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Perspective

Implications of overshoot for climate mitigation strategies

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Abstract

Temporary climate overshoot—especially for 1.5 °C—is now unavoidable. In this Perspective, we show how overshoot emerged in mitigation pathways over the past three decades, from a modelling device enabling the exploration of more stringent climate goals to a structural feature of scenarios. Overshoot affects the pace and feasibility of emissions reductions, the distribution of socio-economic outcomes and climate risks in time and space. We show that the magnitude and consequences of overshoot depend not only on biophysical characteristics and model assumptions but equally on scenario design and social and institutional factors. We outline priorities for a new generation of models and scenarios that integrate different climate sciences, supporting robust climate strategies in a world of overshoot.

Editor's Summary

A temporary breach of the temperature target, or overshoot, is unavoidable. The authors review the history of how overshoot evolved in mitigation pathways, the magnitude and outcomes of potential physical and socio-economic impacts, and priorities for future model and scenario development.

Main

The year 2024 was the first calendar year in which annual global surface temperatures were more than 1.5 °C higher than pre-industrial levels (1850–1900), and there is an 80% chance that this will happen again before 2028[1]. The scenarios assessed in the latest IPCC Working Group III (WGIII) report highlighted the feasibility challenges of pathways featuring no or limited overshoot of 1.5 °C (refs. [2,3]). Since then, growing global emissions have made scenarios under which global warming does not exceed 1.5 °C implausible; in other words, all scenarios of climate transition have to seriously consider an overshoot 1.5 °C of warming[2,3]. AQ1 AQ2 AQ3 AQ4 AQ5 AQ6

Overshoot can be defined in a variety of ways[4,5]. In everyday language, it refers to breaching a given limit. In climate science and scenario development, it is intended as a pathway that “*first exceeds* a specified concentration, forcing, or global warming level, and *then returns* to or below that level again before the end of a specified period (for example, before 2100)”, AQ7 according to the IPCC Sixth Assessment Report (AR6 116) WGI Glossary (WGIII has a similar definition but further specifies that this requires removal from carbon sinks). Overshoot, or exceedance, and return are defined by the limit value (for example, 1.5 °C), the peak level above this limit (for example, 1.8 °C) and the time by which it returns to below the limit (for example, 2100).

The IPCC selected a few Illustrative Mitigation Pathways (IMPs) with different emission dynamics (Fig. 1). To distinguish overshoot characteristics—temperature exceedance and reversal—it introduced a categorization scheme that expressly includes the overshoot category for 1.5 °C pathways, first in the IPCC Special Report on Global Warming of 1.5 °C (ref. [2]) and then in the AR6 WGIII report[3] (Fig. 1). For Paris-compliant climate targets (for example, categories C1 and C2, such as IMP-REN and IMP-NEG in Fig. 1), the overshoot is goal-oriented towards reaching a given temperature by the end of the century. The two categories distinguish the 1.5 °C scenarios in terms of the size of overshoot (no or limited for C1 versus high for C2). In contrast, for higher-warming scenarios (for example, category C3, such as IMP-GS in Fig. 1), the warming limit of staying below 2 °C is imposed throughout the entire twenty-first century. The majority of these scenarios exhibit peak and decline warming trajectories; however, in this case the temperature drawdown is not an explicit goal but instead results from model characteristics (for example, socio-economic and technological changes) and policies, such as the time profile of carbon taxes[6]. Finally, other scenarios explore permanent exceedance of critical temperatures with no peak and decline (for example, Moderate Action).

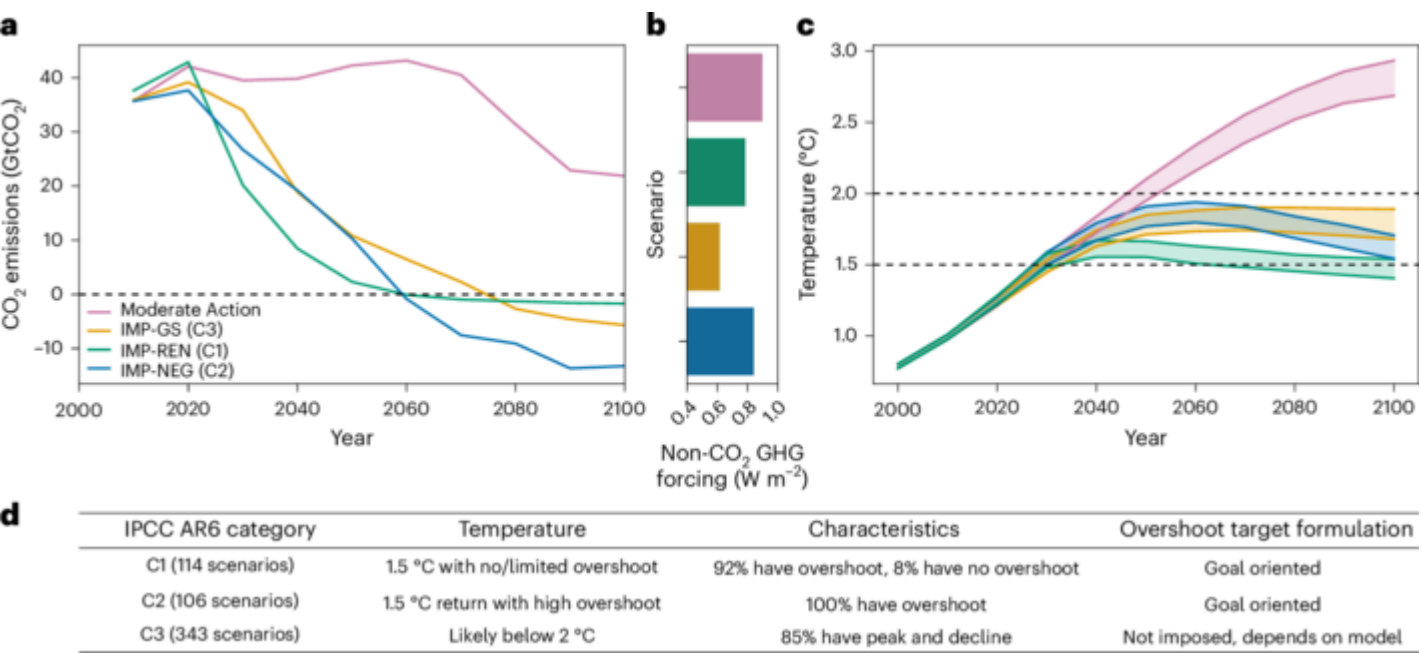
Fig. 1

Typologies of IPCC AR6 emissions pathways in relation to overshoot.

a–c, For four representative scenarios (Moderate Action and three IMPs), we report CO₂ emissions (a), non-CO₂ GHG forcing in 2100 AQ8 (b) and 50th to 67th percentile ranges of global mean temperature (c). IMP-GS (Gradual Strengthening) illustrates a gradual strengthening of

current policies with an increase in ambition and reliance on net-negative emissions in the second half of the century, with the goal of never exceeding 2 °C of warming. IMP-REN (Renewables) illustrates a future with a heavy reliance on renewable energy, targeting 1.5 °C with limited overshoot. IMP-NEG (Negative Emissions) illustrates a future with deployment of CDR that results in net-negative global GHG emissions, targeting 1.5 °C with high overshoot. For additional details, see IPCC AR6 WGIII Annex III Table 9 [117](#) [AQ9](#) . The key in **a** applies to **b** and **c** as well. **d**, Characteristics of IPCC AR6 scenario categories. C1 and C2 have a 2100 mean (for example, 50%) temperature below 1.5 °C with low and high overshoot (for example, up to 0.1 and 0.3 °C, respectively). C3 has a peak temperature probably (67% likelihood) below 2 °C.

[Source data](#)



Overshoot affects mitigation strategies in many ways. It influences energy investment and retirement patterns, land use for low-carbon energy or carbon capture, and the time profile of emissions, resulting in distributional consequences for society. Different overshoot pathways also lead to varying feedbacks from natural and human systems. For example, for a given long-term temperature, longer and bigger overshoot increases the short-term feasibility space at the expense of larger climate feedbacks and increased hazards. These, in turn, affect emission pathways, for example by influencing the effectiveness of land-based carbon removal[[7](#)].

This Perspective examines the relationship between overshoot and climate mitigation strategies, with three primary objectives. First, by reviewing the long history of emission scenarios, we show how overshoot evolved from a modelling device to explore stringent mitigation targets under rising emissions into a structural feature of mitigation pathways, reflecting physical inertia, delayed emissions reductions and socio-economic constraints. Second, we summarize the state of knowledge of the implications of overshoot for mitigation pathways and overcome some common misunderstandings. Finally, we identify priorities for future community research in a world increasingly shaped by overshoot.

