

Distributional Impacts of 1.5 °C Overshoot Pathways: Food, Energy, and the Limits of Carbon Tax Revenue Recycling

Jiarui Zhong

jiarui.zhong@pik-potsdam.de

Potsdam Institute for Climate Impact Research <https://orcid.org/0000-0001-5194-2135>

Franziska Piontek

Potsdam Institute for Climate Impact Research, Member of the Leibniz Association
<https://orcid.org/0000-0003-4305-7552>

Benjamin Bodirsky

Potsdam Institute for Climate Impact Research <https://orcid.org/0000-0002-8242-6712>

David Chen

Potsdam Institute for Climate Impact Research <https://orcid.org/0000-0001-5939-9093>

Leonard Missbach

Potsdam Institute for Climate Impact Research <https://orcid.org/0000-0002-8389-3208>

Robin Hasse

Potsdam Institute for Climate Impact Research (PIK) <https://orcid.org/0000-0003-1818-3186>

Leon Merfort

Potsdam Institute for Climate Impact Research (PIK) e. V. <https://orcid.org/0000-0003-1704-6892>

Tabea Dorndorf

Potsdam Institute for Climate Impact Research

Anne Merfort

Potsdam Institute for Climate Impact Research (PIK) <https://orcid.org/0000-0002-5929-7748>

Benjamin Peeters

Potsdam Institute for Climate Impact Research

Johannes Koch

Potsdam Institute for Climate Impact Research

Elmar Kriegler

Potsdam Institute for Climate Impact Research <https://orcid.org/0000-0002-3307-2647>

Article

Keywords:

Posted Date: June 3rd, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-9892298/v1>

License: © ⓘ This work is licensed under a Creative Commons Attribution 4.0 International License.
[Read Full License](#)

Additional Declarations: There is **NO** Competing Interest.

Distributional Impacts of 1.5 °C Overshoot Pathways: Food, Energy, and the Limits of Carbon Tax Revenue Recycling

Jiarui Zhong^{1,*}, Franziska Piontek¹, Benjamin Leon Bodirsky¹,
David Meng-Chuen Chen^{1,2,3}, Leonard Missbach¹, Robin Hasse^{1,4}, Leon
Merfort^{1,4}, Tabea Dorndorf^{1,5}, Anne Merfort^{1,4}, Benjamin Peeters¹, Johannes
Koch¹, Elmar Kriegler^{1,6}

¹Potsdam Institute for Climate Impact Research

²Humboldt-Universität zu Berlin (HU), Albrecht Daniel Thaer-Institut für
Agrar- und Gartenbauwissenschaften, Germany

³Humboldt-Universität zu Berlin, Integrative Research Institute on
Transformations of Human-Environment Systems (IRI THESys), Berlin,
Germany

⁴Global Energy Systems Analysis, Technische Universität Berlin, Berlin,
Germany

⁵Humboldt-Universität zu Berlin, Geographic Institute, Germany

⁶University of Potsdam

*Corresponding author: jiarui.zhong@pik-potsdam.com

Abstract

Limiting warming to 1.5 °C increasingly depends on pathways with temporary temperature overshoot and large-scale carbon dioxide removal (CDR), yet their distributional implications remain poorly understood. We develop a within-region, decile-level framework that maps pathway-driven price changes to heterogeneous consumption structures to quantify distributional outcomes under low- (LO) and high-overshoot (HO) pathways. Comparing scenarios with the same end-of-century temperature target, we show that LO raises inequality earlier and keeps it elevated, whereas HO delays impacts but leads to a sharper increase in later decades. This shift coincides with rising CDR financing needs, constraining fiscal space for redistribution, particularly under HO. Energy price increases drive early impacts but are transient, while food price pressures are more persistent and increasingly important over time. A climate-fund-type mechanism can ease late-century financing stress, but requires substantial intertemporal and international transfers. Overshoot governance therefore depends not only on technological feasibility, but also on compensation design, fiscal timing, and political feasibility.

