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Multispeed mitigation strategies to limit mid-century overshoot and return to 1.5°C

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Abstract

It is no longer feasible to hold global temperature change to under 1.5°C, but options remain to minimize the duration and extent of mid-century overshoot and reduce temperatures to 1.5°C over the longer term. Using a global integrated assessment model (GCAM-CGS) coupled with a climate model (MAGICC), we develop a "multispeed mitigation" pathway that limits peak warming to 1.9°C in 2060 and returns to 1.5°C by 2130 by combining "fast mitigation" and "slow mitigation" strategies that link to plausible policy actions on appropriate timelines, and a consistent set of decomposition scenarios that deploy only one or multiple fast or slow strategies to quantify the temperature impacts by each policy strategy. We show that the multispeed mitigation pathway greatly lowers long-term temperature compared to the reference case (3.8°C by 2130) and peaks temperature decades earlier at a lower level compared to a pathway that relies solely on slow mitigation (2.3°C post-2100). Fast mitigation levers, particularly reducing key super pollutants and ending deforestation, largely determine temperature overshoot by contributing two-thirds of potential 2050 temperature reduction compared to one-third from slow mitigation levers like the global energy transition. Both levers remain critical for the long-term return to 1.5°C. By 2100, slow mitigation levers contribute over 60% of the total reduction, while sustained fast mitigation strategies, like methane abatement from agriculture and waste sectors continue to have a strong impact and drive more reductions than carbon removal technologies. Our findings directly inform the ongoing policy discussion how to address global overshoot above 1.5°C, including policy-relevant international coordination strategies that situate energy transition efforts within a broader, structured, multispeed mitigation approach.

1. Introduction

The year 2025 marked the tenth anniversary of the Paris Agreement, under which countries seek to hold global temperature rise to well below 2°C above pre-industrial levels and to pursue efforts to limit the increase to 1.5°C. However, as global emissions of greenhouse gases (GHG) continue to rise, limiting warming to 1.5°C with no or limited overshoot is no longer plausible.[1,2] This has prompted calls to jettison the global 1.5°C goal, with the benchmark falling back to 2°C.[3,4] However, the risks and costs of climate change increase nonlinearly with every tenth-degree, and the risk of surpassing dangerous tipping points increases the longer the planet remains above 1.5°C.[5] It is therefore crucial to identify viable pathways to minimize mid-century overshoot and reduce temperatures to 1.5°C or lower as soon as possible.[6–9]

Achieving these dual objectives requires combining a full set of mitigation strategies to deliver comprehensive carbon dioxide (CO_2) and non-CO_2 emissions reductions.[6,7,10–14] While this concept and the associated behaviors of these gases is well known in the science community, the large set of scenarios, policy options, and mitigation strategies has clouded conversations and precluded strong consensus around actions in international policy discussions. A sharper and simpler approach and staging strategy is needed that both is informed quantitatively by the science and that also resonates with the activities that can be implemented in the near term. As a first step toward this goal, based on the speed of their implementation and timeframe of their temperature impacts, we group these mitigation strategies into what we term "fast" and "slow" mitigation categories. When combined, we term this approach "multispeed mitigation".

Policy attention so far has focused heavily on CO_2 reductions through the energy transition, covering fast mitigation strategies inconsistently at best, and rarely considering a full multispeed mitigation strategy. For example, while the first Global Stocktake at COP28 encouraged countries to address non-CO_2 in their

Nationally Determined Contributions (NDCs) and to end deforestation, its main focus was the energy transition, including global targets of tripling renewable energy capacity and doubling energy efficiency improvements by 2030.[15] Similarly, the 2025 G20 declaration addresses energy and deforestation but omits any reference to methane or other non-CO_2 greenhouse gases.[16] Some recent literature even suggests shifting from prioritizing global temperature limits to focusing policy instead on clean energy targets[17], completely missing critical fast mitigation actions.

Fast mitigation strategies can deliver temperature benefits quickly, both because of the potential speed of implementation and the speed with which they deliver net forcing reduction. We have included two fast mitigation levers in this analysis. The first is rapid abatement of a set of "fast super pollutants," which includes both short-lived climate pollutants (SLCPs) with high warming potential as well as longer-lived pollutants that have high warming potential, fast implementation timelines, and/or fewer co-emitted pollutants with cooling effects. All of the pollutants in this lever—methane (CH_4), fluorinated gases, tropospheric ozone precursors, black carbon, and industrial nitrous oxide (N_2O)—are classified as super pollutants by the Climate and Clean Air Coalition (see Supplementary Table 1 for super pollutants mapping).[18] Though agricultural N_2O is also considered a super pollutant, we have placed it in the slow mitigation category due to both a slower implementation timeline and co-emitted pollutants that delay the net cooling benefits of abatement. The second fast mitigation lever is ending tropical deforestation and bolstering land sinks.[19,20] Rapidly reducing deforestation can still generate net temperature benefits by mid-century because of the relative immediacy of the CO_2 reductions and because, unlike the energy transition, these reductions do not coincide with a reduction in cooling sulfur dioxide (SO_2) aerosols. For this lever, we only refer to model the climate impacts of emissions associated with deforestation, not the local temperature effects of albedo and latent heat changes. Incorporating these local effects would likely show larger climate benefits in tropical regions from reducing deforestation.[21]

Slow mitigation strategies can take either longer to implement or longer to yield forcing benefits. As such, they cannot deliver temperature benefits as quickly but are necessary for stabilizing long-term temperature. We have included three slow mitigation levers in this analysis (Supplementary Table 1): the energy transition away from fossil fuels[22,23], fertilizer optimization[24], and carbon dioxide removals through negative emissions technologies (NETs) such as bioenergy with carbon capture and storage (BECCS) and direct air capture (DAC)[25–27]. Due to the long atmospheric lifetime of CO_2 and a short-term cooling effect from the co-emitted pollutants from fossil fuel combustion and industrial processes, such as SO_2 from coal and heavy oils, the net temperature benefit by mid-century from the energy transition is limited. Notably, the cooling effect of co-emitted SO_2 emissions from fossil-fueled global electricity production (particularly from coal) has roughly offset the current warming impact from cumulative CO_2 emitted from power generation since the industrial revolution.[28] Similarly, reducing fertilizer usage also reduces the cooling effect of co-emitted nitrogen oxides (NO_x) and ammonia (NH_3) and thus has a limited net temperature benefit in the near term.[29] Finally, NETs are categorized as "slow" mitigation strategies because they mainly impact CO_2 concentrations (which also respond slowly) and, as expensive, emerging technologies, are not currently on track to be scaled up until the second half of the century.

To fill the research gap for ongoing policy discussion regarding pathways and options for minimizing the magnitude and duration of the now inevitable overshoot above 1.5°C [9] and direct policy attention beyond the energy transition to a full set of multispeed mitigation strategies, this research presents the first

quantitative analysis of how each of the fast and slow mitigation levers contribute to limiting the exceedance of and returning to 1.5°C under the multispeed pathway. By using an open-source, state-of-the-art global integrated assessment model (GCAM-v8-CGS) coupled with a reduced complexity Earth system model (MAGICC), we develop a suite of pathways with different combinations of high-ambition, plausible actions spanning the five mitigation levers described above, capturing economy-wide and cross-system interlinkages and track all GHG emissions and their climate forcing and temperature outcomes. We show that only the multispeed mitigation pathway that deploys all levers can both materially limit the level and duration of temperature overshoot and deliver a return to 1.5°C over the long term. Our scenario design and modeling analysis are based on feasible policies on appropriate timelines with a staging approach that reflects, both scientifically and through policies, the relative priority of different actions at different times. The multispeed mitigation pathway provides a set of concrete strategies to address the unavoidable 1.5°C exceedance, by limiting the magnitude and duration of overshoot, followed by a return toward 1.5°C.

2. Methods

Using an open-source, global model that represents and integrates human and Earth system dynamics, the Global Change Analysis Model[30] (GCAM-v8-CGS, see Supplementary Text S1), we develop seven core scenarios based on different combinations of the fast and slow mitigation strategies through 2100 (Table 1 & Supplementary Text S2), for each lever aiming for ambitious but feasible policy action at the global level.[31,32]. The two fast mitigation levers are targeted abatement of key non-CO_2 super pollutants (Fast Super Pollutants) and ending deforestation & bolstering land carbon sinks (Land), and the three slow mitigation levers are energy transition (Energy), fertilizer optimization (Fertilizer), and carbon dioxide removal through negative emissions technologies (NETs).

First, we start with a reference scenario (*Reference*), following continued trends without explicit policy action. While it includes a very low level of carbon price on energy and industrial CO_2 emissions (Supplementary Figure 2) to reflect the continued trends of energy transition largely driven by cheap clean technologies, it excludes any intervention for the rest of fast and slow mitigation levers (see Supplementary Text S2). Our *Reference* scenario therefore leads to higher 2100 temperature compared to pathways that include current policies.[33,34] Second, we model an SLCP-focused scenario (*Fast-SPs only*) with rapid reductions of CH_4 and other non-CO_2 super pollutants through targeted abatement, while other fast or slow levers have no explicit policy action. The targeted abatements are implemented after 2025 in GCAM through marginal abatement cost curves (MACC) for all non-CO_2 gases except for agricultural N_2O (as a slow lever), where methane prices are used to activate the MACC but not applied to the emissions directly (see Supplementary Text S1). Third, we model a fast mitigation-focused scenario (*Fast only*) that combines both the Fast Super Pollutant and Land levers but no explicit action for any slow levers. In addition to the targeted super pollutant abatement, this scenario also includes achieving net-zero land sinks by 2035 with continued bolstering afterward, which is implemented through regional carbon prices on land-use change CO_2 emissions after 2025 in GCAM (see Supplementary Text S2 and Supplementary Figures 1 and 2).

The fourth scenario is energy transition-focused (*Energy only*) with accelerated energy transition to reach net zero energy and industrial CO_2 before 2070 (including at-scale NETs) but no additional action in any fast mitigation or fertilizer optimization. This is implemented through regional carbon prices on energy and industrial CO_2 emissions after 2025 in GCAM (see Supplementary Text S2). The fifth scenario (*Slow only*) combines all three slow mitigation levers, adding accelerated reduction of agricultural N_2O through

fertilizer optimization. This is implemented after 2025 in GCAM through marginal abatement cost curves (MACC) for fertilizer N_2O emissions, where N_2O prices are used to activate the MACC but not applied to the emissions directly (see Supplementary Text S2). The sixth scenario (*Limit NET*) combines all fast and slow levers, except for limiting the availability of negative emissions technologies (BECCS and DAC). This is implemented by turning off these technologies in GCAM. Finally, the seventh scenario (*Combo*) is the multispeed mitigation pathway that deploys all fast and slow mitigation levers.

Emissions pathways from GCAM are also extended through 2130 (see Supplementary Text S3 for emissions extension method) to run the Model for the Assessment of Greenhouse Gas Induced Climate Change (MAGICC), a reduced-complexity Earth-systems model, to translate greenhouse gas emissions data into projections for atmospheric concentrations, radiative forcing, and global mean surface temperatures (see Supplementary Text S1).

Table 1. Summary of scenario design for seven core scenarios (see Supplementary Table 2 for two additional delay sensitivities)

	LEVERS				
	Fast Mitigation		*Slow Mitigation*		
Scenario	**Fast SPs**	**Land**	**Energy**	**Fertilizer**	**NETs**
Reference	○	○	○	○	○
Fast-SPs only	●	○	○	○	○
Fast only	●	●	○	○	○
Energy only	○	○	●	○	●
Slow only	○	○	●	●	●
Limit NET	●	●	●	●	○
Combo	●	●	●	●	●

● strong action ○ no action beyond current trends

3. Results

Emissions pathways with different combinations of fast and slow mitigation strategies

Under the *Reference* and *Fast only* scenarios, global energy and industrial CO_2 emissions (Figure 1a) remain fairly flat throughout the century. In contrast, under the *Slow only* and *Combo* scenarios, energy and industrial CO_2 emissions achieve deep reductions with an accelerated energy transition (including BECCS), reaching net zero around 2070. Under the *Limit NET* scenario, with no NETs but strong action across all other levers, there are about 3.3 $GtCO_2$ of residual emissions by 2100. Scaling up NETs deployment requires a separate policy framework that covers multiple dimensions, including research, development, demonstration, market and commercialization, standards, and regulations. Global agricultural N_2O

emissions (Figure 1b) nearly double by 2100 under the *Reference* scenario, which is avoided through another slow mitigation lever—fertilizer optimization under the *Slow only*, *Limit NET*, and *Combo* scenarios (Figure 1b).

Absent targeted action in the land sector (e.g. *Reference* and *Slow only*), CO_2 emissions from land use, land use change and forestry (LULUCF) hold roughly constant until 2050 before gradually declining toward zero by the end of the century (Figure 1c). In contrast, emissions drop rapidly in scenarios with strong action (*Fast only*, *Limit NET,* and *Combo*), reaching a net-zero land sink by 2035 and generating around 3.5 to 5.5 Gt of net sink around 2055, which then gradually decreases towards 2100. In contrast to the energy transition, there is no need to wait for technological breakthroughs or lengthy capital stock turnover to end deforestation. Recent experience in Brazil shows that concerted political commitment can quickly drive down deforestation rates.[35] There may also be fast benefits from avoiding key ecosystem tipping points that might otherwise cause rapid emissions increases from forest fires and other adverse events if deforestation rates are not rapidly controlled.[36] Indeed, the severe 2024 fire season in Brazil underscores these risks.[37]

Global CH_4 emissions (Figure 1d) continue to increase under the *Reference* scenario, with energy and waste sector CH_4 emissions staying fairly constant throughout the century, while agriculture CH_4 increases steadily (Supplementary Figure 3). Even without targeted CH_4 abatement measures, an accelerated energy transition alone (e.g. *Slow only*) reduces energy sector CH_4 emissions, while overall CH_4 emissions stay roughly constant and then increase mainly due to agricultural CH_4 growth (Supplementary Figure 3). Targeted CH_4 abatement measures across all sectors (e.g. *Fast only*) deliver faster and deeper reductions in total CH_4 emissions and achieve the Global Methane Pledge reduction target of 30% below 2020 levels by around 2035 (we have assumed a five-year delay from the original 2030 goal). When combined with an accelerated energy transition, further reductions are achieved after 2040 (*Combo* and *Limit NET*). Other components of the fast super pollutants lever include industrial N_2O emissions, which are reduced rapidly under the *Fast-SPs only*, *Fast only*, and *Combo* scenarios (Supplementary Figure 2), HFCs (as part of f-gases in Supplemental Figure 7b), which decline in all scenarios, but are reduced on a much faster timeline in the *Fast-SPs only*, *Fast only*, and *Combo* scenarios by addressing existing stocks of HFCs.