From model experiments to reality and back

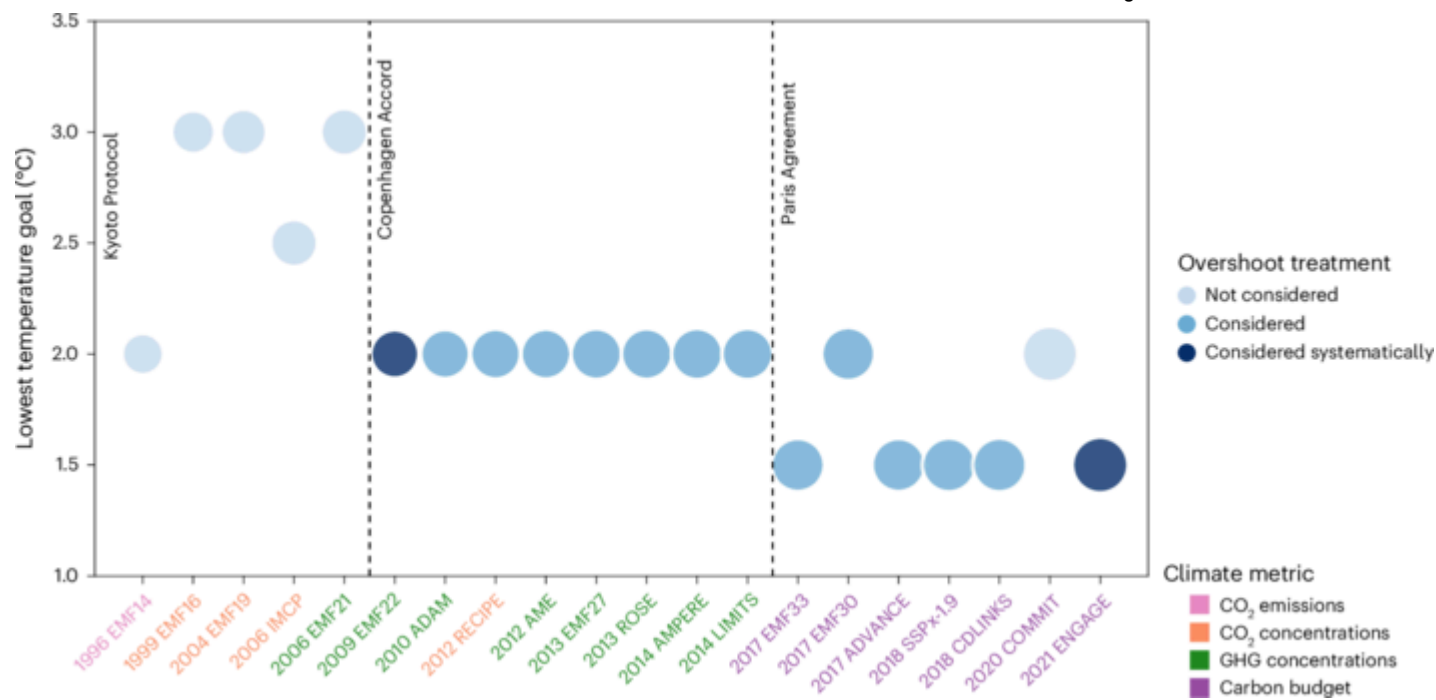
Scenarios have long explored future emission pathways, under various assumptions about socio-economic and technological developments[[8](#)], as well as policy regimes from laissez-faire all the way to ‘climate stabilization’ under full global cooperation. The history of the most relevant model comparisons of mitigation pathways has evolved [significantlysubstantially](#) [AQ10](#) during the past 30 years (Fig. [2](#)). We identify three distinct phases, each spanning a decade, which reflect the conceptual evolution of overshoot from a theoretical device to an enabling mechanism for ambitious targets, and eventually an unavoidable real-world condition.

Fig. 2

Historical evolution of model comparison studies in relation to climate overshoot.

The year and acronym of each model comparison study are plotted against the temperature goals examined (the lowest value achieved in each study). The size of the circles is proportional to the CO₂ concentrations additional to pre-industrial levels, for the year in which the study was published. The circle colour indicates whether overshoot was not considered (by design or because it was not possible), considered or considered and systematically explored by design. The vertical dashed lines identify years of prominent international climate agreements. The *x*-axis labels are colour-coded depending on the climate metric used in the studies. For the references, see Supplementary Table [1](#).

[Source data](#)



The formative age (1996–2006)

From the early ages, scenarios addressed the UNFCCC principle of “stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system” [118]. AQ11 Concentrations were capped at around 550–650 ppm CO₂, leading to global temperature increases of 2.5–3.5 °C relative to pre-industrial levels by the end of the twenty-first century. Global mean temperature would continue to increase until the new equilibrium is reached; decreasing temperature requires decreasing CO₂ concentrations (given constant non-CO₂ forcing). Given the unambitious nature of climate targets and the carbon concentration focus, the major studies in this era did not consider overshoot with declining concentrations over the twenty-first century. Some early work looked at more stringent stabilization objectives and popularized a framework of temporal allocation of emission reductions based on maximizing societal welfare or minimizing the economic costs of mitigation (the “when flexibility”)[9]. This conceptual framework had a significant influence on subsequent work on emission pathways.

With the new millennium, the focus on concentration stabilization expanded to include all GHGs[10,11]. This was necessary to fully understand the climate consequences of emission trajectories. It also allowed models to trade off choices about which gases to abate when (the “what flexibility”). As in previous studies, CO₂-equivalent concentration targets were set for specific periods, such as 2150 for the leading model comparison study on multi-gases (EMF21 (ref. [10])). Notably, this study incorporated short-term constraints regarding maximum decadal temperature change alongside long-term goals, albeit as optional scenarios.

The age of increasing ambition (2006–2016)

As policy discussions on climate intensified and scenarios became more ambitious, yet annual GHG emissions kept increasing, a second phase began. Different types of concentration profiles were studied, including concentration stabilization and peaking, both with and without overshoot[12,13]. The peaking and overshoot profiles made achieving more ambitious climate targets possible[14], especially the 2 °C formalized in the 2010 UNFCCC Cancún Agreements and proposed by the European Union a decade earlier[15]. After 2010, keeping warming below 2 °C became a focal point for scenarios: indeed, all major model comparisons carried out in this second phase have that as their most ambitious objective (Fig. 2).

The exploration of overshoot culminated in an influential model comparison on international climate policy architecture (EMF22 (ref. [16])), which examined various CO₂-equivalent concentration limits, including those with and without overshooting these limits by the end of the century. The model comparison highlighted the essential role of speed and breadth of international cooperation in stabilizing the climate, finding that overshooting was a necessary but not sufficient condition for reconciling ambition with feasibility. The trade-off between short-term mitigation capacity and long-term climate stringency is the defining characteristic of this age and of the mainstreaming of overshoot. It was already clear at the time that overshoot would increase environmental risks and intergenerational injustices[17]. Yet, modellers were facing increasing difficulties in performing simulations that embedded the growing concerns about climate change: in EMF22, the impossibility of achieving stringent climate outcomes became apparent, with several models unable to generate scenarios, especially under fragmented international cooperation (Supplementary Table 2). Whether models included carbon removal technologies was an important, though not the only, determinant of model solvability. The selected capacity to simulate the more ambitious climate targets by specific models limited the interpretability and external validity of scenario ensembles[18].

The dividing line between phases 1 and 2 was the broadening of mitigation options and the generalized introduction of carbon dioxide removal (CDR) in models. The concept of carbon removal had emerged a decade earlier[19,20], with afforestation and the combination of carbon capture and storage with biomass to extract CO₂ from the atmosphere (bio-CCS or BECCS). By the middle of the 2000s AQ12, bio-CCS was incorporated into the first integrated assessment models -IAMs-[15,21,22], achieving lower GHG forcing targets than before (for example, 450 ppm CO₂-equivalent). This became more relevant during the 2007 IPCC expert meeting on mitigation scenarios and the IPCC Fourth Assessment Report, which included only six scenarios (from two models) in the lowest climate category, most of which featured overshoot. The report emphasized the potential benefits of an overshoot of a predetermined target as it allowed more realistic emission reduction profiles, but equally warned about its risks[23], both physical and for mitigation deterrence (for example, windows of opportunity for abatement).

The age of reckoning (2016–2025)

With the adoption of the Paris Agreement in 2015, the scenario modelling community moved from targeted individual studies[24] to coordinated research efforts that explored the stringent temperature goal of 1.5 °C. With CO₂ concentrations exceeding 400 ppm,

temperature overshoot and carbon removal have become indispensable to address the new policy ambitions. During the same time, the scientific community adopted carbon budgets, or cumulative CO₂ emissions, as a key climate metric, given their growing policy relevance and direct connection to temperature[25]. Community work focused on the attainability of 1.5 °C through various lenses (technological change, finance, sustainability, lifestyle change, equity and so on), including the role of CDR technologies[26]. As concerns grew about the feasibility and sustainability of large-scale CO₂ drawdown[27,28], modellers worked to better incorporate environmental sustainability concerns over bioenergy production systems. Additional types of CDR were also introduced, thus broadening the portfolio of CDR options[29,30,31]. As a result, CDR continued to provide a significant, mostly unavoidable, way to meet the most stringent climate targets.

Many model comparisons allowed overshoot, but few explicitly explored it (Fig. 2). Most model comparisons focused on end-of-century climate targets, allowing for temporary exceedance. The necessity to separately treat emission reductions from carbon removal led to alternative scenario designs[32] and model developments. End-of-century cumulative carbon budget targets have been combined with or in some cases replaced by peak or net-zero budgets, essentially constraining net CO₂ emissions once they reach net zero[32,33]. Concurrently, models developed new environmental and social components to simulate multiple sustainable development objectives, which also influenced overshoot[34,35].

Implications for mitigation pathways and climate strategies

As evident from the history of scenarios, temperature exceedance and reversal have emerged chiefly as a way to meet low-temperature targets against growing carbon concentrations. Overshoot attempts to decrease the tension between the feasibility of rapidly and deeply cutting emissions and the ambition to keep temperature increase as low as possible. Unsurprisingly, scenarios with the largest drop between peak and end-of-century temperatures are also the most climate ambitious (Supplementary Fig. 1a).

