °C, several tipping points have high uncertainty in the tipping point temperature. We do not know whether the length and magnitude of an overshoot would affect the likelihood of a tipping occurring if the global temperature were on the threshold. We also do not know whether it would be possible to respond to early signs of a tipping point occurring by deploying rapid CDR to reduce global warming below the threshold.
10. **Human system impacts:** our lack of understanding of the human system impacts of overshoot reflects the high uncertainty in climate damage costs mentioned above. We broadly understand the human system consequences of global warming but have less confidence in the magnitude of each impact. There is a need to better understand local climate impacts and their consequences for all types of human systems. There is an evidence gap to inform actionable policies, for example for effective and flexible adaptation strategies, that affects the IPCC more generally.

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