Together, global total GHG emissions (measured in CO_2-equivalent using 100-year global warming potentials from IPCC AR5, Figure 1e) remain fairly flat throughout the century under the *Reference* scenario. Relative to the *Reference scenario,* the *Fast only* scenario lowers emissions by about 25% in 2100 and *Slow only* by about 90% in 2100. The multispeed *Combo* scenario is the only one that delivers net zero GHG emissions, reaching that threshold by 2075.

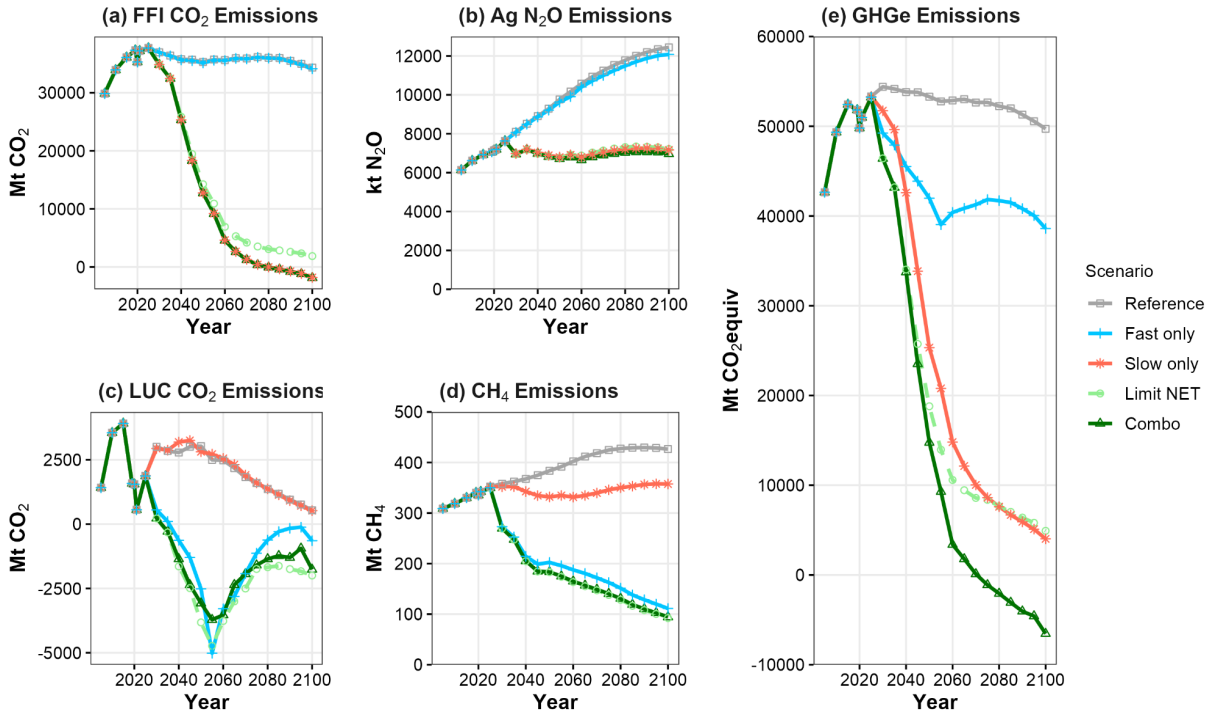


Figure 1. Global emissions pathways across five of the core scenarios: (a) energy and industrial (FFI) CO_2 emissions, (b) total agriculture N_2O emissions, (c) land use change CO_2 emissions, (d) total CH_4 emissions, and (e) total GHG emissions (measured in CO_2-equivalent using 100-year global warming potential from IPCC AR5). See Supplementary Figures 4-7 for emission pathways for all seven core scenarios.

Temperature implications of multispeed mitigation

Under the *Reference* scenario, global temperature increases by 2.11°C in 2050 and by 3.23°C in 2100 from the pre-industrial levels (Figure 2a and Table 2). Extended emissions pathways (Supplementary Table 4) for the *Reference* scenario lead to a 3.76°C increase by 2130 (Supplementary Table 5). By implementing the full set of fast and slow mitigation strategies (*Combo*), global warming is kept at 1.88°C around 2050, a quarter of a degree reduction from the reference, peaks at 1.89°C around 2060, and declines to 1.71°C by the end of the century. With the extended emissions pathways, warming by 2130 is reduced to 1.54°C, a 2.22°C reduction from the reference.

In comparison, under the scenario that only focuses on the energy transition (*Energy only*), temperature exceeds 1.89°C almost 20 years earlier than the multispeed mitigation scenario, and peaks at 2.28°C post-2100. Temperature overshoot above 1.5°C under the *Energy only* scenario is sustained for the duration of the analysis at a much higher peak level. Adding fertilizer optimization (*Slow only*) has a marginal impact on both near- and long-term temperature. In scenarios that only deploy the fast mitigation strategies (*Fast-SPs only* and *Fast only*), on the other hand, 2050 temperatures are substantially lower in 2050 but grow afterwards without stabilization.

In sum, fast mitigation levers are essential to limit mid-century peak warming and remain important over the longer term, while the energy transition is the dominant driver of long-term temperature stabilization.

Minimizing mid-century overshoot and stabilizing 1.5°C over the longer term requires a multispeed pathway that simultaneously and rapidly deploys complementary fast and slow mitigation strategies.

Temperature implications of individual fast and slow mitigation levers

Through a decomposition analysis, we assess each mitigation lever's relative contribution to temperature reductions in the multispeed mitigation scenario (see Supplementary Text S4 for decomposition method). Energy CH_4 reductions can be achieved through both targeted abatement (a fast mitigation lever) and fossil phaseout (a slow mitigation lever). To attribute these reductions under *Combo* (Figure 1d), we first allocate the targeted CH_4 reductions from *Reference* to *Fast-SPs only* to fast mitigation and then the additional reductions from *Fast-SPs only* to *Combo* to slow mitigation. This approach shows the temperature reductions delivered through targeted fast super pollutant abatement even without an accelerated energy transition. An alternative approach is also presented in the Supplementary Information that separates the CH_4 reductions achieved through fossil phaseout under *Energy only* and allocates it to energy transition (Supplementary Tables 5 & 6).

In the *Combo* scenario, fast mitigation strategies dominate mid-century cooling, contributing two-thirds of the total temperature reductions from *Reference* in 2050 (Fast SPs and Land in Figure 2c). Sustained fast mitigation strategies remain crucial throughout the analysis period, contributing 45% of the total reductions in 2075, 38% in 2100, and 34% in 2125 (Figure 2c). For fast mitigation to deliver long-term climate stabilization benefits, sustained progress in both of the two fast mitigation levers is required. First, innovation and sustained structural shifts, such as adopting lower-methane agricultural and waste management practices, can deliver temperature reductions that grow steadily from 0.13°C in 2050 to 0.46°C in 2100 and 0.58°C by 2125 (Table 2). The fast super pollutants lever continues to deliver a larger temperature reduction than NETs after 2100. Second, reductions in CO_2 from bolstering land carbon sinks can further reduce warming by 0.11°C from *Reference* in 2100 and by 0.14°C in 2125 (Table 2).

By contrast, the energy transition delivers only 0.06°C of cooling in 2050, or 26% of the total reductions from *Reference* under the multispeed mitigation pathway, due to the reduced short-term cooling effect from the co-reduction of particulates, such as sulfur dioxide (SO_2), together with mitigation delays due to slow capital stock turnover in energy systems and the long atmospheric lifetime of CO_2. The contribution to temperature reductions from the energy transition increases over time to 0.35°C (42%) by 2075, 0.69°C (46%) by 2100, and 0.99°C (47%) in 2125 (Table 2). CDR through NETs does not generate temperature reduction from *Reference* until 2050 and contributes a 0.20°C reduction (13% of total) in 2100 and a 0.33°C reduction (15% of total) in 2125 (Table 2).

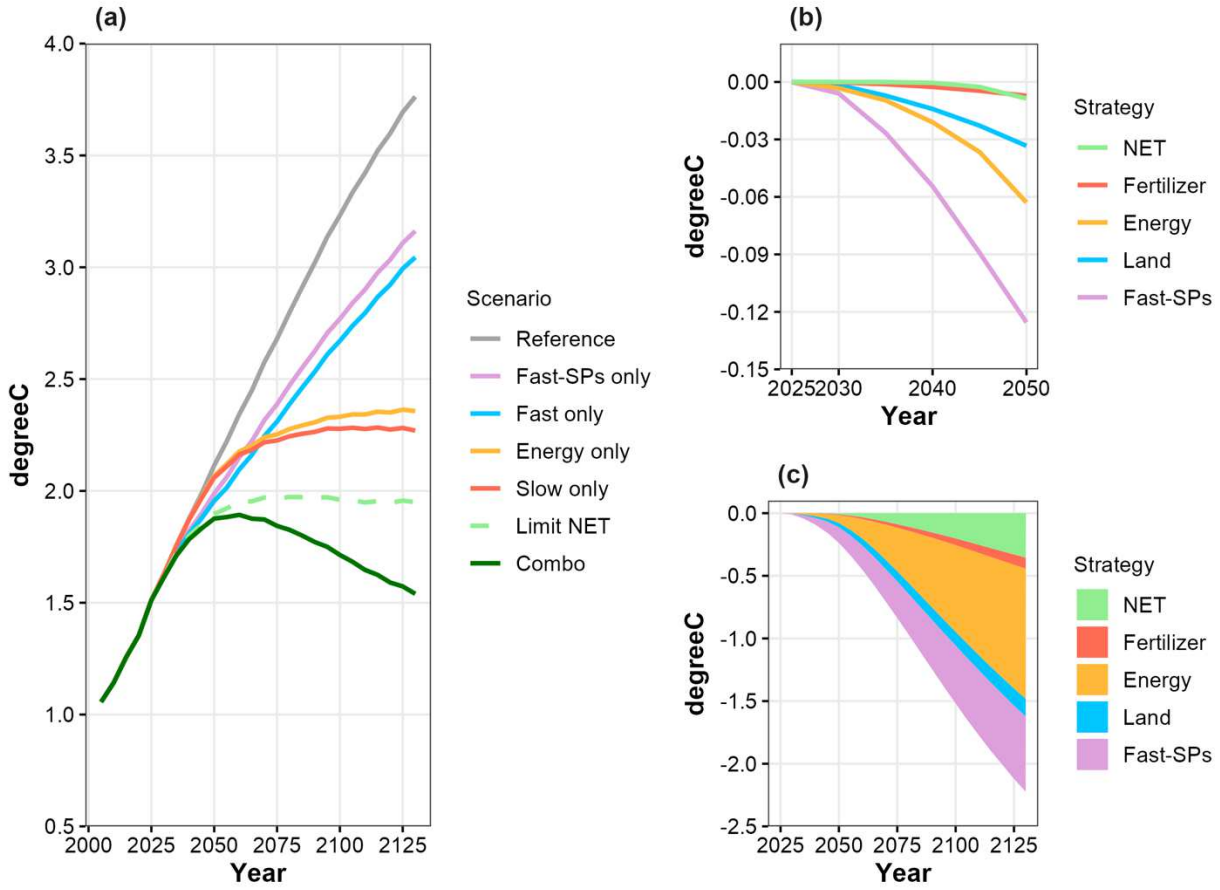


Figure 2. Global mean temperatures (a) trajectories across the seven core scenarios, 2005-2130; (b) temperature impacts from individual fast mitigation (fast super pollutants and land) and slow mitigation (energy transition, fertilizer optimization, and NETs deployment) levers, 2025-2050; and (c) total temperature impacts by individual strategies, 2025-2130.

Table 2. Changes in global temperatures from *Reference* to *Combo* scenario in 2050, 2075, 2100, and 2125, driven by individual fast and slow mitigation strategies (see Supplementary Table 5 for results from 2030 to 2130 by a five-year interval).

	2050	**2075**	**2100**	**2125**
Reference case (*Reference*)	2.11°C	2.68°C	3.23°C	3.69°C
Fast mitigation strategies	Reductions:	Reductions:	Reductions:	Reductions:
- **Fast Super Pollutants:** Targeted abatement of non-CO_2 pollutants	-0.13°C	-0.29°C	-0.46°C	-0.58°C
- **Land:** Ending deforestation & bolstering land carbon sinks	-0.03°C	-0.08°C	-0.11°C	-0.14°C
Slow mitigation strategies	Reductions:	Reductions:	Reductions:	Reductions:
- **Energy Transition:** Reducing	-0.06°C	-0.35°C	-0.69°C	-0.99°C

energy and industrial CO_2 - **Fertilizer Optimization:** Reducing agricultural N_2O - **NETs:** Technological CO_2 removal, e.g. BECCS and DAC	-0.01°C -0.01°C	-0.03°C -0.09°C	-0.05°C -0.20°C	-0.08°C -0.33°C
Multispeed mitigation pathway (*Combo*)	1.88°C	1.84°C	1.71°C	1.57°C

Delaying the immediate implementation of ambitious fast and slow strategies in the near term[38–40] has different impacts on temperatures. Using two sensitivity scenarios, we show that a 10-year delay in fast mitigation strategies until post-2035 (*Combo-fast delay*) has a stronger impact on limiting mid-century peak warming, while a 10-year delay in slow mitigation strategies until post-2035 (*Combo-slow delay*) has a stronger impact on long-term temperature stabilization (see Supplementary Text S5 for sensitivity results).