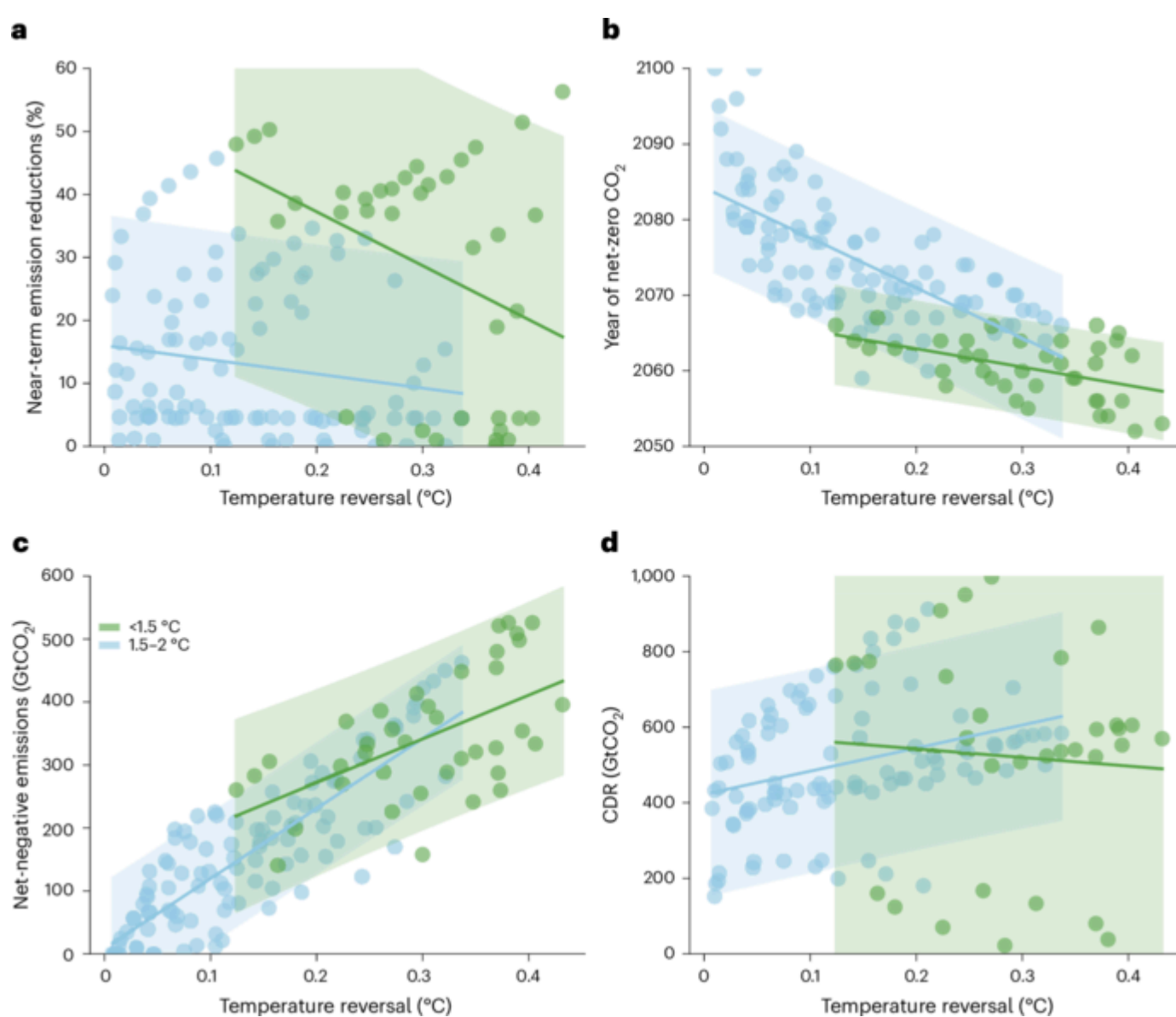
For a given temperature limit, a higher overshoot results in a forward shift of emission reductions, with smaller short-term cuts being compensated by equal efforts in later decades (Fig. 3a and Supplementary Fig. 1b). The temporal shift of emission reductions increases with the stringency of the long-term temperature goal (Fig. 3a). The need for overshoot becomes apparent when accounting for the reality of near emission dynamics: if we take the COVID-19 year CO₂ emission reduction rates (around 6%[36]) as upper values of what is currently feasible and account for the rebound of CO₂ emissions to above 2019 levels in 2025, global emission cuts in 2030 above 25% relative to 2019 would be ruled out, leading to overshoot of at least 0.2 °C and most likely close to 0.5 °C.

Fig. 3

Mitigation trade-offs in overshoot scenarios.

a–d, Relation between peak-temperature reversal (the difference between median peak and 2100 temperatures) and near-term CO₂ emission reductions (% , 2030 versus 2019) (**a**), the year of net-zero CO₂ (**b**), cumulative net-negative CO₂ emissions (2010–2100, GtCO₂) (**c**) and cumulative CDR (GtCO₂) (**d**), colour-coded by 2100 median temperature (<1.5 °C or 1.5–2 °C). The lines indicate linear regressions, and the shaded areas indicate 90% prediction intervals. Data from the IPCC AR6 scenario database[115] for the subset of vetted scenarios from the ENGAGE project.

[Source data](#)



The time of net-zero CO₂—a focal point for climate policy—is relatively insensitive to overshoot when the ultimate climate goal is to bring back temperature to 1.5 °C, but not for less stringent goals (Fig. 3b). Notice the significant spread across scenarios, often dominating the signal of temperature reversal. Besides carbon, other GHGs have important implications for temperature overshoot (Fig. 1). Limiting overshoot and attaining stringent temperature hinges on a comprehensive mitigation strategy that integrates non-CO₂ mitigation measures in addition to a net-zero CO₂ commitment[37]; however, the uncertainty on the costs and feasibility of non-CO₂ GHG mitigation remains large, further exacerbating the risks of longer overshoots[38].

Overshoot is also tightly linked to net-negative CO₂ emissions. The relation between the two is roughly linear, given the proportionality of temperature and cumulative emissions[25] (Fig. 3c). The causal link between overshoot and CDR is bidirectional: as discussed in the previous section, CDR technologies were introduced in the models to achieve stringent climate goals in the face of rising historical emissions, and these in turn allowed for higher temperature overshooting (when allowed by design). Scenarios exhibit significant variations in net-negative emissions[39]. In the first journal special issue on negative emissions[26], some models reported only a small overshoot (around 0.05 °C)[29,40], whereas others were much larger (up to 0.5 °C)[41]. Ultimately, whether CDR technologies lead to temperature-overshoot scenarios is predominantly driven by the scenario design and modelling choices (for example, the definition of climate target and of equity preferences) rather than the characteristics of these technologies[32].

Counter to a common assumption, higher overshoot does not automatically translate into more CDR (Fig. 3d). The total amount of CDR over the twenty-first century is, in large part, used to offset emissions in the same period rather than just offsetting excess emissions of early periods towards the end of the century. Excluding or minimizing the carbon budget overshoot shows only small reductions of cumulative CDR over the twenty-first century (maximum 20%), with lower deployment in the long term and higher and earlier deployment in the near term[6,42,43]. Moreover, early CDR deployment in limited-overshoot scenarios relies more on afforestation[44], whereas direct air capture is more deployed in the long term in high-overshoot scenarios. In contrast, the amount of bioenergy and CCS deployment is affected mainly by technology or scenario design choices that are unrelated to overshoot, such as direct limits on CDR or bioenergy use[34,45]. Furthermore, even if CDR or BECCS is limited directly, the use of bioenergy can remain high or even increase as it is driven by increased demand for biofuels from more substantial reductions in oil use[46]. A further important determinant of CDR is the capacity to mitigate non-CO₂ GHGs at the time when CO₂ reaches net zero[39,40]. Methane removal has been recently discussed in the context of limiting overshoot[47,48] but is not yet included in existing scenarios given its early stage.

Assumptions about CDR affordability, availability and sustainability have important repercussions for emission pathways with overshoot. Given that even small temperature overshoot implies massive amounts of net-negative CO₂ emission (about 200 GtCO₂ per 0.1 °C) and that, as we have seen, CDR is needed not just for net-negative CO₂ emissions but mostly for compensating residual CO₂ and non-CO₂ emissions, scenarios with significant net-negative emissions might be unattainable[27,28,49,50]. Modelling studies have indeed shown that land-based CDR without appropriate policy provisions can compromise food security and exacerbate biodiversity losses[51,52]. When sustainability and desirability constraints are taken into account, the potential of biological CDR is reduced, and so is overshoot[49,53]. Smaller overshoots can also be achieved through alternative mitigation strategies with stronger emphasis on demand-side and lifestyle change[54,55] and progressive redistributions[34]. Ultimately, overshoot is determined by whether we can achieve feasible short-term emission reductions in the face of institutional constraints or manage a long-run system reversal based on unproven or unforeseen technological and biological solutions and uncertain climate responses. The work focused on scenario feasibility indicates that the corridor to returning warming to 1.5 °C in this century is exceptionally narrow, severely limiting the number of realistic scenarios[56,57,58,59].