15 Introduction

16 Limiting global warming to 1.5 °C remains a cornerstone of international climate policy^{1,2}. Yet
17 current pledges remain insufficient, and many 1.5 °C-compatible pathways now assume a tempo-
18 rary overshoot followed by large-scale carbon dioxide removal (CDR) to compensate for insufficient
19 near-term mitigation³. Such overshoot pathways are now central in IPCC assessments and policy
20 debates⁴⁻⁶. While their technological feasibility and physical and ecological risks have been widely
21 discussed⁷⁻⁹, their broader consequences for who bears the costs and benefits—across time, regions,
22 and within countries—remain less clearly understood. This includes growing concerns about un-
23 equal regional ability to deploy CDR and in general how the benefits and costs of climate change
24 mitigation distribute across income groups and over time¹⁰.

25 Evaluating long-term transformation pathways has been the central task of Integrated Assessment
26 Modeling (IAMs) frameworks. However, the assumption that each region is represented by a
27 single average household limits their ability to capture differences in impacts across household
28 groups within each region^{3,11}. Recent advances that incorporate household heterogeneity, income
29 groups, and inequality metrics have begun to address this limitation, providing new insights into
30 the distributional implications of mitigation policies¹²⁻¹⁷.

31 These distributional effects have recurrently been found to be regressive, disproportionately bur-
32 dening low-income households, and are primarily transmitted through the consumer price system.
33 Mitigation raises consumer prices, particularly for basic necessities such as energy and food, which
34 comprise a large share of consumption expenditures among poorer households^{18,19}. These price
35 changes translate macro-level mitigation costs into heterogeneous welfare impacts across house-
36 holds²⁰⁻²⁴. However, most existing long-term and global assessments provide limited insight into
37 how heterogeneous household consumption patterns mediate these effects.

38 Another consistent finding across these studies is that governments can offset regressive effects
39 by returning carbon-pricing revenues progressively to households. This compensatory potential,
40 however, relies on a temporal alignment: distributional pressures arise when carbon pricing still
41 generates substantial revenue for compensation. In stringent no-overshoot pathways, this condition
42 can plausibly hold because high carbon prices are levied while emissions remain high enough to
43 sustain redistribution.

44 Pathways including overshoot, however, could disrupt this alignment by altering the temporal
45 profile of carbon prices and emissions. With large-scale CDR deployment, carbon prices tend to be
46 lower in the near term^{10,25}, but rise sharply later, when emissions have already declined or turned
47 negative, thus decreasing the available tax base. Expanded CDR also creates new distributional
48 pressures, including higher food prices from land competition²⁶⁻²⁸, and potential concentration of
49 profits or land rents and financial stress^{4,29}. As a result, inequality can rise just as fiscal capacity
50 for redistribution weakens for CDR financing.

Quantifying the distributional effects of overshoot pathways is important, but has not been sufficiently addressed. Existing studies focus mainly on differences across temperature targets, paying less attention to how alternative pathways to the same target generate different distributional outcomes, and to how the main sources of those outcomes change as household consumption patterns evolve. Because overshoot pathways reshape both the timing and composition of distributional burdens, outcomes depend not only on the target but also on the pathway used to reach it. We therefore ask the following question: How do alternative 1.5 °C overshoot pathways redistribute mitigation burdens across income groups over time? We focus in particular on their implications for economic inequality, the scope for revenue recycling, and the role of policy instruments such as a global climate fund as a necessity.

To address these questions, we link overshoot scenario results from the REMIND–MAGPIE^{30–34} to a post-processing distributional framework across household expenditure deciles within each region. This framework maps scenario-driven price changes into heterogeneous welfare outcomes measured by real consumption across ten expenditure groups in 12 world regions (see Methods). We focus on distributional effects arising from mitigation policies and therefore exclude climate impacts, another important driver of distributional outcomes, from the analysis. We provide a dynamic assessment of mitigation-induced distributional impacts under alternative pathways, identify their main consumption drivers, and show how high overshoot misaligns inequality pressures with CDR financing stress.