4. Discussion

The 2015 Paris Agreement and 2016 Kigali Amendment to the Montreal Protocol have helped reduce 2100 warming projections from a dangerous 4°C to a still perilous 3°C.[41,42] Despite deeply concerning developments, including U.S. withdrawal from the Paris Agreement for the second time and absence of global climate leadership, we have shown in this paper that a comprehensive and ambitious multispeed mitigation strategy can still keep 1.5°C within reach and, importantly, minimize the extent and duration of mid-century overshoot above 1.5°C. This requires simultaneously tackling fast mitigation and long-term stabilization strategies, as summarized in Table 2. While our quantitative results hinge on detailed assumptions on feasible action on each lever (see Methods), the qualitative insights are robust as they relate to inherent properties of the involved capital turnover and climate system dynamics.

The presented multispeed mitigation pathway includes immediate implementation of policy actions that reverse the current course or substantially accelerate the pace of transitions along each of the fast and slow mitigation strategies. Among these levers, the energy transition has received the vast majority of policy attention and investments and has achieved rapid cost reductions and cost competitiveness for many key technologies, such as renewables, batteries, and electric vehicles. Of the $1.8 trillion mobilized to mitigate GHG emissions in 2023, about $1.7 trillion flowed into the energy transition, while less than 5 percent flowed into fast mitigation strategies—at least an order of magnitude less than needed to keep 1.5°C within reach.[43] The energy transition remains the single most important lever for stabilizing long-term climate, and we must continue to ramp up clean energy investments steadily. However, even ambitious energy transitions deliver minimal mid-century net cooling benefits; we therefore must also rapidly scale up investment in complementary fast mitigation strategies to slow the rate of warming as well as limit the duration and level of temperature peak. Our finding reinforces the need for quickly ramping up policy actions and faster knowledge dissemination to enable effective global implementation.

To deliver the pace of energy system CO_2 reductions envisioned in this analysis, governments must accelerate policies that drive another doubling in the pace of energy transformation investment and ensure that the transformation is broadly shared and global. Governments and industry must also tackle sectors with limited low-carbon options through innovation and deployment policies, such as industrial processes

emissions and international shipping and aviation, including electrification, sustainable fuels, demand-side measures, and carbon capture technologies that pave the way for a diverse set of CDR approaches.[44,45]

At the same time, mitigating mid-century overshoot above 1.5°C and stabilizing long-term temperature to 1.5°C would require a transformation in global fast mitigation efforts. Most urgently, governments would need to set standards and mobilize investments to deeply reduce fossil methane emissions over the next decade—a singular opportunity that could deliver up to 0.1°C of peak warming reductions.[46] At the same time, governments would need to build on the recent success of Brazil to drive tropical deforestation rates towards zero globally, as well as rapidly scale investments in immediate measures to drive down waste and agricultural methane, such as cutting food waste and enhancing livestock and dairy productivity, while investing in new technologies to achieve deeper and more durable reductions from this sector. In parallel, governments can eliminate industrial N_2O emissions and accelerate HFC emission reductions by encouraging faster implementation of the Kigali Amendment and better management of existing HFC stocks. Tropospheric ozone can be reduced through separate strategies targeting ozone precursors, which would simultaneously deliver substantial benefits in local air pollution and health.

In parallel, this work also demonstrates that, for purposes of focusing policy priorities, simply tracking the metric of $GtCO_2e$ will not suffice to assess the relative impact or efficacy of policy and technology strategies. Even using GWP20 to reflect the impact of shorter-lived climate forcers, an approach deliberately targeting the need to highlight some aspects of fast mitigation, unfortunately, significantly underestimates the benefits of ending deforestation or cutting industrial N_2O to deliver net cooling benefits by mid-century versus energy or fertilizer transition, which addresses the same long-lived climate forcers but comes bundled with unmasking from reducing co-emitted cooling aerosols. The approach we have taken here—assessing the time-specific temperature impacts of individual mitigation levers—could be applied in a range of policy contexts to support prioritization.

While the world can no longer avoid breaching the 1.5°C temperature goal in the near term, the goal itself remains critically important and attainable. Vigorous multispeed mitigation can minimize the magnitude and duration of mid-century overshoot above this critical threshold while driving global temperatures back to 1.5°C over the next century.

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442 **Data availability**
443 The input and output data of the seven core GCAM scenarios will be deposited on Zenodo upon publication.
444
445 **Code availability**
446 The Global Change Analysis Model is an open-source integrated assessment model, available at:
447 https://github.com/JGCRI/gcam-core/releases. The Model for the Assessment of Greenhouse Gas Induced
448 Climate Change (MAGICC7) is available at https://magicc.org/.
449
450 **Author contributions**
451 R.D., R.C., and N.H. conceptualized the study, R.C. and C.B. designed the GCAM scenarios, R.C.
452 implemented the GCAM scenarios and conducted the analysis and visualization, V.G. and S.S. set up and
453 ran the MAGICC scenarios and analysis, R.C., R.D., and N.H. wrote the first draft, and all authors
454 contributed to editing the paper.
455
456 **Competing interests**
457 The authors declare no competing interests.
458

459
460 **Supplementary Information for**

461 # Multispeed mitigation strategies to limit mid-century overshoot and
462 # return to 1.5°C

463
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Supplementary Texts

Text S1. Models used in the analysis

Global Change Analysis Model (GCAM-CGS-v8.0)

The Global Change Analysis Model (GCAM) is an open-source, global model that represents and integrates human and Earth system dynamics across five systems: energy, water, agriculture and land use, the economy, and the climate [1]. GCAM tracks 24 greenhouse gas emissions, short-lived species, and air pollutant emissions from various human activities in these systems. This analysis employs a version of GCAM (GCAM-CGS-v8.0) that is based on the publicly released version of GCAM 8.0 [2], with additional adjustments, including emission factors for F-gases and air pollutants, and updated Shared Socioeconomic Pathways (SSP) socioeconomic and transport demand assumptions [3].

By using GCAM, we can develop economy-wide pathways of energy transition, agriculture and land-use change, water, emissions, and climate in a consistent and integrated framework. The integrated nature of GCAM also allows us to capture the co-emitted species, such as CO_2 and SO_2 emissions from fossil fuel combustion, and the interlinkages between individual fast and slow mitigation strategies, for example, the reduction of CH_4 emissions through energy transition and the increase in LUC CO_2 emissions through bioenergy deployment.

The Model for the Assessment of Greenhouse Gas Induced Climate Change (MAGICC)

The Model for the Assessment of Greenhouse Gas Induced Climate Change (MAGICC) is a reduced-complexity Earth-systems model that translates greenhouse gas emissions data into projections for atmospheric concentrations, radiative forcing, and global mean surface temperatures (see Supplementary Figures 10 and 11). We employ the deterministic version of MAGICC7 (https://magicc.org/) to calculate the effect of different mitigation pathways on global temperatures.

Our inputs to MAGICC consist of emissions projections from 2025 to 2130 obtained through GCAM for different mitigation scenarios. MAGICC converts these emissions projections into temperature pathways, allowing us to analyze whether different combinations of fast and slow mitigation strategies can stabilize global temperatures and keep them within Paris Agreement thresholds. We substitute MAGICC's historical data with more up-to-date historical data from GCAM's climate models to improve the accuracy of MAGICC's model calibration.

Text S2. Scenario design and implementation

Supplementary Table 2 summarizes the seven core scenarios based on different combinations of deploying the fast and slow mitigation strategies and the two sensitivity scenarios. Supplementary Table 3 summarizes how we implement the different assumptions for each of the fast and slow mitigation levers. Each lever includes two alternative pathways, which are explained below.

Fast Super Pollutants: GCAM applies Marginal Abatement Cost Curves (MACC) to model aggregate non-CO_2 emissions abatement over time. The default MACCs are mapped directly to GCAM's technologies from the EPA's 2019 report on non-CO_2 greenhouse gas mitigation, including technology improvements over time that shift the entire MACCs towards the left [4]. In this analysis, we made additional adjustments to the MACCs for agriculture CH_4 emissions to deliver deeper reductions over time and better represent a plausible convergence of emission intensities across regions, and replaced the EPA MACCs for fossil fuel CH_4 emissions with IEA data [5,6]. To model the scenarios with targeted abatements of non-CO_2 super pollutants (*Fast-SPs only*, *Fast only*, *Limit NET*, and *Combo*), we include global prices to represent the marginal cost levels for the associated non-CO_2 abatements based on the MACCs, without applying the price to these emissions directly. To model the scenarios without targeted abatements of non-CO_2 super pollutants (*Reference*, *Energy only*, and *Slow only*), we completely turned off the MACCs in GCAM.

Land: We apply different regional carbon prices for LUC CO_2 emissions to model two different levels of LUC policies across the seven core scenarios (Supplementary Figure 1). For business as usual without policy action, a zero carbon price is applied to LUC CO_2 emissions under *Reference*, *Fast-SPs only*, *Energy only*, and *Slow only*. For accelerated forest and land actions, we implement different levels of LUC carbon prices according to the level of competition with bioenergy through energy transition. When the energy transition follows the current trend with very low carbon prices, deployment of bioenergy is limited, and a low level of LUC carbon prices can deliver the net zero land sinks with continued afforestation under *Fast only*. When energy transition is accelerated, achieving similar land sinks requires a high level of LUC carbon prices under *Combo* due to the deployment of bioenergy but only a medium level of LUC carbon prices when BECCS is not available under *Limit NET*.

Energy transition: We apply different regional carbon prices for energy and industrial CO_2 emissions to model two different levels of energy transitions across the seven core scenarios (Supplementary Figure 2). For continued current trends, very low carbon prices are sustained throughout 2100 under *Reference*, *Fast-SPs only*, and *Fast only*. For high-ambition transitions, carbon prices increase rapidly through 2050 and are sustained at the high level afterwards under *Energy only*, *Slow only*, *Combo*, and *Limit NET*.

Fertilizer optimization: We use the same approach as the targeted SLCP abatements for agricultural N_2O emissions. We made additional adjustments to the default EPA MACCs in GCAM for faster and deeper reductions, where regional mitigation potentials converge at higher carbon price levels. To model the scenarios with targeted abatements of agriculture N_2O emissions (*Slow only*, *Limit NET*, and *Combo*), we use the same regional CO_2 prices from energy transition (Supplementary Figure 2) to represent the marginal cost levels for the associated agriculture N_2O abatements based on the MACCs, without applying the price to these emissions directly. To model the scenarios without targeted abatements of agriculture N_2O (*Reference*, *Fast-SPs only*, *Fast only*, and *Energy only*), we completely turned off the MACCs.

Carbon removal technologies (NET): GCAM deploys logit functions to determine the technology choices in each period, where the parameter of "share-weights" represents non-cost drivers in the selection. When a technology's share-weight is set to zero, it is excluded from adoption in that period. For the *Limit NET* scenario, we set zero shareweights for BECCS and DAC across all periods and sectors.

Text S3. Method for emissions extension beyond 2100

Supplementary Table 4 describes how we extended GCAM emissions projections beyond 2100. We projected CO_2 emissions for each GCAM scenario up to 2130 using ScenarioMIP-CMIP7 scenario extension methods [7], with each scenario assigned an extension approach that best matched the ambition of its CO_2 mitigation policies. For all non-CO_2 species, we assumed that emissions remain constant at 2100 levels through 2130.

The *Reference* and fast mitigation (*Fast-SPs only*, *Fast only*) pathways use the **Medium extension**, which assumes that CO_2 reductions begin after 2100 to reach net-zero emissions by 2250. The Medium CMIP7 scenario reaches 3°C by 2100 and continues to rise. It reflects the continuation of current policy actions without the strengthening of mitigation actions, making it comparable to the Reference and Fast pathways given their lack of long-term CO_2 mitigation strategies.

The slow (*Energy only*, *Slow only*, *Limit NET*) and multispeed (*Combo*) mitigation pathways use the **Low extension**, which maintains net CO_2 emissions at 2100 levels in the few decades following 2100. The Low CMIP7 scenario assumes that countries go beyond current policies by implementing their NDC pledges for 2030, and global temperatures level out at 2°C end-of-century. It is comparable to the Slow and Multispeed mitigation pathways, which achieve stabilized temperatures by 2100 through ambitious long-term CO_2 emissions reductions.

Text S4. Decomposition analysis of temperature impacts by individual strategy

In Table 1 and Figure 2, we allocate the total temperature reduction achieved from *Reference* to *Combo* to five policy strategies: Fast-SPs, Land, Energy, Fertilizer, and NET. We used Equations 1-5 below to calculate how much each strategy contributed to the difference between *Reference* and *Combo*.

Equation 1: $\text{Fast-SPs} = \text{Temp}_{\textit{Fast-SPs only}} - \text{Temp}_{\textit{Reference}}$

Equation 2: $\text{Land} = \text{Temp}_{\textit{Land decomposition}} - \text{Temp}_{\textit{Reference}}$

Equation 3: $\text{Fertilizer} = \text{Temp}_{\textit{Slow only}} - \text{Temp}_{\textit{Energy only}}$

Equation 4: $\text{NET} = \text{Temp}_{\textit{Combo}} - \text{Temp}_{\textit{NET decomposition}}$

Equation 5: $\text{Energy} = (\text{Temp}_{\textit{Combo}} - \text{Temp}_{\textit{Reference}}) - (\text{Fast-SPs} + \text{Land} + \text{Fertilizer} + \text{NET})$

Where:

- Temp_{X} is the temperature pathway under scenario *X*.
- $\text{Temp}_{\textit{Land decomposition}}$ is obtained from MAGICC using the *Reference* scenario, but with land-use CO_2 emissions replaced with those from *Combo*
- $\text{Temp}_{\textit{NET decomposition}}$ is obtained from MAGICC using the *Combo* scenario, but with industrial CO_2 emissions replaced with those from *Limit NET*

When determining the contributions from each strategy to the temperature difference between *Reference* and *Combo*, we cannot simply rely on temperature results from the seven core scenarios. This is due to an overlap of CH_4 emissions reductions between targeted mitigation under the *Fast-SPs only* scenario and from fossil phaseout under the *Energy only* scenario. Due to CH_4 interactions between these levers, the sum of CH_4 reductions from *Reference* to *Fast-SPs only* and CH_4 reductions from *Reference* to *Energy only* exceeds the total CH_4 reductions achieved from *Reference* to *Combo* (Figure 1c).