Overshoot has also been discussed in relation to higher temperature reversals resulting from continued emissions and increased climate risks. Given the limitations of CDR already discussed, these arguments have supported the development of alternative pathways, featuring provisional interventions such as solar radiation modification (SRM)[60,61]. So-called napkin scenarios envision a portfolio of mitigation and CDR, complemented by SRM, to mitigate the harmful temperature peak by leveraging the rapid climate response to SRM, particularly through stratospheric aerosol injection. Only a few process-based IAMs have contributed to this literature[62], given the difficulties in representing the physical, social and governance dynamics and challenges of SRM.

Implications for socio-economics

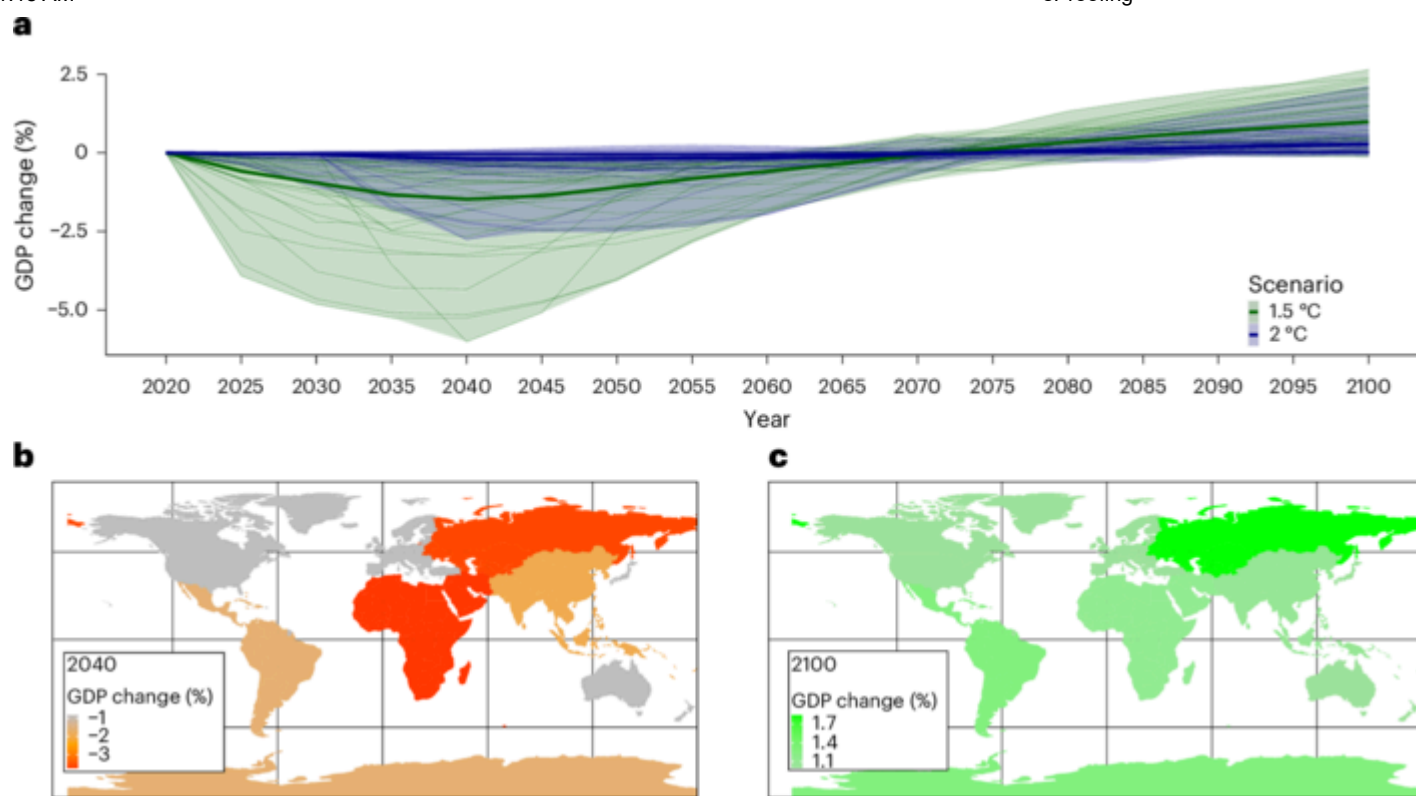
The complex relation between overshoot and mitigation strategies has broad societal repercussions. Scenarios that limit the magnitude of temperature overshoot require higher upfront investments, leading to higher near-term carbon, energy and land prices, and thus mitigation costs. These early efforts eventually pay back by reducing mitigation efforts and net-negative emissions in later decades[32,33] (Fig. 4a).

Fig. 4

Distributional economic impacts of temporary overshoot in time and space.

a, Temporal evolution of global GDP for 1.5 °C and 2 °C climate targets. The solid lines indicate the median across all scenarios, shown in the shaded areas. **b,c**, Geographical patterns in the years 2040 (**b**) and 2100 (**c**). The median across 1.5 °C scenarios is shown. All plots show differences in GDP between no-overshoot (net-zero carbon budget) and overshoot (end-of-century carbon budget) scenarios with the same 2100 temperature. Positive values indicate higher GDP in no-overshoot scenarios. The economic damages from climate change are not included in the GDP. Data from the IPCC AR6 WGIII scenario database[115] for the subset of vetted scenarios from the ENGAGE project. Basemaps in **b** and **c** from Natural Earth (<https://www.naturalearthdata.com>).

[Source data](#)



The economic temporal trade-off—not considering the economic benefits of reduced warming—depends on how near-term costs are valued against long-term gains. A time discount rate of 2% per year or below makes scenarios with limited overshoot economically competitive from today’s perspective[33]. This value is below market rates but is the one recommended for social valuation of climate change[63]. It is also the value that equally distributes mitigation efforts across time and halves the use of carbon removal compared with traditionally used rates (for example, 5%)[64]. However, time preferences matter insofar as there is sufficient flexibility to shift emissions reductions in time, such as in end-of-century scenarios. With not-to-exceed carbon budgets, overshoot is effectively controlled, and the sensitivity of CDR deployment to discount rate is significantly reduced. Once more, this highlights that scenario design matters as much as (and often more than) modelling choices.

Overshoot affects different countries differently. The short-term cost increases of more drastic emission reductions and lower overshoot are more concentrated in developing and fossil-exporting economies due to their higher carbon intensity and fossil fuel exports (Fig. 4b)[42,65]. The long-term economic mitigation benefits of front-running emissions cuts are more evenly spread (Fig. 4c), with differences often attributable to land use patterns: increasing overshoot shifts land removals from afforestation to bio-CCS, with its own trade-offs and sustainability limits[49]. Generally, the trade-offs between short-term mitigation costs and longer-term impacts and damages (the latter are discussed in the next section) are stronger in developing and emerging economies than in developed ones[42]. Factoring in equity shrinks the carbon budget of developed economies due to their larger responsibility for past emissions, thus requiring them to commit to more CDR[66,67]. The regional consequences of overshoot also depend on whether carbon removal will be predominantly biological or industrial, with the former having more limited capacity in developed regions.

Institutional factors reflecting different regions’ and countries’ governance and policy implementation capabilities also matter. Incorporating elements of institutional realism by regionally differentiating mitigation capacity decreases climate ambition and increases overshoot[56,68]. This highlights the critical role of enabling factors, such as lifestyle change[69], financing costs[70] and technology access[71], to limit overshoot. A governance concern of overshoot is that, by shifting emission reduction efforts to the future (characterized by higher reliance on unproven or unforeseen technologies), overshoot could lead to not just a temporary but also a permanent reduction of emission abatement. Moral hazard[72]—the extent of mitigation postponement and deterrence induced by overshoot—can be limited by appropriate policy design with a focus on limiting peak warming, reshaping the carbon price trajectory[6], choice of time discounting[64], separation of targets for gross emissions and removals[45] and accounting of ecological constraints for mitigation and CDR[54]. The governance challenges of CDR are also financial: financing net-negative emissions—especially in high-overshoot scenarios—at the same rate as mitigation increases economic inequality[73] and absorbs public finances[74]. Differential policy and economic treatment of mitigation and carbon removal and intertemporal policy instruments such as “carbon removal obligations”[75] can mitigate these concerns.

As previously noted, mitigation delays, climate hazards and overshoot have motivated discussions around alternative climate interventions, such as solar radiation management, to shave off peak temperatures. However, solar geo-engineering raises potentially disruptive governance issues[76] and increases uncertainties; only a few individual modelling studies have looked into it[62,77], with a community assessment too premature given the current state of modelling.

Implications for climate risks

Temperature overshoot exacerbates social and physical hazards with implications for mitigation pathways. These are associated with uncertainties in climate response, regional climatic patterns, time-lagged and irreversible responses (including potential tipping points) and related climate risks to nature and society[78]. A thorough discussion of physical and social impacts of climate change goes beyond the scope of this Perspective and can be found elsewhere[4,5].