Results

We analyze two REMIND–MAGPIE mitigation scenarios with temperature overshoot under SSP2 and compare them with a current-policy baseline scenario (NPi)³⁵. Both overshoot scenarios meet the same 1.5 °C-compatible cumulative CO₂ budget of 500 Gt CO₂ by 2100, but differ in mitigation timing and overshoot magnitude. The low-overshoot (LO) pathway reduces emissions earlier and allows only a limited temporary budget exceedance (150–225 Gt CO₂), whereas the high-overshoot (HO) pathway delays mitigation, allows a larger exceedance, and relies on greater late-century CDR to bring cumulative emissions back to the same budget (ED Fig. 1a). As a result, HO reaches a higher peak temperature before returning to 1.5 °C (ED Fig. 1b).

These pathways also imply distinct trajectories for carbon pricing and CDR deployment. In LO, carbon prices rise rapidly and stabilize after mid-century; in HO, they remain lower until the mid-2030s and then increase sharply (ED Fig. 1c). CDR deployment is earlier and more moderate in LO, but later and much larger in HO, reaching 10–15 Gt CO₂ yr^{−1} by 2100.

We feed regional consumption and category-level price changes from the two scenarios into the post-processing distributional framework to map real-consumption losses across within-region expenditure deciles based on heterogeneous consumption patterns.

Intertemporal redistribution of mitigation burdens

We first compare the two scenarios along four global dimensions: mitigation costs borne by consumers, consumption-inequality effects, the emissions-revenue balance, and climate impacts that motivate emissions reductions (Fig. 1). Together, these dimensions show how LO and HO differ in their welfare implications globally over time.

We measure mitigation costs as global real consumption losses from the macroeconomic framework (Fig. 1a). In LO, earlier and more concentrated mitigation produces larger near-term consumption loss, peaking at around 3–4% compared to baseline real consumption by mid-century before declining towards 2100. In HO, mitigation costs are delayed: near-term impacts remain limited, but losses rise steadily and exceed those under LO by around 2065.

Because households differ in their consumption patterns, the mitigation costs borne by consumers are unevenly distributed across income groups and regions. Mitigation also increases global consumption inequality in both scenarios relative to the baseline (Fig. 1b), measured as the change in the real-consumption Gini index under an inequality-neutral recycling benchmark, in which GHG revenues are returned to households in proportion to baseline income shares. Under LO, global consumption inequality increases rapidly until around 2050, after which it stabilizes and declines only slightly. Unlike aggregate consumer mitigation costs, which ease over time, consumption-inequality effects remain persistent under LO. By contrast, consumption-inequality effects in the HO pathway rise more gradually and exceed LO levels only after around 2080, ultimately reaching a higher level than the peak observed in LO.

While the LO pathway entails higher near-term welfare losses and higher global inequality, it also generates substantial emission-tax revenues in early decades due to the rapid increase in carbon prices (Fig. 1c), potentially enabling governments to offset these burdens. In the main analysis, we focus on revenues from the energy system¹. In 2030, revenues under LO exceed 3% of global GDP, but as emissions decline rapidly, GHG-based revenues fall correspondingly and largely disappear by around 2050. In contrast, the HO pathway yields limited revenues in the near term because carbon prices rise more slowly, but maintains positive revenues for longer as net zero is reached later. A key divergence emerges after mid-century: when net-negative emissions from CDR are financed through carbon revenues, large-scale CDR deployment under HO drives net revenues below zero, with carbon-pricing deficits reaching around 6–7% of global GDP and marking the onset of pronounced late-century fiscal stress.

¹We focus on revenues from the energy system as these more plausibly accrue to governments. As a sensitivity analysis, we also consider a broader tax base that includes agricultural emissions (see SI section 8).