To remove the effects of CH_4 interactions, we recalculated the temperature impacts of the Land and NET strategies using two decomposition scenarios, *Land Decomposition* and *NET decomposition*. *Land Decomposition* is based on the *Reference* scenario, but substitutes land-use CO_2 emissions with those from *Combo* to isolate the effects of land-use strategies. We can then compare the temperature difference between *Land Decomposition* and *Ref* to derive the temperature effects of land-use policies. *NET decomposition* is based on the *Combo* scenario, but uses industrial CO_2 emissions from *Limit NET* to isolate the effect of the NET lever. By comparing the temperature difference between *NET decomposition* and *Combo*, we obtain the impacts that NET strategies can yield on global temperatures.

Equations 1-4 allow us to capture the effects of Fast-SPs, Land, Fertilizer, and NET strategies on global temperature reductions. To obtain the contribution of energy transition policies, we subtract the contributions of the four other strategies from the temperature difference between *Reference* and *Combo*. This ensures that the sum of all five strategies equals the temperature reduction from *Reference* to *Combo*.

We use Equation 1 to calculate the impact of targeted fast super pollutants reductions, but Equation 1 may still capture some CH_4 interactions from the energy transition. To remove these interactions, we test another decomposition method that substitutes Equation 1 and Equation 5 with the following:

643
644 Equation 6: $\text{Fast-SPs}_2 = \text{Temp}_{\underline{\textit{SLCP decomposition}}} - \text{Temp}_{\underline{\textit{Reference}}}$
645
646 Equation 7: $\text{Energy}_2 = (\text{Temp}_{\underline{\textit{Combo}}} - \text{Temp}_{\underline{\textit{Reference}}}) - (\text{Fast-SPs}_2 + \text{Land} + \text{Fertilizer} + \text{NET})$
647
648 Where:
649 - Temp $_{\underline{\textit{SLCP decomposition}}}$ is obtained from MAGICC using the *Fast-SPs only* pathway, but the CH_4
650 trajectory is replaced with *Combo* + (*Reference* – *Energy only*)
651
652 The *Fast-SPs decomposition* scenario allows us to better isolate the impacts of targeted mitigation strategies
653 by removing emissions impacts from an energy transition. Compared to Equation 1, Equation 6 shows us a
654 smaller benefit from incremental fossil methane action beyond what a fast energy transition would deliver.
655 While Equation 1 may contain some CH_4 energy interactions, it still allows us to understand how much we
656 could mitigate rising temperatures with fast super pollutant action alone, even if the energy transition is
657 very slow.
658

Text S5. Effects of a near-term delay in fast and slow mitigation strategies

In addition to the seven core scenarios, we also develop two sensitivity scenarios with near-term delays of the immediate deployment of either the fast or slow strategies under *Combo*. Instead of implementing the enhanced actions immediately after 2025, the delayed scenarios follow current trends without explicit policy until after 2035 and reach the same price or reduction levels by 2040 in GCAM. The *Combo-fast delay* scenario assumes a 10-year delay for both the Fast Super Pollutant and Land levers through 2035, while the *Combo-slow delay* scenario assumes a 10-year delay for both the Energy Transition and Fertilizer Optimization levers in the near term.

Under the multispeed pathway (*Combo*), a 10-year delay in fast mitigation strategies until post-2035 (*Combo-fast delay*) leads to a nearly 0.05°C increase in mid-century temperature (Supplementary Figure 12e), mainly driven by the near-term increase in annual CH_4 emissions (Supplementary Figure 12d). As CH_4 abatement accelerates and land sinks grow over the long run, the temperature impact of delayed action of fast strategies declines to 0.01°C in 2100. In comparison, a 10-year delay in slow mitigation strategies until post-2035 (*Combo-slow delay*) first slightly lowers the temperature in 2030 due to the increased short-term cooling from co-emitted sulfates and then increases the temperature by 0.02°C post-2060 through the end of the century. This is mainly driven by the near-term increase in cumulative CO_2 emissions by about 35 $GtCO_2$, which sustains at the level after ambition in slow mitigation catches up by 2040 (Supplementary Figure 13).

Our modeled impact of a nominal decade delay finds that delayed implementation of fast strategies has a larger adverse impact on the near-term temperature. On the other hand, the larger adverse impact on the long-term temperature by delayed implementation of slow strategies demonstrates the need for increased implementation speed of the energy transition. Since our assumptions of energy transition in the core scenarios already reflect the near-term implementation challenges, the modeled decadal delay in slow strategies (*Combo-slow delay*) does not generate a substantial difference in the energy and industrial CO_2 emissions pathways from the core *Combo* scenario (Supplementary Figure 12a), and thus a smaller temperature impact compared to the near-term effect.

690 **Supplementary Tables**
691
692 Supplementary Table 1. Mapping of each fast and slow mitigation lever components to Short-Lived
693 Climate Pollutant (SLCP) and Super Pollutant (SP) classifications by the Climate & Clean Air Coalition
694 (CCAC).
695

			CCAC Classification	
Strategy	**Lever**	**Component**	**SLCP[a]**	**Super pollutant[b]**
Fast Mitigation	Fast Super Pollutants	*CH_4*	●	●
		F-gases: HFCs	●[e]	●
		F-gases: PFCs and SF_6		●
		non-CH_4 O_3 precursors: CO, NMVOCs[c]	●	●
		Tropospheric O_3[d]	●	●
		Black carbon	●	●
		Industrial N_2O		●
	Land	*Ending deforestation and bolstering land sinks*		
Slow Mitigation	Energy Transition	*CO_2 emissions from all economic sectors*		
	Fertilizer Optimization	*Agricultural N_2O*		●
	Carbon dioxide removals through NETs	*BECCS, DAC, and other technologies*		

[a] CCAC focuses on four SLCPs in its 2030 Strategy; [b] CCAC identifies super pollutants in its 2025 Super Pollutant Fact Sheet; [c] NO_x, also an O_3 precursor, is not included as a mitigation component because reducing NO_x has a warming impact; [d] changes in O_3 forcing are derived from precursor emissions; [e] some HFCs are long lived.

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699 Supplementary Table 2. Modeled core and sensitivity scenarios
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Scenario name	Fast mitigation strategies		Slow mitigation strategies		
	Fast Super Pollutants	**Land**	**Energy Transition**	**Fertilizer Optimization**	**NETs**
Core scenarios (7)					
Reference	No action	No action	Continue trend	No action	n.a.
Fast-SPs only	Rapid reductions of fast super pollutants	No action	Continue trend	No action	n.a.
Fast only	Rapid reductions of fast super pollutants	Net-zero land sink by 2035	Continue trend	No action	n.a.
Energy only	No action	No action	Net-zero by 2070	No action	BECCS & DAC at scale
Slow only	No action	No action	Net-zero by 2070	Reductions of Ag N_2O	BECCS & DAC at scale
Limit NET	Rapid reductions of fast super pollutants	Net-zero land sink by 2035	Net-zero by 2070	Reductions of Ag N_2O	BECCS & DAC not available
Combo	Rapid reductions of fast super pollutants	Net-zero land sink by 2035	Net-zero by 2070	Reductions of Ag N_2O	BECCS & DAC at scale
Sensitivity scenarios with near-term delays under Combo (2)					
Combo - fast delay	Delay fast super pollutants reductions by 10 years, starting post-2035	Delay land policy by 10 years, starting post-2035	Accelerated energy transition starting post-2025	Ag N_2O reductions starting post-2025	BECCS & DAC at scale
Combo - slow delay	Immediate fast super pollutants reductions starting post-2025	Immediate land policy starting post-2025	Continue current trend for 10 years, accelerated energy transition starting post-2035	No action for 10 years, Ag N_2O reductions starting post-2035	BECCS & DAC at scale

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703 Supplementary Table 3. Description of assumptions for fast and slow mitigation levers
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Fast & slow mitigation levers	**GCAM implementation**
Fast Super Pollutants: Targeted abatement of non-CO_2 pollutants	MACCs for non-CO_2 superpollutants based on global CO_2 prices ● MACCs activated ● MACCs turned off
Land: Ending deforestation & bolstering land carbon sinks	Regional LUC CO_2 prices ● No action: zero LUC CO_2 prices ● High ambition: increasing LUC CO_2 prices, low to high levels based on land-use competition with bioenergy
Energy Transition: Reducing energy and industrial CO_2	Regional energy & industrial CO_2 prices ● Current trends: very low CO_2 prices ● High ambition: rapidly increasing CO_2 prices through 2050, sustained at high levels afterwards
Fertilizer Optimization: Reducing agricultural N2O	MACCs for Ag N_2O based on regional CO_2 prices ● MACCs activated ● MACCs turned off
NETs: Technological CO_2 removal, e.g. BECCS and DAC	Share-weights for BECCS and DAC technologies across sectors ● Available: non-zero share-weights, constraints on bioenergy linear to 100 EJ/year by 2100 ● Not available: zero share-weights for individual technologies

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Supplementary Table 4. Methodologies to extend GCAM emissions projections from 2100 to 2130, based on ScenarioMIP-CMIP7 extensions in Van Vuuren *et al* (2026)[4].

	Net CO_2 emissions (Industrial + AFOLU) by 2100	**CMIP7 CO_2 Extension Pathway until 2130**
Reference pathway • **Reference** Fast mitigation pathways • **Fast-SPs only** • **Fast only**	 32.5 $GtCO_2$/yr 34.4 $GtCO_2$/yr 33.3 $GtCO_2$/yr	**M-ext:** CO_2 emission reduction begins after 2100 with reductions to net zero CO_2 by 2250 (linear interpolation between 2100 and 2250)
Slow mitigation pathways • **Energy only** • **Slow only** • **Limit NET** Multispeed pathway • **Combo**	 -9.02 $GtCO_2$/yr -9.02 $GtCO_2$/yr -0.121 $GtCO_2$/yr -11.3 $GtCO_2$/yr	**L-ext:** Net CO_2 emissions are maintained at 2100 levels

713 Supplementary Table 5. Changes in global temperatures from *Reference* to *Combo* scenario from 2030 to
714 2130, 5-year intervals. Each column in between represents each lever's and total °C reduction from
715 *Reference* temperature to reach *Combo* temperature.
716

Year	***Reference*** temperature	Fast mitigation levers		Slow mitigation levers			Total reduction	***Combo*** temperature
		Fast-SPs	Land	Energy	Fertilizer	NET		
2030	1.62	-0.01	-0.00	-0.00	-0.00	-0.00	-0.01	1.61
2035	1.76	-0.03	-0.01	-0.01	-0.00	-0.00	-0.05	1.71
2040	1.88	-0.05	-0.01	-0.02	-0.00	-0.00	-0.09	1.78
2045	1.99	-0.09	-0.02	-0.04	-0.01	-0.00	-0.16	1.83
2050	2.11	-0.13	-0.03	-0.06	-0.01	-0.01	-0.24	1.88
2055	2.22	-0.16	-0.04	-0.11	-0.01	-0.02	-0.34	1.88
2060	2.34	-0.19	-0.06	-0.16	-0.01	-0.03	-0.45	1.89
2065	2.45	-0.23	-0.07	-0.21	-0.02	-0.05	-0.57	1.88
2070	2.58	-0.26	-0.07	-0.28	-0.02	-0.07	-0.70	1.87
2075	2.68	-0.29	-0.08	-0.35	-0.03	-0.09	-0.84	1.84
2080	2.80	-0.33	-0.09	-0.42	-0.03	-0.11	-0.97	1.83
2085	2.91	-0.36	-0.09	-0.49	-0.04	-0.13	-1.11	1.80
2090	3.02	-0.39	-0.10	-0.56	-0.04	-0.15	-1.25	1.77
2095	3.14	-0.43	-0.10	-0.63	-0.05	-0.18	-1.39	1.75
2100	3.23	-0.46	-0.11	-0.69	-0.05	-0.20	-1.52	1.71
2105	3.33	-0.49	-0.11	-0.76	-0.06	-0.23	-1.65	1.68
2110	3.42	-0.52	-0.12	-0.82	-0.07	-0.25	-1.77	1.65
2115	3.52	-0.55	-0.13	-0.88	-0.07	-0.28	-1.90	1.62
2120	3.60	-0.56	-0.13	-0.93	-0.08	-0.30	-2.01	1.59
2125	3.69	-0.58	-0.14	-0.99	-0.08	-0.33	-2.12	1.57
2130	3.76	-0.60	-0.14	-1.04	-0.09	-0.35	-2.22	1.54