Fewer papers have quantified the risks arising from overshoot for mitigation pathways[42,79,80,81]. The carbon cycle responds differently to equivalent positive and negative emissions[82,83,84], with the oceans playing a significant role when ramping down carbon concentrations[85], depending on the speed of drawdown[86]. When including ocean outgassing in an IAM, one study found that the amount of CDR was reduced by a third[29]. In addition to carbon cycle dynamics, higher overshoot increases climate risks, including increasing cooling energy demands, lowering agricultural and forest productivity and affecting river runoffs (Fig. 5a). Such physical impacts have important effects on decision variables in emission pathways, for example by increasing energy use for adaptation[87],

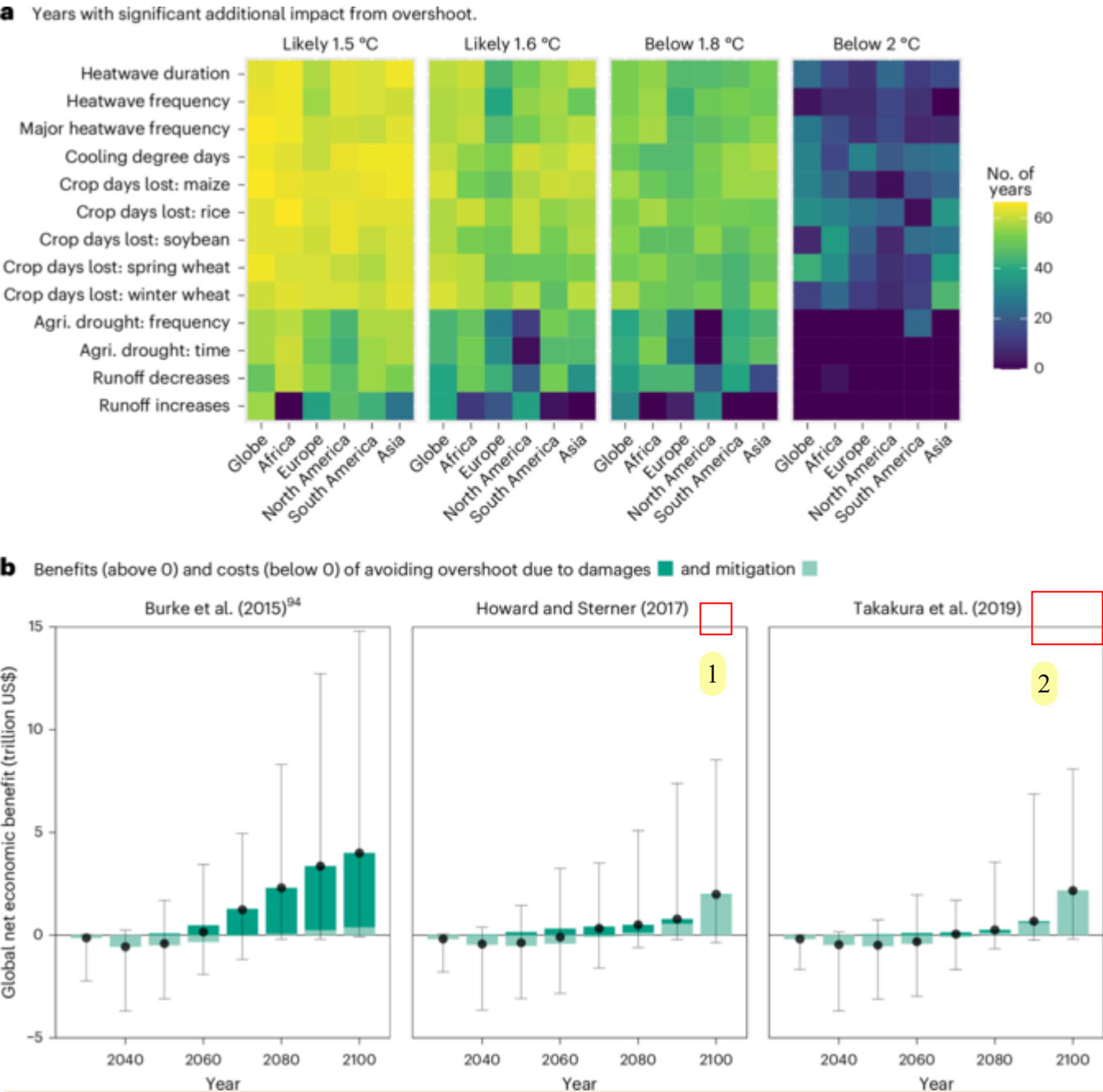
reducing forest carbon uptake[7] and affecting electricity generation[88,89]. The net effect of climate impacts on energy demand can be significant, especially in hot regions[90,91] and on future technologies, and is now often included in mitigation scenarios. Indeed, energy systems are becoming more vulnerable to climate change and extreme weather events[88,92].

Fig. 5

Physical and economic impacts of overshoot.

a,b, Differences in physical and economic impacts between scenarios allowing or not allowing temporary overshoot and net-negative emissions while targeting the same temperature in 2100. Panel a shows the number of years with increased physical risk from overshoot for four warming categories in 2100, for various impacts (rows) and regions (columns) AQ13. Panel b shows the global net economic benefits of avoiding overshoot arising from reduced economic damages (dark green, for three different damage functions from refs. [94], [119], [120]) and changes in mitigation costs (light green). The points represent the median values, and the error bars represent the 5–95% confidence intervals. Figure reproduced with permission from ref. [80], Springer Nature Limited.

Source data



1.119

2.120

The additional physical risks of overshoot percolate to socio-economic impacts and natural systems. Permanent temperature exceedance leads to enduring climate economic damages. For transient overshoot, the economic damages will depend on their persistence: recent estimates point to a persistence of climate shocks on the economy of almost a decade[93], but there is significant uncertainty, especially on the possible role of adaptation. Longer persistence increases the negative economic consequences of global warming substantially, as well as the additional effect of a temporary overshoot[42]. The global climate economic benefits of limiting even a temporary overshoot outweigh the short-term costs of higher mitigation efforts, but only under the assumption of long-lasting economic impacts of temperature exceedance[79] (Fig. 5b). The economic consequences from temperature overshoot are particularly concentrated in developing communities and economies, given their higher climate exposure and vulnerability[94]. On one hand, accounting for the climate benefits of mitigation across and within countries increases the desirability and feasibility of reducing emissions, as these can also help reduce economic inequality[35,95]. On the other hand, climate risks increase adaptation needs, put the stability of sovereign debts at risk[96] and result in non-adaptable losses and damages[97].

Scenario making in future overshoot times

Over three decades of research, during which global emissions continued to rise while climate targets became increasingly stringent, overshoot pathways have become a core component of mitigation scenarios. This interconnectedness underscores the ongoing need to enhance the realism of emission reduction strategies in light of ongoing technological and societal changes, including the geopolitical

fragmentation and unrelenting advancement of low-carbon solutions. The focus should also include non-CO₂ gases, given the current large scenario uncertainties, their relevance for peak temperature and the uncertainties in their carbon cycle and climate feedbacks[98].

This paper has also highlighted some unique features of overshoot, which open important research avenues across natural, social and policy systems (Table 1). Research on carbon removal is advancing[99], and as additional CDR strategies are included in models (for example, ocean based[100]), their trade-offs must be carefully considered. In addition to removal effectiveness and environmental sustainability, models should consider infrastructure needs, public acceptance, policy design, financial and monitoring feasibility, and legal constraints. These are all crucial elements of CDR technologies, only partly captured in existing assessments[49,101,102,103,104]. The Earth system response to overshoot in terms of carbon cycle behaviour, climate extremes, local climate signals and tipping risks[105,106] is also not fully integrated into climate-society modelling. Overshoot implications for ecological and natural systems, such as land and water[107,108], should also be accounted for as they play essential roles in mitigation pathways. Translating physical hazards into societal consequences across different countries and stakeholders is crucial for designing effective adaptation and mitigation strategies to recover from the inevitable overshoot and fostering a well-purposed net-zero/net-negative society.

Table 1

Promising avenues of research for overshoot and mitigation pathways

Physical and natural systems	Social and economic systems	Policy and governance frameworks
(1) Earth system response to positive and negative emissions, including fast and slow feedbacks (1) Removal capacity and environmental sustainability of CO ₂ and CH ₄ removal (land-based, industrial, ocean-based) (2) Climate impacts on energy, land and water systems and their irreversibility (2) Climate extremes globally and regionally (3) Adaptation capacity for energy, land and water systems (3) Carbon cycle responses from terrestrial and marine ecosystems (4) Tipping points (4) SRM climate effectiveness and physical impacts	(1) Trade-offs between overshoot and near-term emissions reductions integrating mitigation, CDR and climate risks (1) Socio-economic impacts across sectors (for example, energy or economic), activities (for example, labour and capital productivity, education and health) and groups (for example, income, gender, age and race) (2) Responsibility of countries and actors (for example, carbon majors) (2) Public acceptance of CDR and negative emissions (3) Social and economic adaptation to rising hazards (3) Financial and economic sustainability of a net-negative economy (4) SRM socio-economic impacts within and across countries	(1) Extent of temporary overshoot given the feasibility of short-term emission reductions (1) Moral hazard of overshoot for reduced mitigation efforts (2) Policy instruments for CDR (for example, separate markets, intertemporal instruments, subsidies, regulation, and research and development) (2) International and intertemporal governance of CDR rights (for example, carbon banks) (2) Public finance policies (3) Governance of mitigation and CDR in a fragmented world (4) International governance of SRM
Readiness levels: (1) currently ongoing, (2) feasible by enhancing current tools, (3) requires structured interaction and coupling with other scientific communities and (4) still speculative/requires fundamental advances.		