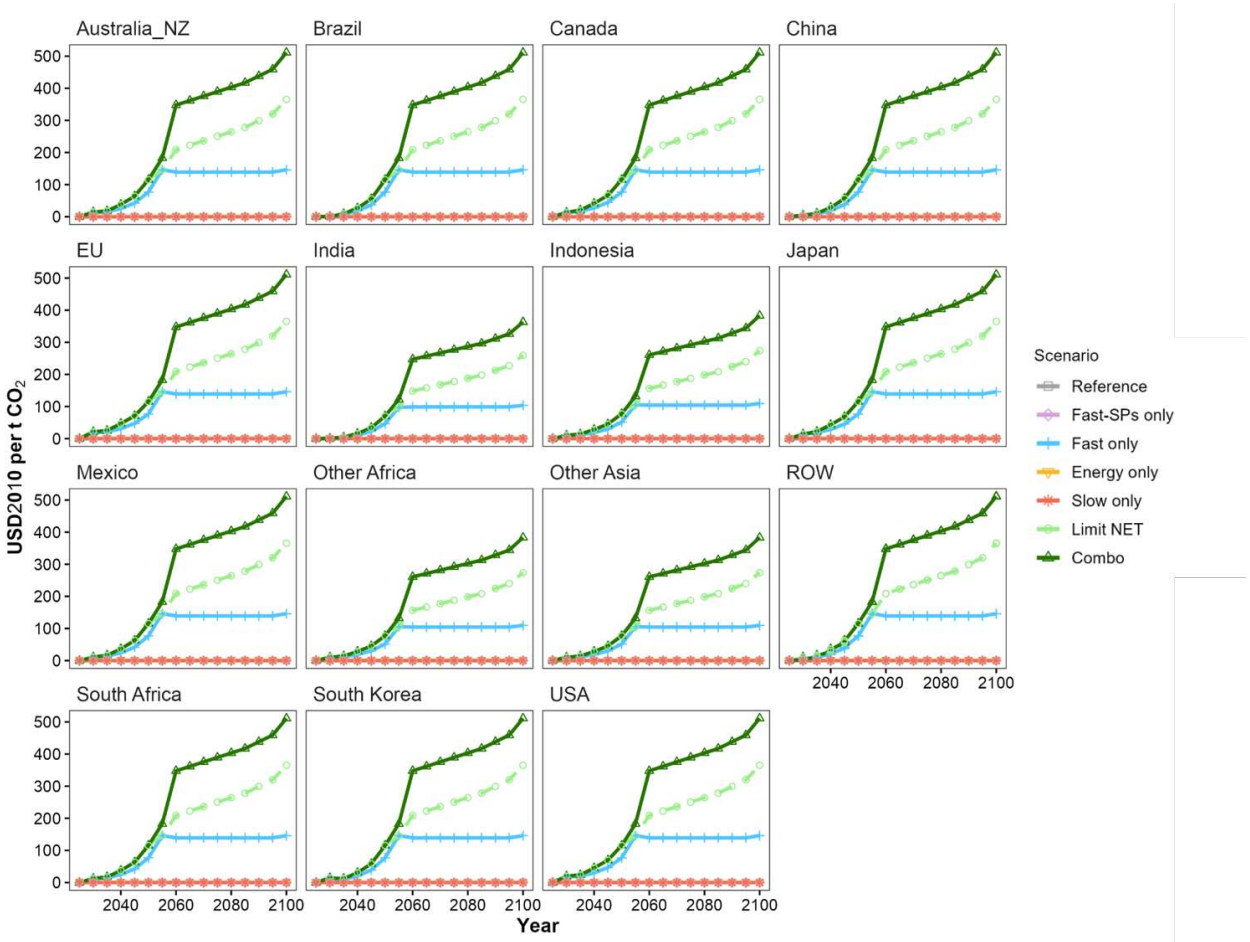
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720 Supplementary Table 6. Changes in global temperatures from *Reference* to *Combo* scenario from 2030 to
721 2130, 5-year intervals, with alternative decompositions for Fast-SPs and Energy (Fast-SPs$_2$ and Energy$_2$,
722 from Equations 6 and 7).
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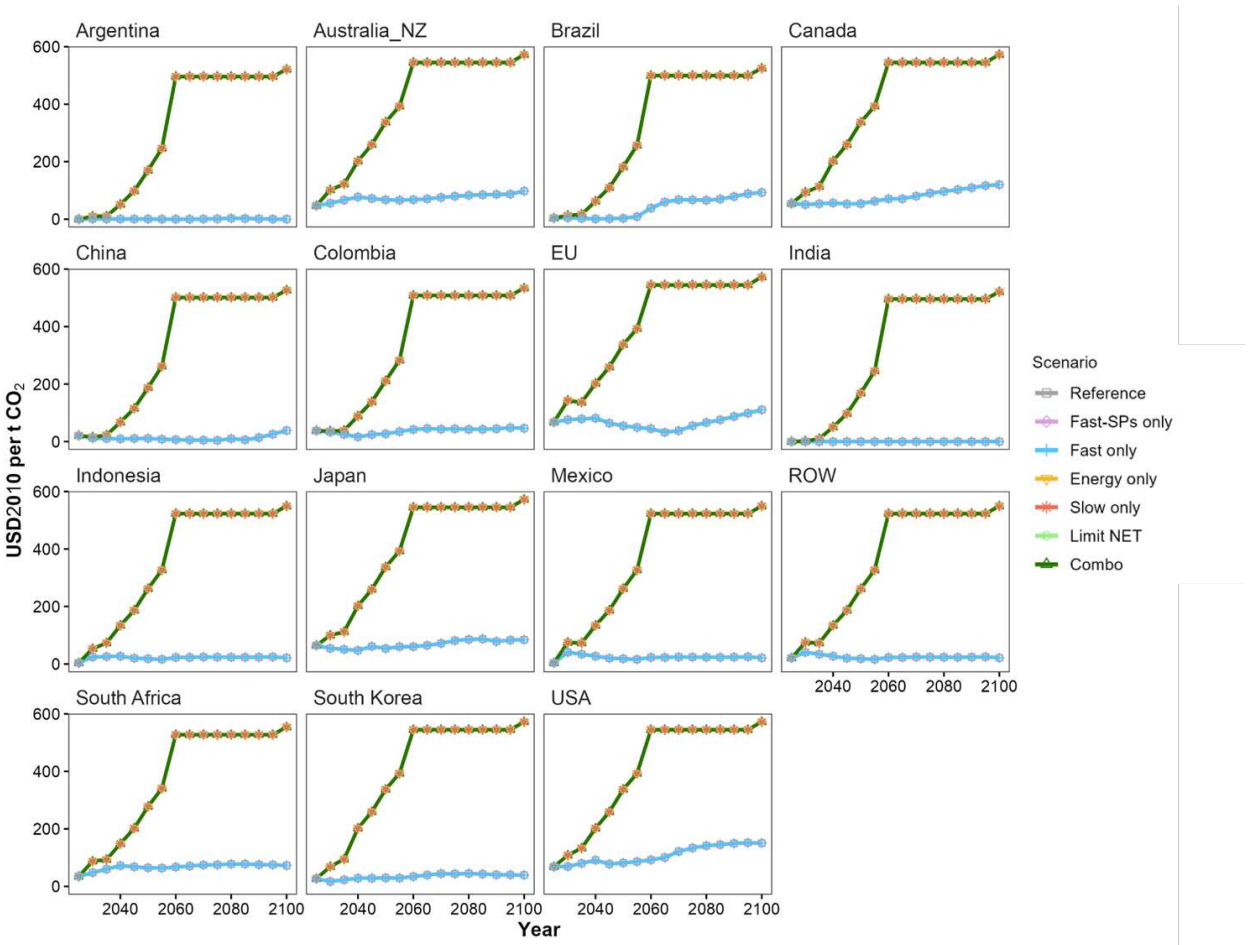
Year	*Reference* temperature	Fast mitigation levers		Slow mitigation levers			Total reduction	*Combo* temperature
		Fast-SPs$_2$	Land	Energy$_2$	Fertilizer	NET		
2030	1.62	-0.01	-0.00	-0.00	-0.00	-0.00	-0.01	1.61
2035	1.76	-0.03	-0.01	-0.01	-0.00	-0.00	-0.05	1.71
2040	1.88	-0.05	-0.01	-0.02	-0.00	-0.00	-0.09	1.78
2045	1.99	-0.08	-0.02	-0.04	-0.01	-0.00	-0.16	1.83
2050	2.11	-0.11	-0.03	-0.08	-0.01	-0.01	-0.24	1.88
2055	2.22	-0.14	-0.04	-0.13	-0.01	-0.02	-0.34	1.88
2060	2.34	-0.16	-0.06	-0.19	-0.01	-0.03	-0.45	1.89
2065	2.45	-0.18	-0.07	-0.26	-0.02	-0.05	-0.57	1.88
2070	2.58	-0.21	-0.07	-0.33	-0.02	-0.07	-0.70	1.87
2075	2.68	-0.23	-0.08	-0.41	-0.03	-0.09	-0.84	1.84
2080	2.80	-0.26	-0.09	-0.49	-0.03	-0.11	-0.97	1.83
2085	2.91	-0.28	-0.09	-0.57	-0.04	-0.13	-1.11	1.80
2090	3.02	-0.31	-0.10	-0.64	-0.04	-0.15	-1.25	1.77
2095	3.14	-0.34	-0.10	-0.72	-0.05	-0.18	-1.39	1.75
2100	3.23	-0.37	-0.11	-0.79	-0.05	-0.20	-1.52	1.71
2105	3.33	-0.39	-0.11	-0.86	-0.06	-0.23	-1.65	1.68
2110	3.42	-0.42	-0.12	-0.92	-0.07	-0.25	-1.77	1.65
2115	3.52	-0.44	-0.13	-0.98	-0.07	-0.28	-1.90	1.62
2120	3.60	-0.46	-0.13	-1.04	-0.08	-0.30	-2.01	1.59
2125	3.69	-0.48	-0.14	-1.10	-0.08	-0.33	-2.12	1.57
2130	3.76	-0.49	-0.14	-1.15	-0.09	-0.35	-2.22	1.54

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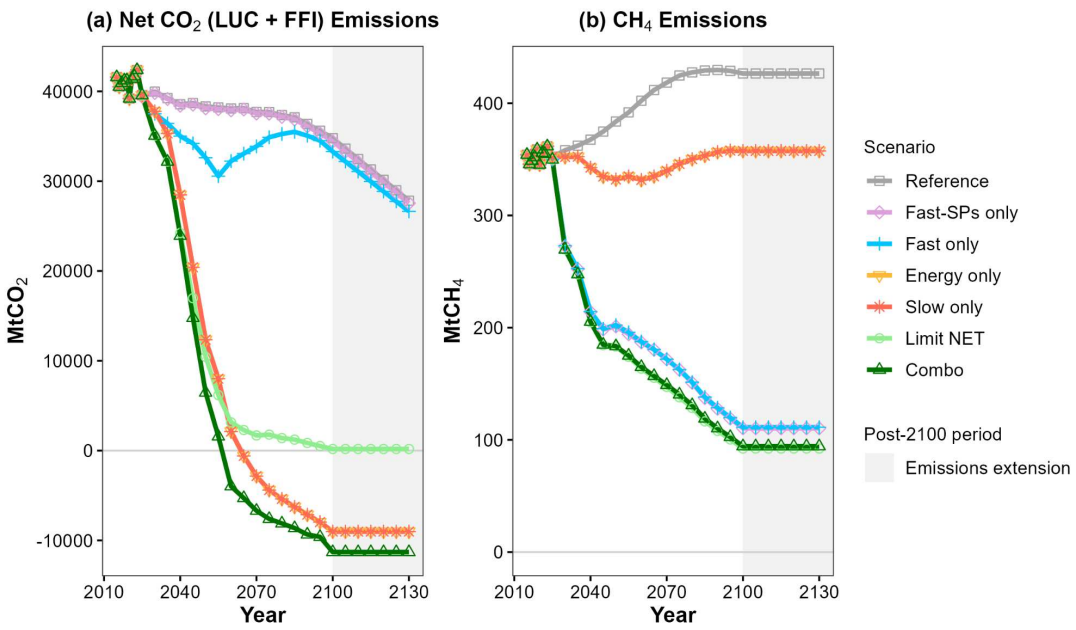
Supplementary Figures



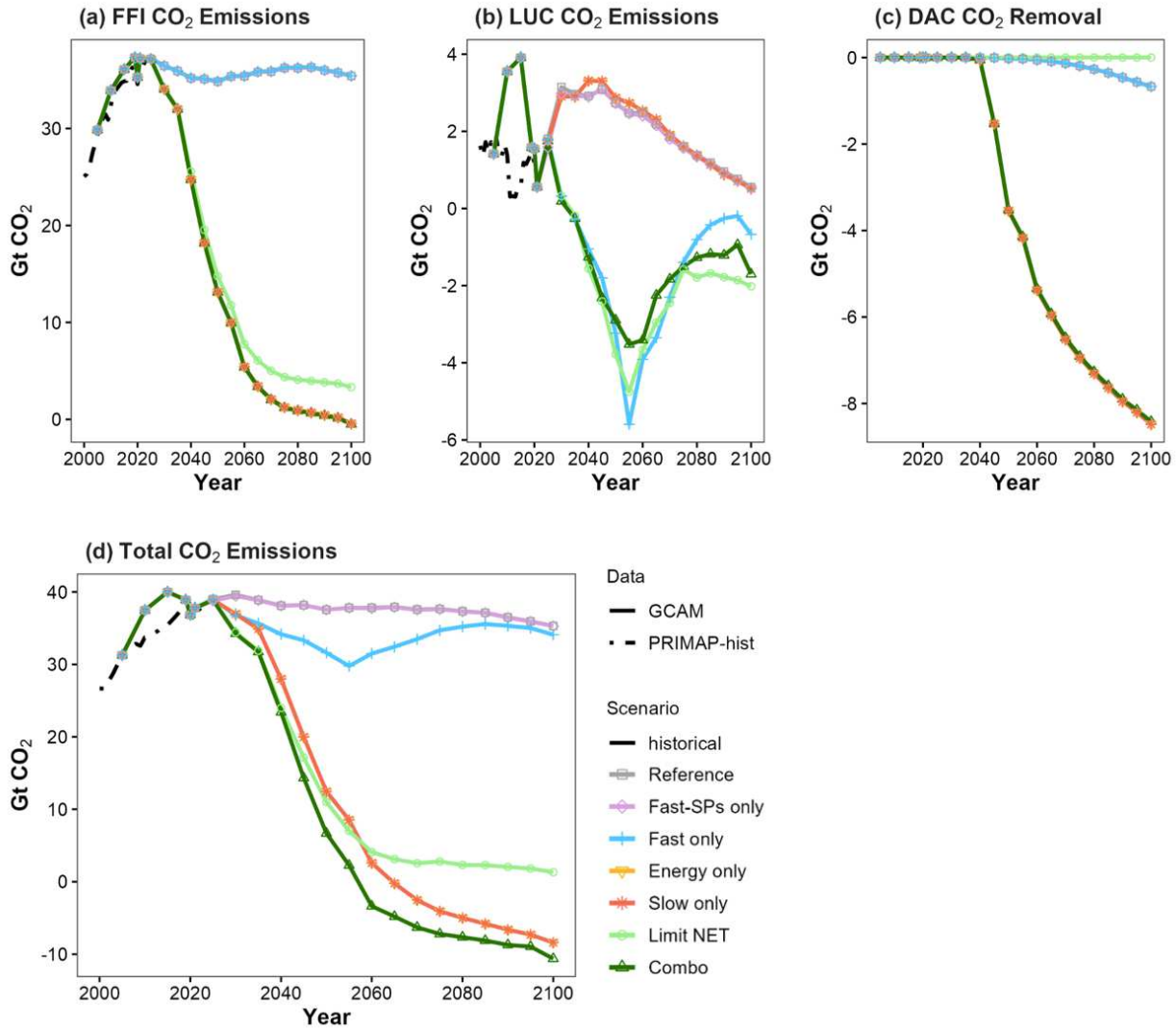
Supplementary Figure 1. Regional carbon prices on land use change CO_2 emissions under the seven core scenarios, 2025-2100. Price = 0 under *Reference*, *Fast-SPs only*, *Energy only*, and *Slow only*; price = low under *Fast only*; price = medium under *Limit NET*; and price = high under *Combo*.



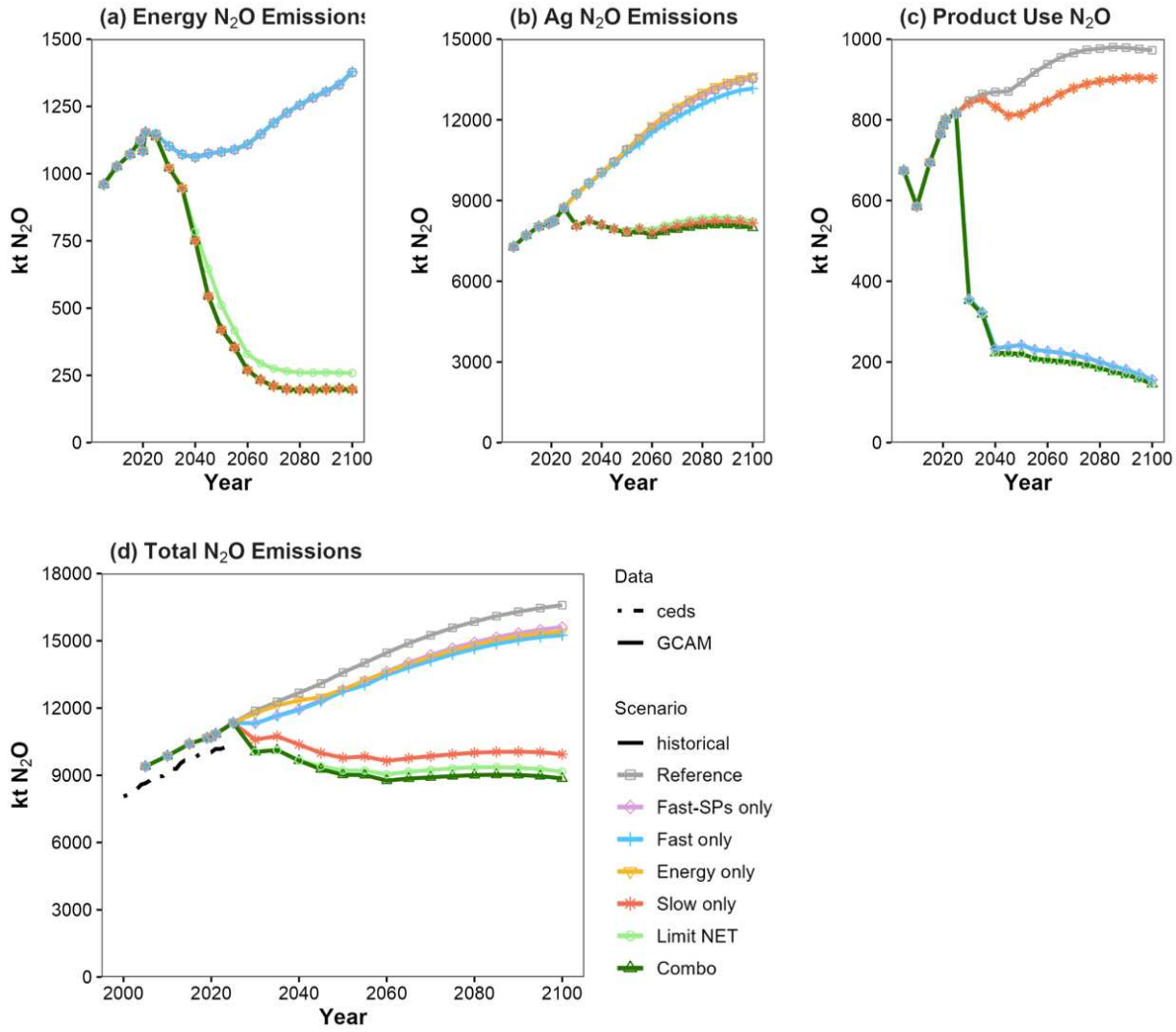
Supplementary Figure 2. Regional carbon prices on energy and industrial CO_2 emissions under the seven core scenarios, 2025-2100. Price = low under *Reference*, *Fast-SPs only*, and *Fast only*; and price = high under *Energy only*, *Slow only*, *Limit NET*, and *Combo*.



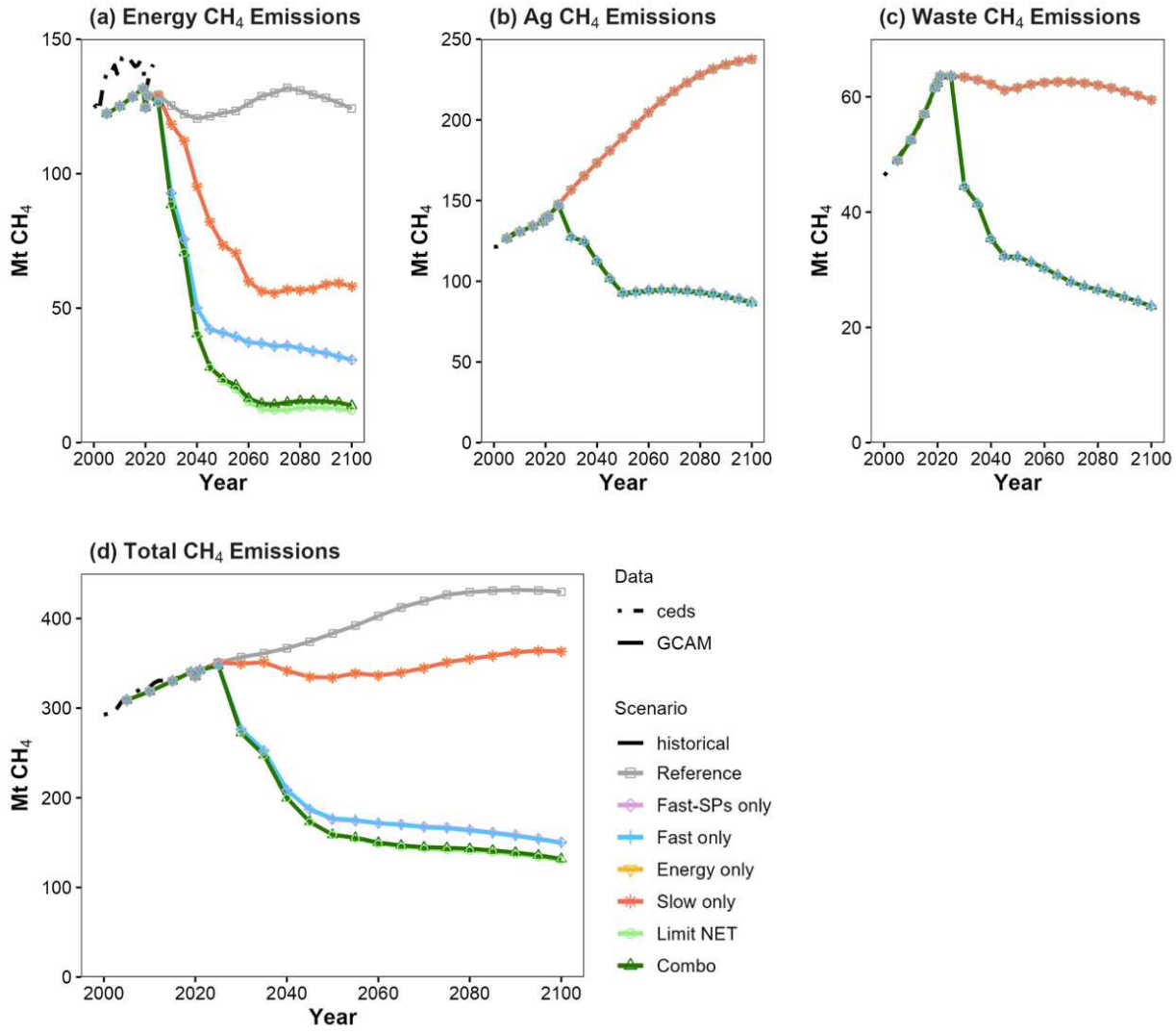
Supplementary Figure 3: Global emissions pathways across the seven core scenarios with extensions to 2130: (a) net CO_2 (energy, industrial, land use change) emissions, (b) total CH_4 emissions.



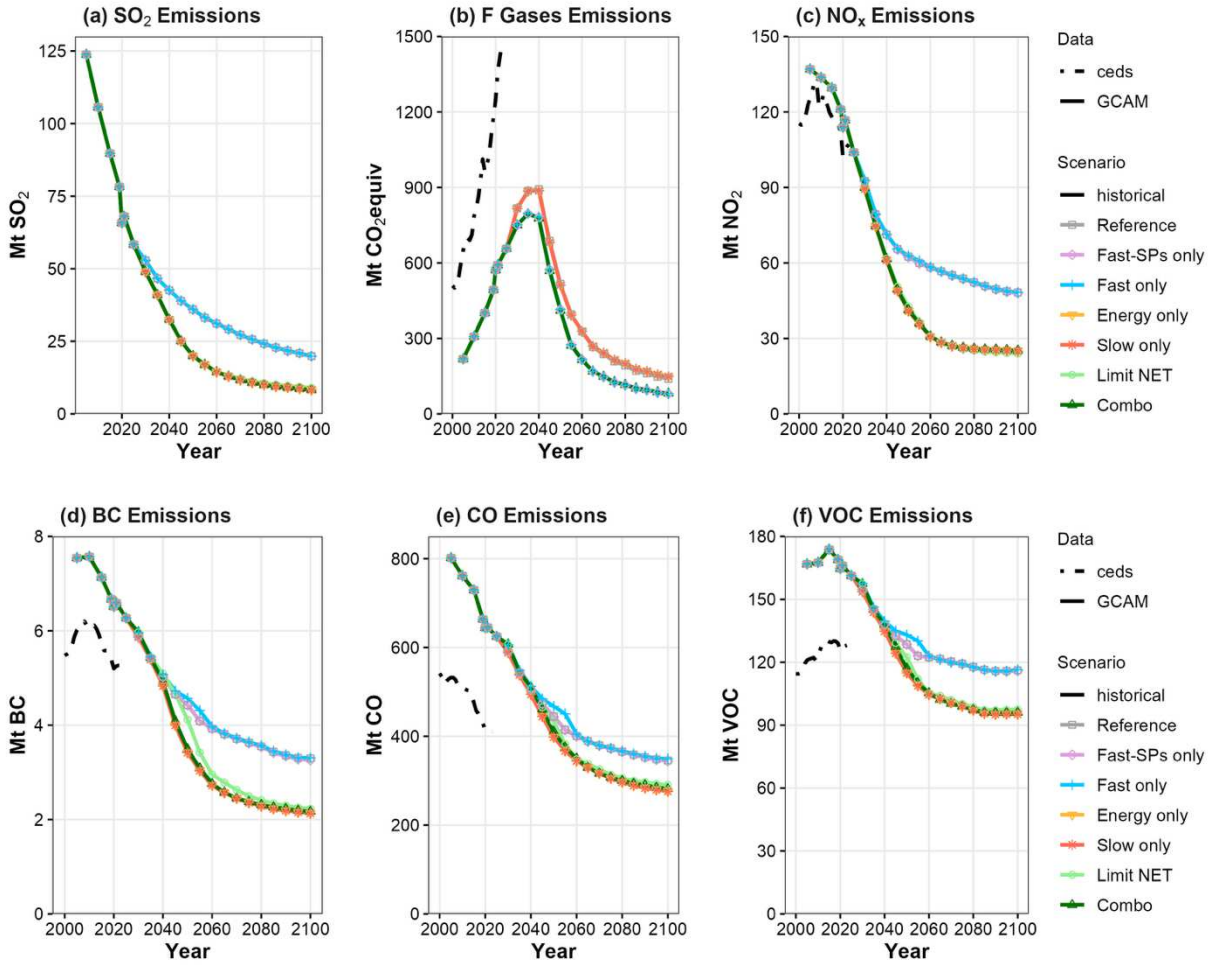
Supplementary Figure 4. Global CO_2 emissions pathways across seven core scenarios: (a) energy and industrial CO_2 emissions, (b) land use change CO_2 emissions, (c) CO_2 emissions removal from direct air capture, and (d) total CO_2 emissions (where d = a + b + c). Historical data are from PRIMAP.