These developments necessitate a deeper integration of natural, environmental and socio-technical systems into models; although some of these are ongoing, others require advancements in methods and disciplinary integration (Table 1). Given the complexity of the Earth system, climate impact and mitigation pathways modelling, full integration is not only impossible but also undesirable, given the different epistemologies of the social, economic and physical modelling sciences[109]. However, soft connecting models of varying natures through reduced-complexity approaches allow for the exchange of critical information while retaining native methodological features. Soft linking requires methodological advances, especially on computationally tractable emulators for use by integrated assessment and other models, and the definition of clear interfaces between physical and societal system models on vegetation and land use[110]. Advancements in artificial intelligence can help develop fast and robust statistical emulators of physical processes[111]; for socio-economic processes, more work is needed, which can also incorporate qualitative judgements, such as those provided by stakeholders through interviews, surveys and other means. A key methodological and community development need is the robust quantification of uncertainties in physical and social responses to overshoot. The community practice of model comparison needs to be complemented by extensive sensitivity auditing of the coupled models, uncertainty quantification and robust decision-making in the face of radical uncertainties.

Important community activities are already ongoing. The emission scenarios for CMIP7 from the Scenario Model Intercomparison explore different levels of overshoot[112]. Some align with the Paris Agreement, but others feature longer and deeper overshoots and reversals. Earth system models will explicitly explore the overshoot issue in fast track (for example, CDR-MIP), feeding emulators that can be coupled to IAMs. The climate impact community (for example, ISIMIP) will also explore these scenarios and their consequences for climate hazards. Improved modelling of climate risks and their interaction with socio-economic systems is a key priority of future research, with a need to understand and explicitly represent transmission channels and the extent of damage persistence. In addition to the three main modelling communities related to the IPCC, other model classes that have made significant contributions to mitigation strategies will be progressively involved in the discussions around overshoot. These include energy system models, land and water models, and social and economic models such as agent-based, computable general equilibrium and stock-flow consistent models.

Scenarios exploring overshoots need to account for the fragmented nature of the climate transition and the geographically varying speed of adoption of low-carbon technologies, especially in emerging economies. In a world where climate change is not the top policy priority, research will need to quantify the societal and economic consequences of overshooting, for example, on other policy-relevant issues such as air pollution[113], biodiversity loss, structural economic reform and economic inequalities. The scenario community will be increasingly asked to evaluate non-conventional approaches, including solar geo-engineering. Doing it properly requires careful modelling of the physical and social details as well as a thorough assessment of uncertainties and deep unknowns. It should thus be addressed through novel methods that can treat uncertainties and represent the critically important governance aspects.

Conclusion

We have shown how overshoot has evolved from a modelling artefact to a structural feature of mitigation pathways and how this requires rethinking scenario design, community interactions and methodological innovation to address a multi-decadal era of overshoot effectively.

Climate overshoot generates significant distributional consequences, particularly in terms of the geographical and temporal allocation of emission reductions, technology deployment, and social and economic impacts resulting from increased climate risks. We have shown that overshoot does not automatically translate into carbon removal and that the relationship between overshoot and mitigation is mediated by scenario design and policy stringency as much as by model assumptions.

As society moves into a prolonged and uncertain overshoot future, analytical tools that provide robust insights will be essential. Yet, understanding how to manage and overcome overshoot in societally beneficial ways requires both disciplinary methodological innovation and interdisciplinary collaboration. Strengthening model interactions between socio-economic and physical processes is key to overshoot research. Methodological advancements through statistical and dynamic approaches can enhance the understanding and quantification of uncertainty in peak temperature management, climate impact feedbacks and institutional constraints on mitigation capacity.

Developing such tools and integration strategies is now a central task for the climate modelling and policy communities. Overshoot is no longer a hypothetical deviation but a defining characteristic of the climate transition, one still fraught by many scientific uncertainties. How societies understand and govern this phase will shape the prospects for limiting long-term warming and safeguarding human and natural systems.

Supplementary information

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Author contributions

M.T. conceived the study and designed the study with initial contributions from E.K., J.R., K.R. and D.v.V. M.T. wrote the draft and revised the paper, with all authors contributing to the writing. E.K. provided specific ideas and comments, particularly on sections 1 and 3.

Peer review

Peer review information

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Data availability

All the data used to produce the original figures and tables in this paper are freely available via the IAMC IPCC AR6 scenario database (<https://data.ene.iiasa.ac.at/ar6/#/login>). **Source data** are provided with this paper.

Code availability

The code for producing the paper’s original figures is available via Zenodo **AQ14** at <https://doi.org/10.5281/zenodo.17603848> (ref. [**114**]).

Competing interests

The authors declare no competing interests **AQ15 AQ16**.

Supplementary information

Supplementary Information

Supplementary Tables 1 and 2, Fig. 1 and references.

Source data

Source Data Fig. 1

Statistical source data.

Source Data Fig. 2

Statistical source data.

Source Data Fig. 3

Statistical source data.

Source Data Fig. 4

Statistical source data.

Source Data Fig. 5

Statistical source data.

References

1. WMO Global Annual to Decadal Climate Update (2024–2028) (World Meteorological Organization, 2024); <https://wmo.int/publication-series/wmo-global-annual-decadal-climate-update-2024-2028>

2. Rogelj, J. et al. in *Special Report on Global Warming of 1.5 °C* (eds Masson-Delmotte, V. et al.) 93–174 (IPCC, WMO, 2018).

3. Riahi, K. et al. in *Climate Change 2022: Mitigation of Climate Change* (eds Shukla, P. R. et al.) 295–408 (IPCC, Cambridge Univ. Press, 2023); <https://doi.org/10.1017/9781009157926.005>

4. Schleussner, C.-F. et al. Overconfidence in climate overshoot. *Nature* **634**, 366–373 (2024).

5. Reisinger, A. et al. Overshoot: a conceptual review of exceeding and returning to global warming of 1.5 °C. *Annu. Rev. Environ. Resour.* **50**, 185–217 (2025). **A review article discussing the concept of overshoot in climate science.**

6. Strefler, J. et al. Alternative carbon price trajectories can avoid excessive carbon removal. *Nat. Commun.* **12**, 2264 (2021).

7. Jäger, F. et al. Fire weather compromises forestation-reliant climate mitigation pathways. *Earth Syst. Dyn.* **15**, 1055–1071 (2024).

8. Bosetti, V. in *Oxford Research Encyclopedia of Economics and Finance* (Oxford Univ. Press, 2021 **AQ17**); <https://doi.org/10.1093/acrefore/9780190625979.013.572>

9. Wigley, T. M. L., Richels, R. & Edmonds, J. A. Economic and environmental choices in the stabilization of atmospheric CO₂ concentrations. *Nature* **379**, 240–243 (1996). **The paper that introduced the concept of welfare maximization in determining emission pathways for a given climate objective.**

10. Weyant, J. P., de la Chesnaye, F. C. & Blanford, G. J. Overview of EMF-21: multigas mitigation and climate policy. *Energy J.* **27**, 1–32 (2006).

11. den Elzen, M., Meinshausen, M. & van Vuuren, D. Multi-gas emission envelopes to meet greenhouse gas concentration targets: costs versus certainty of limiting temperature increase. *Glob. Environ. Change* **17**, 260–280 (2007).

12. Swart, R., Mitchell, J., Morita, T. & Raper, S. Stabilisation scenarios for climate impact assessment. *Glob. Environ. Change* **12**, 155–165 (2002).

13. Hare, B. & Meinshausen, M. How much warming are we committed to and how much can be avoided? *Climatic Change* **75**, 111–149 (2006).

14. den Elzen, M. G. J. & van Vuuren, D. P. Peaking profiles for achieving long-term temperature targets with more likelihood at lower costs. *Proc. Natl Acad. Sci. USA* **104**, 17931–17936 (2007).

15. Vuuren, D. P. et al. Stabilizing greenhouse gas concentrations at low levels: an assessment of reduction strategies and costs. *Climatic Change* **81**, 119–159 (2007).

16. Clarke, L. et al. International climate policy architectures: overview of the EMF 22 International Scenarios. *Energy Econ.* **31**, S64–S81 (2009). **An influential model comparison explicitly exploring the role of overshoot in international climate policy.**

17. O’Neill, B. C. & Oppenheimer, M. Climate change impacts are sensitive to the concentration stabilization path. *Proc. Natl Acad. Sci. USA* **101**, 16411–16416 (2004).