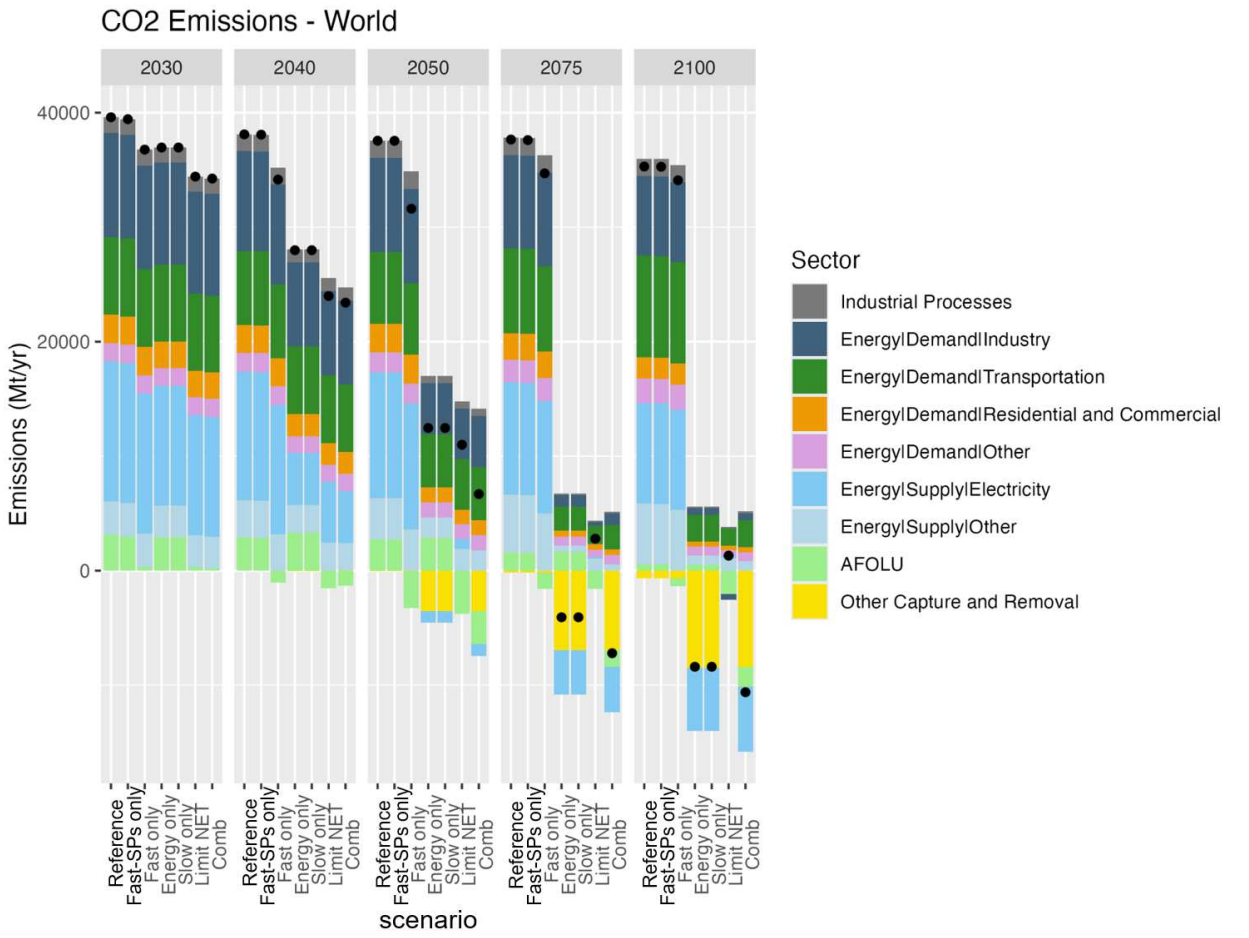
Supplementary Figure 5. Global N_2O emissions pathways across seven core scenarios: (a) energy sector N_2O emissions, (b) agriculture sector N_2O emissions, (c) product use N_2O emissions, and (d) total N_2O emissions (where d = a + b + c). Historical data are from CEDS.



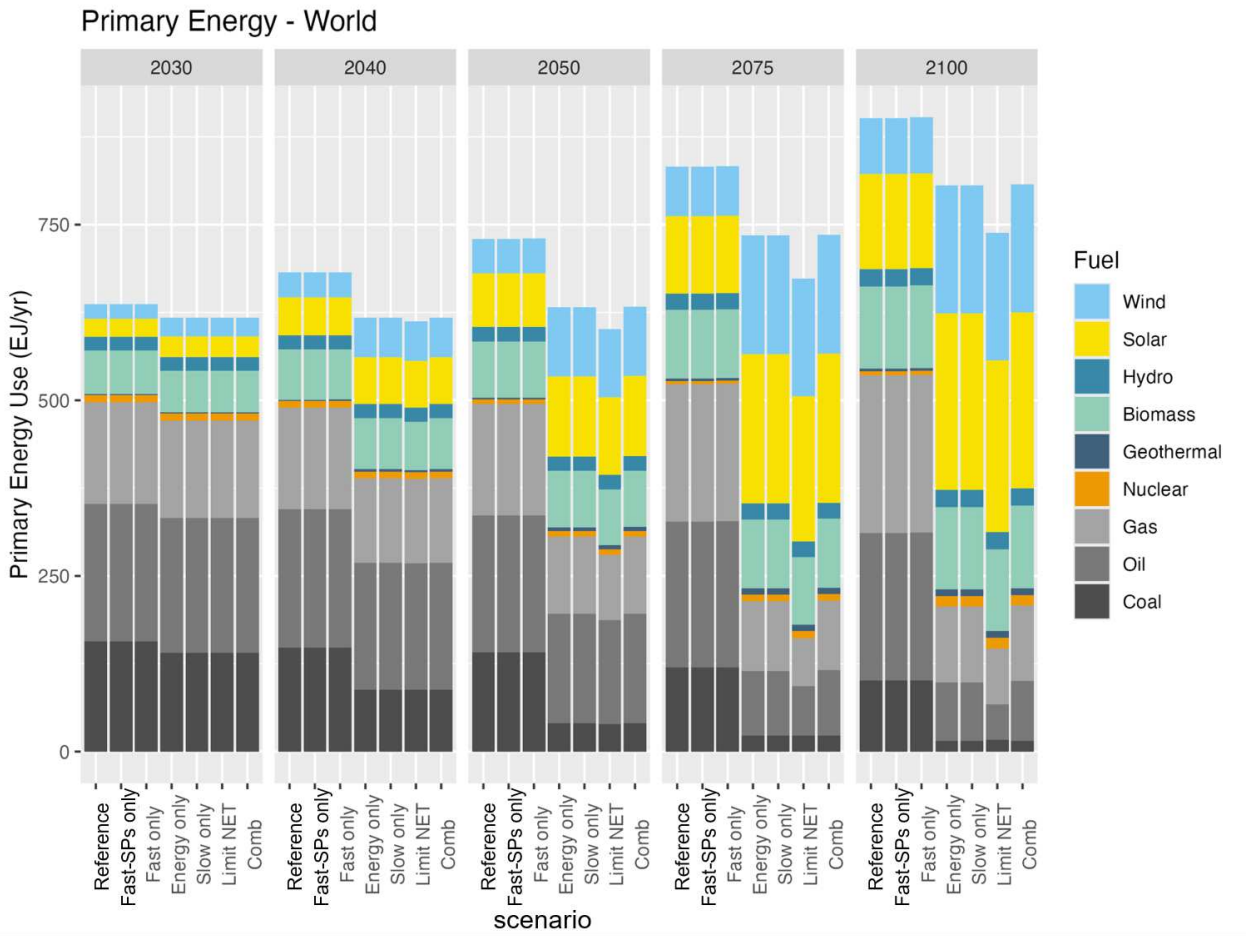
Supplementary Figure 6. Global CH_4 emissions pathways across seven core scenarios: (a) energy sector CH_4 emissions, (b) agriculture sector CH_4 emissions, (c) waste sector CH_4 emissions, and (d) total CH_4 emissions (where d = a + b + c). Historical data are from CEDS.



Supplementary Figure 7. Global other gases emissions pathways across seven core scenarios: (a) SO_2 emissions, (b) F-gases emissions, (c) NOx emissions, (d) BC emissions, (e) CO emissions, and (f) VOC emissions. Historical data are from CEDS.

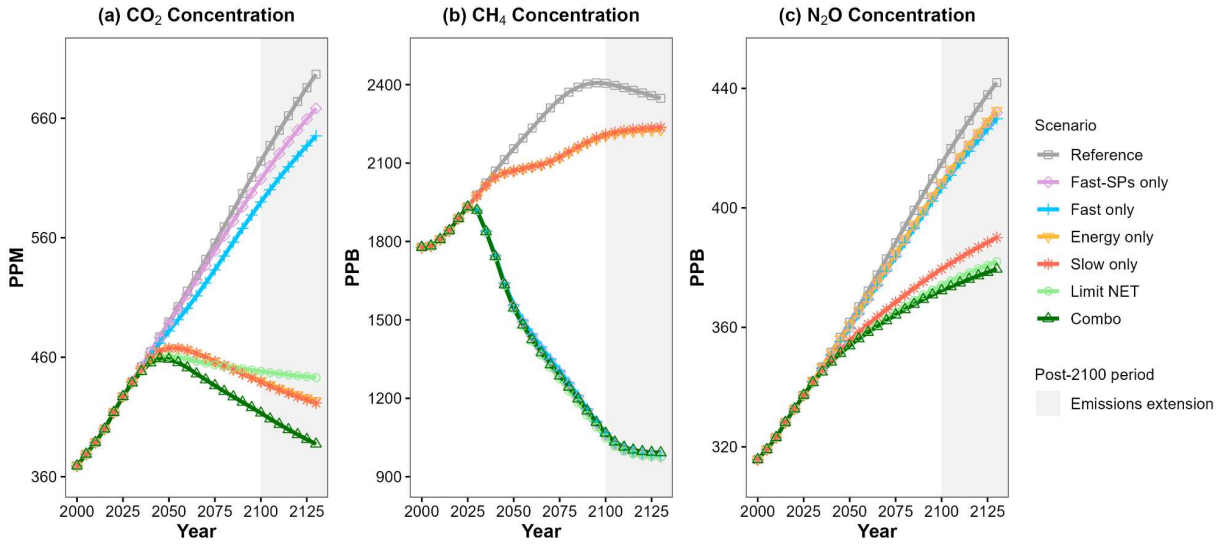


Supplementary Figure 8. Global total CO_2 emissions by sector under the seven core scenarios.



Supplementary Figure 9. Global primary energy consumption by fuel under the seven core scenarios.

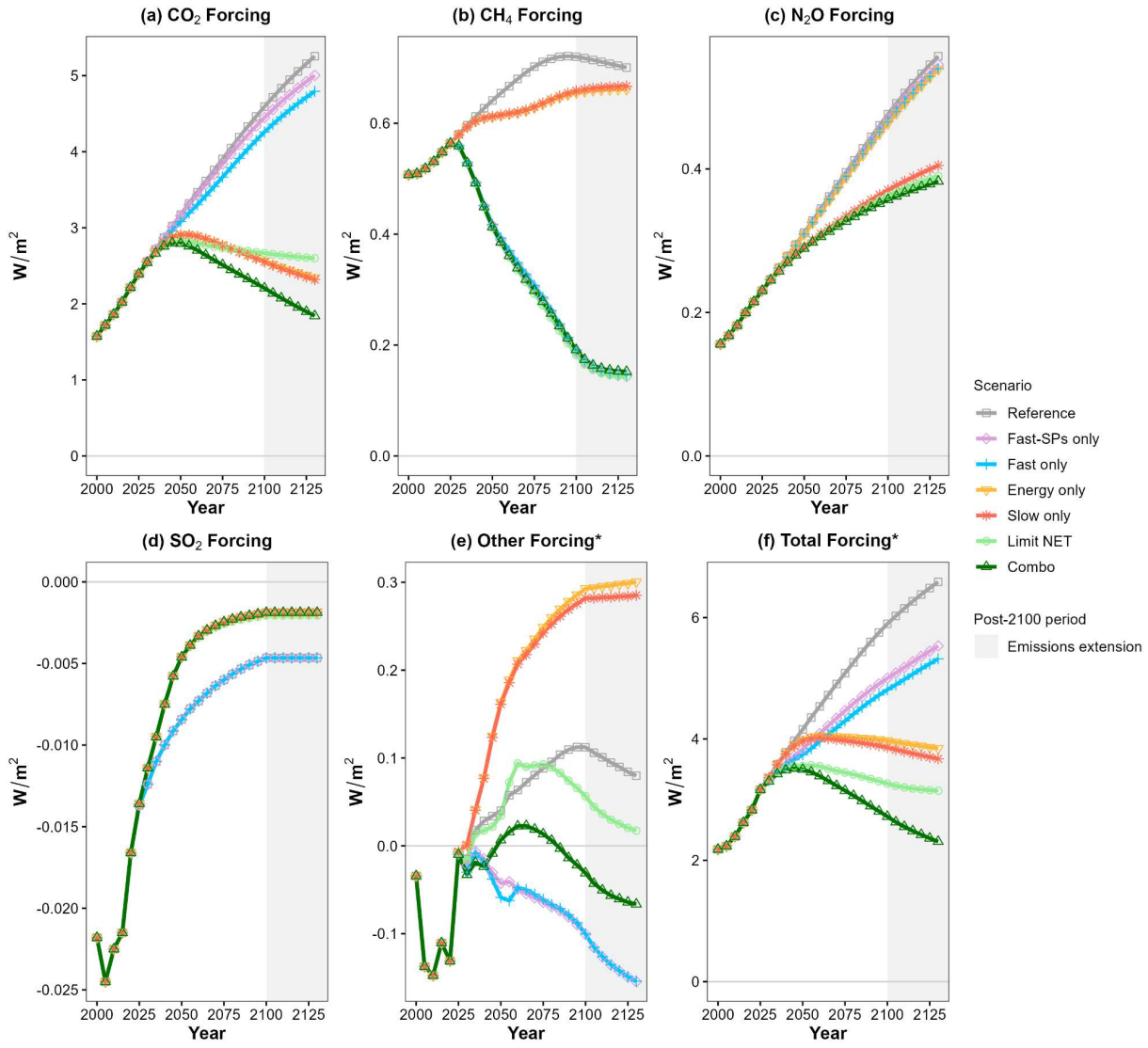
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773 Supplementary Figure 10. Concentrations of key greenhouse gases across the seven core scenarios: (a)
774 carbon dioxide, (b) methane, and (c) nitrous oxide.

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Supplementary Figure 11. Atmospheric forcing of key greenhouse gases and other atmospheric species across the seven core scenarios: (a) carbon dioxide, (b) methane, (c) nitrous oxide, (d) sulfur dioxide, (e) other species, and (f) total atmospheric forcing. *Other and total forcing do not include forcing from solar radiation.

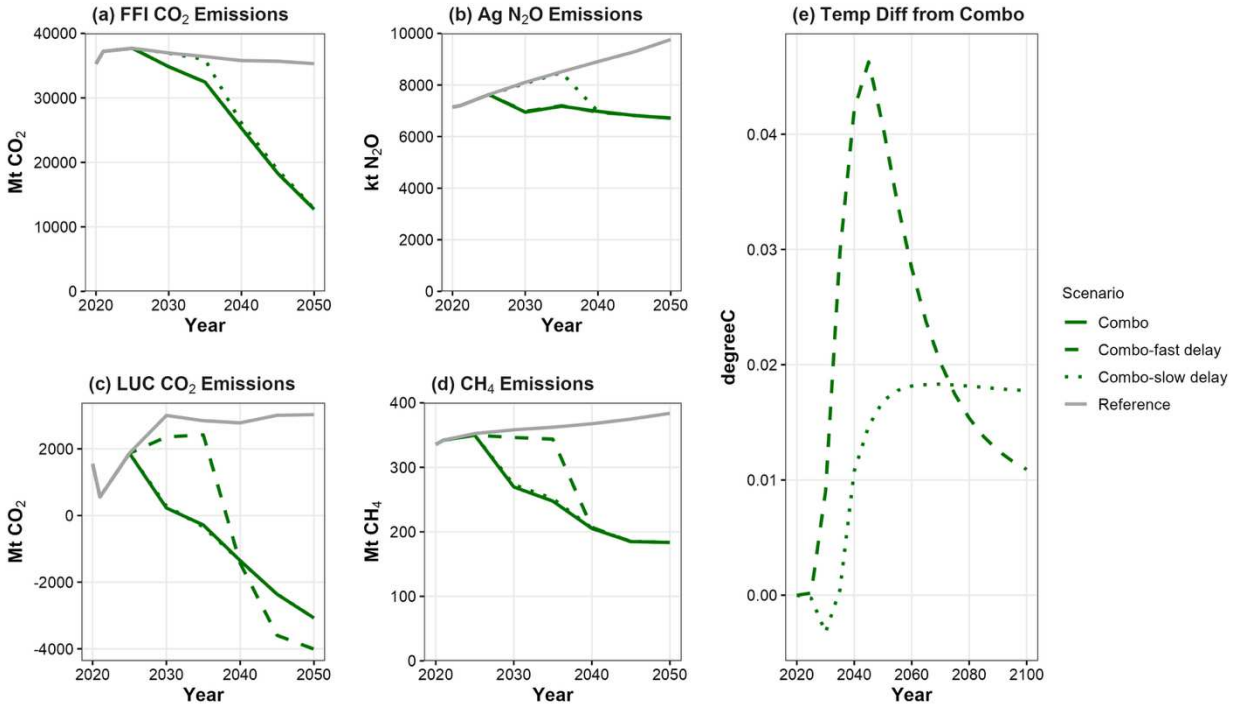
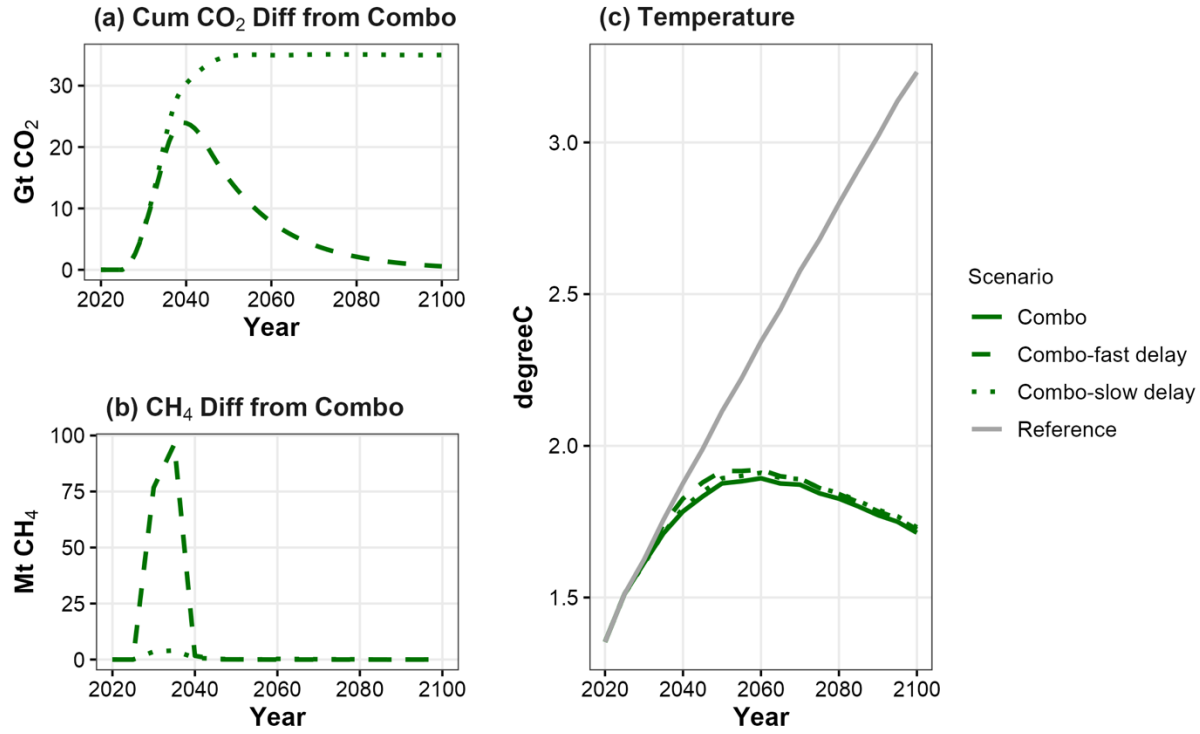
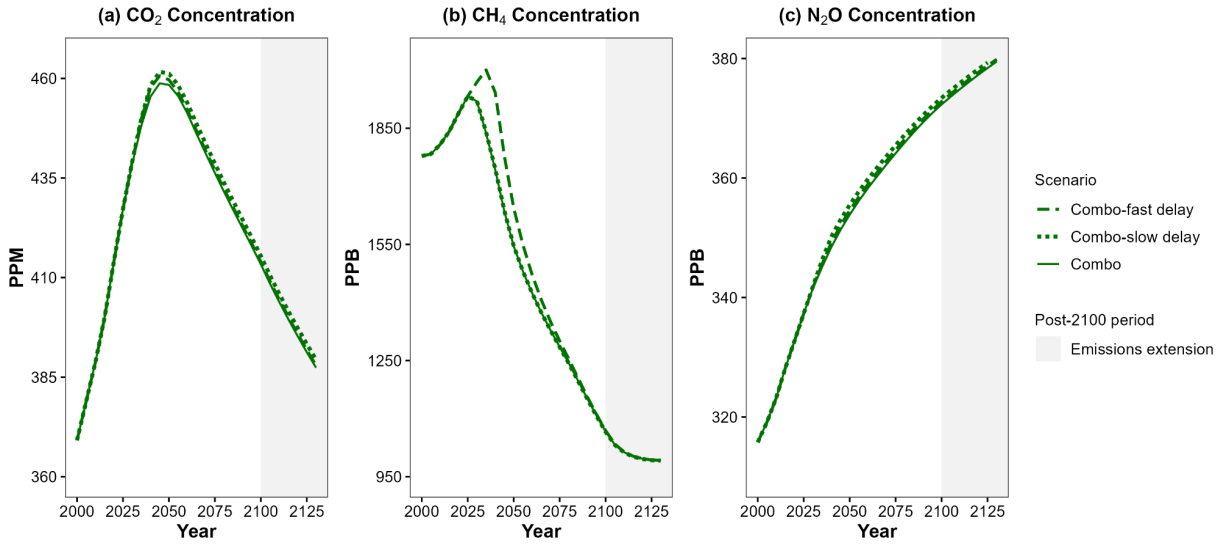


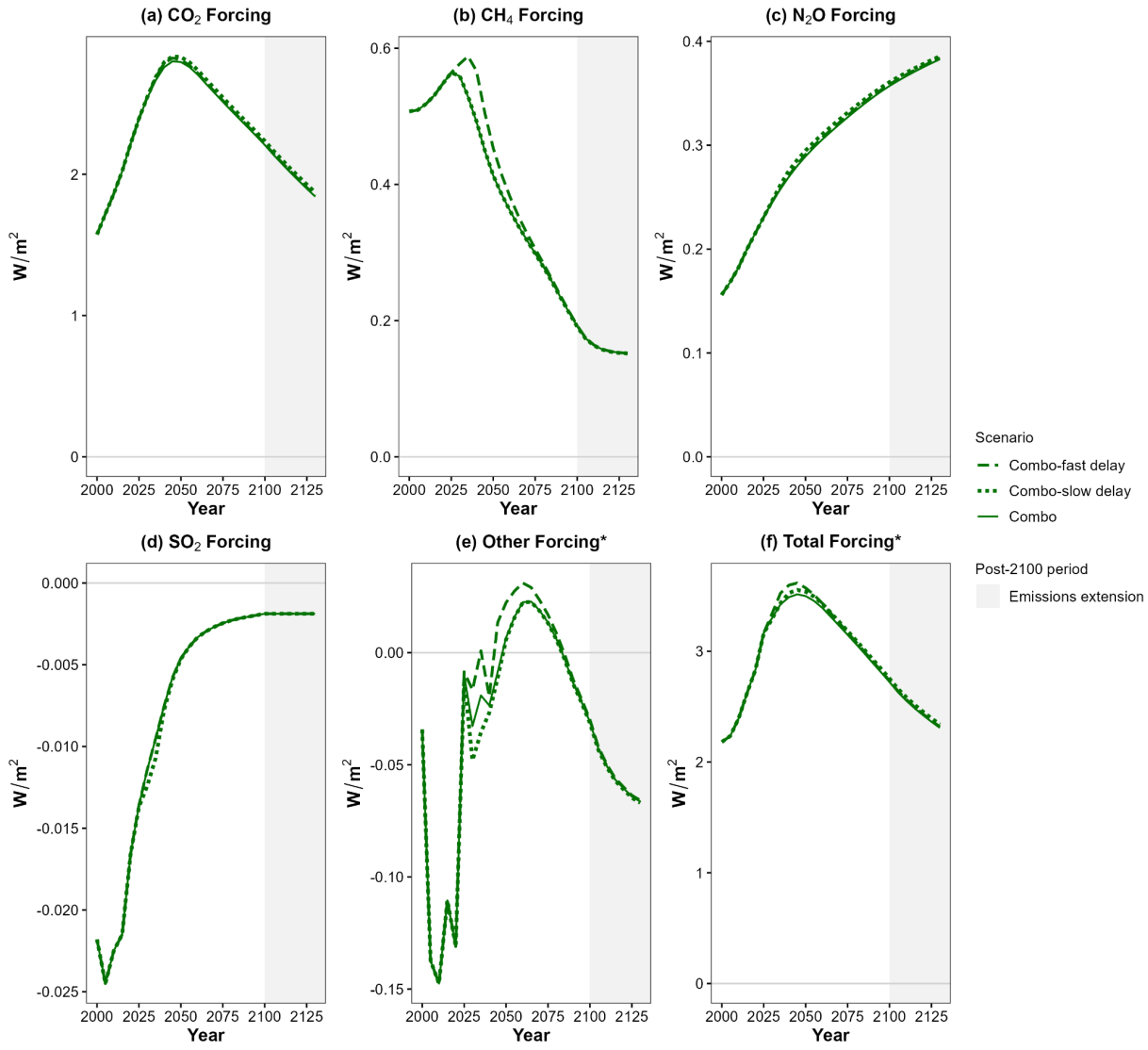
Figure 12. Sensitivity scenarios with delayed actions. (a) energy and industrial CO_2 emissions, (b) total agriculture N_2O emissions, (c) land use change CO_2 emissions, and (d) total CH_4 emissions under *Reference*, *Combo*, *Combo-fast delay* and *Combo-slow delay* scenarios through 2050; and (e) global mean temperature difference between two sensitivities (*Combo-fast delay* and *Combo-slow delay*) and core *Combo* scenario.



Supplementary Figure 13. Delayed sensitivities for the combo scenario: (a) differences in cumulative CO_2 emissions between two sensitivities (*Combo-fast delay* and *Combo-slow delay*) and core *Combo* scenario, (b) differences in annual CH_4 emissions between two sensitivities and core *Combo* scenario, methane, and (c) global mean temperature under *Reference*, *Combo*, *Combo-fast delay* and *Combo-slow delay* scenarios through 2100.



Supplementary Figure 14. Delayed sensitivities for the combo scenario - concentrations of key greenhouse gases: (a) carbon dioxide, (b) methane, and (c) nitrous oxide.



Supplementary Figure 15. Delayed sensitivities for the combo scenario - atmospheric forcing of key greenhouse gases and other atmospheric species: (a) carbon dioxide, (b) methane, (c) nitrous oxide, (d) sulfur dioxide, (e) other species, and (f) total atmospheric forcing. *Other and total forcing do not include forcing from solar radiation.

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