18. Tavoni, M. & Tol, R. S. J. Counting only the hits? The risk of underestimating the costs of stringent climate policy. *Climatic Change* **100**, 769–778 (2010).
19. Williams, R. in *Eco-Restructuring: Implications for Sustainable Development* (eds Ayres, R. U. & Weaver, P. M.) 180–222 (UN Univ. Press, 1998) **AQ18**.
20. Obersteiner, M. et al. Managing climate risk. *Science* **294**, 786–787 (2001). **The paper that introduced the concept of negative emission as a climate strategy.**
21. Azar, C., Lindgren, K., Larson, E. & Möllersten, K. Carbon capture and storage from fossil fuels and biomass—costs and potential role in stabilizing the atmosphere. *Climatic Change* **74**, 47–79 (2006).
22. Rao, S. & Riahi, K. The role of non-CO₂ greenhouse gases in climate change mitigation: long-term scenarios for the 21st century. *Energy J.* **27**, 177–200 (2006).
23. Keller, K., Bolker, B. M. & Bradford, D. F. Uncertain climate thresholds and optimal economic growth. *J. Environ. Econ. Manage.* **48**, 723–741 (2004).
24. Rogelj, J. et al. Energy system transformations for limiting end-of-century warming to below 1.5 °C. *Nat. Clim. Change* **5**, 519–527 (2015). **A model intercomparison on 1.5 °C.**
25. IPCC: Summary for Policymakers. In *Climate Change 2021: The Physical Science Basis* (eds Masson-Delmotte, V. et al.) (Cambridge Univ. Press, 2021).
26. Tavoni, M. & Socolow, R. Modeling meets science and technology: an introduction to a special issue on negative emissions. *Climatic Change* **118**, 1–14 (2013). **A special issue on negative emissions, combining modelling and techno-environmental assessments.**
27. Smith, P. et al. Biophysical and economic limits to negative CO₂ emissions. *Nat. Clim. Change* **6**, 42–50 (2016).
28. Fuss, S. et al. Betting on negative emissions. *Nat. Clim. Change* **4**, 850–853 (2014).
29. Chen, C. & Tavoni, M. Direct air capture of CO₂ and climate stabilization: a model based assessment. *Climatic Change* **118**, 59–72 (2013).
30. Fuhrman, J. et al. The role of direct air capture and negative emissions technologies in the shared socioeco pathways towards +1.5 °C and +2 °C futures. *Environ. Res. Lett.* **16**, 114012 (2021).
31. Strefler, J., Amann, T., Bauer, N., Kriegler, E. & Hartmann, J. Potential and costs of carbon dioxide removal by enhanced weathering of rocks. *Environ. Res. Lett.* **13**, 034010 (2018).
32. Rogelj, J. et al. A new scenario logic for the Paris Agreement long-term temperature goal. *Nature* **573**, 357–363 (2019). **Proposal for revising the scenario design to allow achieving long-term climate goals without temporary overshoot.**
33. Riahi, K. et al. Cost and attainability of meeting stringent climate targets without overshoot. *Nat. Clim. Change* **11**, 1063–1069 (2021). **A model comparison explicitly comparing scenarios with and without overshoot.**
34. Soergel, B. et al. A sustainable development pathway for climate action within the UN 2030 Agenda. *Nat. Clim. Change* **11**, 656–664 (2021).
35. Emmerling, J., Andreoni, P. & Tavoni, M. Global inequality consequences of climate policies when accounting for avoided climate impacts. *Cell Rep. Sustain.* **1**, 100008 (2024).
36. Liu, Z. et al. Global patterns of daily CO₂ emissions reductions in the first year of COVID-19. *Nat. Geosci.* **15**, 615–620 (2022).
37. Ou, Y. et al. Deep mitigation of CO₂ and non-CO₂ greenhouse gases toward 1.5 °C and 2 °C futures. *Nat. Commun.* **12**, 6245 (2021).
38. Harmsen, M. et al. Uncertainty in non-CO₂ greenhouse gas mitigation contributes to ambiguity in global climate policy feasibility. *Nat. Commun.* **14**, 2949 (2023).

39. Prütz, R., Strefler, J., Rogelj, J. & Fuss, S. Understanding the carbon dioxide removal range in 1.5 °C compatible and high overshoot pathways. *Environ. Res. Commun.* **5**, 041005 (2023).

40. Kriegler, E., Edenhofer, O., Reuster, L., Luderer, G. & Klein, D. Is atmospheric carbon dioxide removal a game changer for climate change mitigation? *Climatic Change* **118**, 45–57 (2013).

41. Edmonds, J. et al. Can radiative forcing be limited to 2.6 W m⁻² without negative emissions from bioenergy AND CO₂ capture and storage? *Climatic Change* **118**, 29–43 (2013).

42. Bauer, N. et al. Exploring risks and benefits of overshooting a 1.5 °C carbon budget over space and time. *Environ. Res. Lett.* **18**, 054015 (2023). **A thorough model evaluation of overshoot in stringent climate goals.**

43. Johansson, D. J. A., Azar, C., Lehtveer, M. & Peters, G. P. The role of negative carbon emissions in reaching the Paris climate targets: the impact of target formulation in integrated assessment models. *Environ. Res. Lett.* **15**, 124024 (2020).

44. Moustakis, Y., Nützel, T., Wey, H.-W., Bao, W. & Pongratz, J. Temperature overshoot responses to ambitious forestation in an Earth system model. *Nat. Commun.* **15**, 8235 (2024).

45. Merfort, A. et al. Separating CO₂ emission from removal targets comes with limited cost impacts. *Nat. Commun.* **16**, 5298 (2025).

46. Bauer, N. et al. Global energy sector emission reductions and bioenergy use: overview of the bioenergy demand phase of the EMF-33 model comparison. *Climatic Change* **163**, 1553–1568 (2020).

47. Jackson, R. B. et al. Atmospheric methane removal: a research agenda. *Phil. Trans. R. Soc. A* **379**, 20200454 (2021).

48. Smith, C. & Mathison, C. How much methane removal is required to avoid overshooting 1.5 °C?. *Environ. Res. Lett.* **19**, 074044 (2024).

49. Deprez, A. et al. Sustainability limits needed for CO₂ removal. *Science* **383**, 484–486 (2024).

50. Forster, J., Vaughan, N. E., Gough, C., Lorenzoni, I. & Chilvers, J. Mapping feasibilities of greenhouse gas removal: key issues, gaps and opening up assessments. *Glob. Environ. Change* **63**, 102073 (2020).

51. Fujimori, S. et al. A multi-model assessment of food security implications of climate change mitigation. *Nat. Sustain.* **2**, 386–396 (2019).

52. Hirata, A. et al. The choice of land-based climate change mitigation measures influences future global biodiversity loss. *Commun. Earth Environ.* **5**, 259 (2024).

53. Ai, Z., Hanasaki, N., Heck, V., Hasegawa, T. & Fujimori, S. Global bioenergy with carbon capture and storage potential is largely constrained by sustainable irrigation. *Nat. Sustain.* **4**, 884–891 (2021).

54. Vuuren, D. P. et al. Alternative pathways to the 1.5C target reduce the need for negative emission technologies. *Nat. Clim. Change* **8**, 391–397 (2018).

55. Grubler, A. et al. A low energy demand scenario for meeting the 1.5 °C target and sustainable development goals without negative emission technologies. *Nat. Energy* **3**, 515–527 (2018).

56. Bertram, C. et al. Feasibility of peak temperature targets in light of institutional constraints. *Nat. Clim. Change* **14**, 954–960 (2024).

57. Brutschin, E. et al. A multidimensional feasibility evaluation of low-carbon scenarios. *Environ. Res. Lett.* **16**, 064069 (2021).

58. Gambhir, A. et al. Assessing the feasibility of global long-term mitigation scenarios. *Energies* **10**, 89 (2017).

59. Warszawski, L. et al. All options, not silver bullets, needed to limit global warming to 1.5 °C: a scenario appraisal. *Environ. Res. Lett.* **16**, 064037 (2021).

60. MacMartin, D. G. et al. Scenarios for modeling solar radiation modification. *Proc. Natl Acad. Sci. USA* **119**, e2202230119 (2022).

61. MacMartin, D. G., Ricke, K. L. & Keith, D. W. Solar geoengineering as part of an overall strategy for meeting the 1.5 °C Paris target. *Phil. Trans. R. Soc. A* **376**, 20160454 (2018).
62. Emmerling, J. & Tavoni, M. Exploration of the interactions between mitigation and solar radiation management in cooperative and no n-cooperative international governance settings. *Glob. Environ. Change* **53**, 244–251 (2018).
63. Drupp, M. A., Freeman, M. C., Groom, B. & Nesje, F. Discounting disentangled. *Am. Econ. J. Econ. Policy* **10**, 109–134 (2018).
64. Emmerling, J. et al. The role of the discount rate for emission pathways and negative emissions. *Environ. Res. Lett.* **14**, 104008 (2019).
65. Tavoni, M. et al. Post-2020 climate agreements in the major economies assessed in the light of global models. *Nat. Clim. Change* **5**, 119–126 (2015).
66. Fyson, C. L., Baur, S., Gidden, M. & Schleussner, C.-F. Fair-share carbon dioxide removal increases major emitter responsibility. *Nat. Clim. Change* **10**, 836–841 (2020).
67. Pozo, C., Galán-Martín, Á, Reiner, D. M., Mac Dowell, N. & Guillén-Gosálbez, G. Equity in allocating carbon dioxide removal quotas. *Nat. Clim. Change* **10**, 640–646 (2020).
68. Steg, L. et al. A method to identify barriers to and enablers of implementing climate change mitigation options. *One Earth* **5**, 1216–1227 (2022).
69. Humpenöder, F. et al. Food matters: dietary shifts increase the feasibility of 1.5 °C pathways in line with the Paris Agreement. *Sci. Adv.* **10**, eadj3832 (2024).
70. Calcaterra, M. et al. Reducing the cost of capital to finance the energy transition in developing countries. *Nat. Energy* **9**, 1241–1251 (2024).
71. Iyer, G. et al. Diffusion of low-carbon technologies and the feasibility of long-term climate targets. *Technol. Forecast. Soc. Change* **90**, 103–118 (2015).
72. Markusson, N. et al. Carbon removal and the empirics of climate delay. *Environ. Sci. Policy* **161**, 103884 (2024).
73. Andreoni, P., Emmerling, J. & Tavoni, M. Inequality repercussions of financing negative emissions. *Nat. Clim. Change* **14**, 48–54 (2024).
74. Bednar, J., Obersteiner, M. & Wagner, F. On the financial viability of negative emissions. *Nat. Commun.* **10**, 1783 (2019).
75. Bednar, J. et al. Operationalizing the net-negative carbon economy. *Nature* **596**, 377–383 (2021).
76. Victor, D. G. On the regulation of geoengineering. *Oxf. Rev. Econ. Policy* **24**, 322–336 (2008).
77. Ricke, K. L., Moreno-Cruz, J. B. & Caldeira, K. Strategic incentives for climate geoengineering coalitions to exclude broad participation. *Environ. Res. Lett.* **8**, 014021 (2013).
78. Ritchie, P. D. L., Clarke, J. J., Cox, P. M. & Huntingford, C. Overshooting tipping point thresholds in a changing climate. *Nature* **592**, 517–523 (2021).
79. Drouet, L., Bosetti, V. & Tavoni, M. Net economic benefits of well-below 2 °C scenarios and associated uncertainties. *Oxf. Open Clim. Change* **2**, kgac003 (2022).
80. Drouet, L. et al. Net zero-emission pathways reduce the physical and economic risks of climate change. *Nat. Clim. Change* **11**, 1070–1076 (2021). **A multi-model assessment of the physical and economic consequences of temporary overshoot.**
81. van der Wijst, K.-I., Hof, A. F. & van Vuuren, D. P. Costs of avoiding net negative emissions under a carbon budget. *Environ. Res. Lett.* **16**, 064071 (2021).
82. Zickfeld, K., Azevedo, D., Mathesius, S. & Matthews, H. D. Asymmetry in the climate–carbon cycle response to positive and negative CO₂ emissions. *Nat. Clim. Change* **11**, 613–617 (2021).

83. Cao, L., Jin, X.-Y. & Jiang, J. Simulated carbon cycle and Earth system response to atmospheric CO₂ removal. *Adv. Clim. Change Res.* **14**, 313–321 (2023).
84. Asaadi, A. et al. Carbon cycle feedbacks in an idealized simulation and a scenario simulation of negative emissions in CMIP6 Earth system models. *Biogeosciences* **21**, 411–435 (2024).
85. Chimuka, V. R., Nzotungicimpaye, C.-M. & Zickfeld, K. Quantifying land carbon cycle feedbacks under negative CO₂ emissions. *Biogeosciences* **20**, 2283–2299 (2023).
86. Vichi, M., Navarra, A. & Fogli, P. G. Adjustment of the natural ocean carbon cycle to negative emission rates. *Climatic Change* **118**, 105–118 (2013).
87. Colelli, F. P., Emmerling, J., Marangoni, G., Mistry, M. N. & De Cian, E. Increased energy use for adaptation significantly impacts mitigation pathways. *Nat. Commun.* **13**, 4964 (2022).
88. Yalew, S. G. et al. Impacts of climate change on energy systems in global and regional scenarios. *Nat. Energy* **5**, 794–802 (2020).
89. Cronin, J., Anandarajah, G. & Dessens, O. Climate change impacts on the energy system: a review of trends and gaps. *Climatic Change* **151**, 79–93 (2018).
90. De Cian, E. & Sue Wing, I. Global energy consumption in a warming climate. *Environ. Resour. Econ.* **72**, 365–410 (2019).
91. van Ruijven, B. J., De Cian, E. & Sue Wing, I. Amplification of future energy demand growth due to climate change. *Nat. Commun.* **10**, 2762 (2019).
92. Cruz, T. et al. How climate change will affect the Brazilian energy system: evidence from a systematic review. *Annu. Rev. Environ. Resour.* **50**, 1–27 (2025).
93. Bastien-Olvera, B. A., Granella, F. & Moore, F. C. Persistent effect of temperature on GDP identified from lower frequency temperature variability. *Environ. Res. Lett.* **17**, 084038 (2022).
94. Burke, M., Hsiang, S. M. & Miguel, E. Global non-linear effect of temperature on economic production. *Nature* **527**, 235–239 (2015).
The best-known empirical assessment of the impacts of climate change on economic growth.
95. Emmerling, J. et al. A multi-model assessment of inequality and climate change. *Nat. Clim. Change* **14**, 1254–1260 (2024).
96. Calcaterra, M., Consiglio, A., Martorana, V., Tavoni, M. & Zenios, S. A. Sovereigns on thinning ice: debt sustainability, climate impacts, and adaptation. *SSRN* <https://doi.org/10.2139/ssrn.5074531> (2024).
97. Tavoni, M. et al. Economic quantification of loss and damage funding needs. *Nat. Rev. Earth Environ.* **5**, 411–413 (2024).
98. Melnikova, I. et al. Carbon cycle and climate feedbacks under CO₂ and non-CO₂ overshoot pathways. *Earth Syst. Dyn.* **16**, 257–273 (2025).
99. Lück, S. et al. Scientific literature on carbon dioxide removal revealed as much larger through AI-enhanced systematic mapping. *Nat. Commun.* **16**, 6632 (2025).
100. Kowalczyk, K. A. et al. Marine carbon dioxide removal by alkalization should no longer be overlooked. *Environ. Res. Lett.* **19**, 074033 (2024).
101. Stuart-Smith, R. F., Rajamani, L., Rogelj, J. & Wetzer, T. Legal limits to the use of CO₂ removal. *Science* **382**, 772–774 (2023).
102. Low, S., Fritz, L., Baum, C. M. & Sovacool, B. K. Public perceptions on carbon removal from focus groups in 22 countries. *Nat. Commun.* **15**, 3453 (2024).
103. Becattini, V. et al. Carbon dioxide capture, transport and storage supply chains: optimal economic and environmental performance of infrastructure rollout. *Int. J. Greenh. Gas Control* **117**, 103635 (2022).
104. Edenhofer, O., Franks, M., Gruner, F., Kalkuhl, M. & Lessmann, K. The economics of carbon dioxide removal. *Annu. Rev. Resour. Econ.* **17**, 301–321 (2025).

105. Pfliegerer, P., Schleussner, C.-F. & Sillmann, J. Limited reversal of regional climate signals in overshoot scenarios. *Environ. Res. Clim.* **3**, 015005 (2024).

106. Möller, T. et al. Achieving net zero greenhouse gas emissions critical to limit climate tipping risks. *Nat. Commun.* **15**, 6192 (2024).

107. Meyer, A. L. S. & Trisos, C. H. Ecological impacts of temperature overshoot: the journey and the destination. *One Earth* **6**, 1614–1617 (2023).

108. Marshall, A., Grubert, E. & Warix, S. Temperature overshoot would have lasting impacts on hydrology and water resources. *Water Resour. Res.* **61**, e2024WR037950 (2025).

109. Müller, T., Boccaletti, G., Schneider, T. & Tavoni, M. Actionable coupling of climate science and socio-economics: a philosophy of science perspective on trustworthy model chains. *mimeo* (2025) **AQ19**.

110. Collins, W. D. et al. The integrated Earth system model version 1: formulation and functionality. *Geosci. Model Dev.* **8**, 2203–2219 (2015).

111. Camps-Valls, G. et al. Artificial intelligence for modeling and understanding extreme weather and climate events. *Nat. Commun.* **16**, 1919 (2025).

112. van Vuuren, D. et al. The Scenario Model Intercomparison Project for CMIP7 (ScenarioMIP-CMIP7). Preprint at *EGUsphere* **AQ20** <https://doi.org/10.5194/egusphere-2024-3765> (2025).

113. Rodés-Bachs, C., Drouet, L., Rafaj, P., Tavoni, M. & Reis, L. A. Beyond the limit: the estimated air pollution damages of overshooting the temperature target. *Sci. Adv.* **11**, eadu7590 (2025).

114. Tavoni, M. et al. Data and code for reproducing figures of ‘Implications of overshoot for climate mitigation strategies’. *Zenodo* <https://doi.org/10.5281/zenodo.17603848> (2026).

115. Byers, E. et al. AR6 Scenarios Database. *Zenodo* <https://doi.org/10.5281/zenodo.5886911> (2022).

116. IPCC, 2021: Annex VII: Glossary [Matthews, J.B.R., et al. (eds.)]. In: *Climate Change 2021: The Physical Science Basis*

117. Intergovernmental Panel on Climate Change (IPCC) Climate Change 2022 - Mitigation of Climate Change Working Group III Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change Annex III: Scenarios and Modelling Methods Cambridge University Press 1841-1908

118. United Nations, United Nations Framework Convention on Climate Change (1992), art. 2

119. Peter H., Howard Thomas, Sterner (2017) Few and Not So Far Between: A Meta-analysis of Climate Damage Estimates *Environmental and Resource Economics* 68(1) 197-225 10.1007/s10640-017-0166-z

120. Jun’ya, Takakura Shinichiro, Fujimori Naota, Hanasaki Tomoko, Hasegawa Yukiko, Hirabayashi Yasushi, Honda Toshichika, Iizumi Naoko, Kumano Chan, Park Zhihong, Shen Kiyoshi, Takahashi Makoto, Tamura Masahiro, Tanoue Koujiro, Tsuchida Hiromune, Yokoki Qian, Zhou Taikan, Oki Yasuaki, Hijioka (2024) Author Correction: Dependence of economic impacts of climate change on anthropogenically directed pathways *Nature Climate Change* 14(4) 407-407 10.1038/s41558-024-01930-6