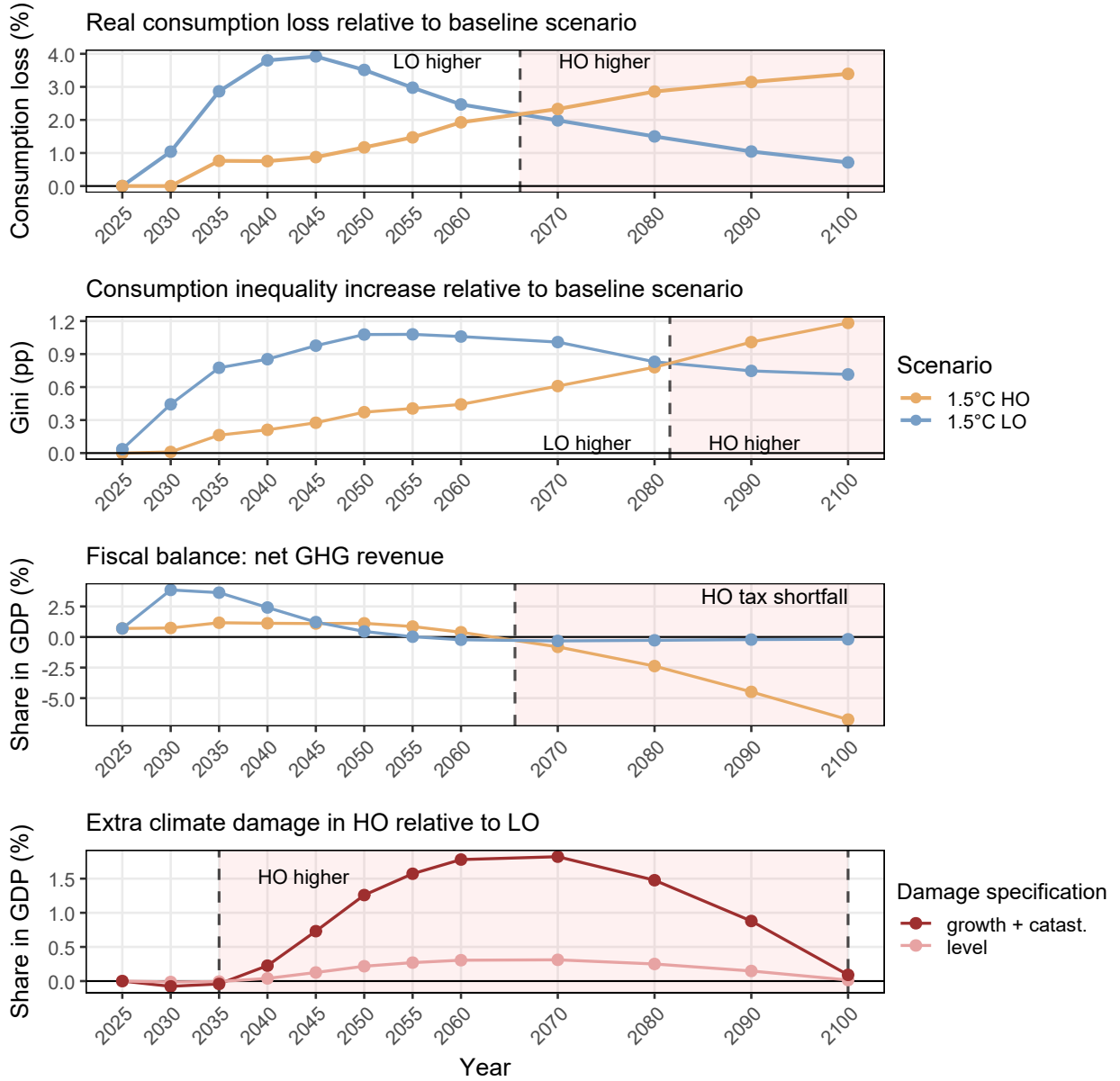


Figure 1: Intertemporal redistribution of global welfare, inequality, fiscal balance and impacts | (a) Consumption-based welfare loss (% change) under LO and HO scenarios relative to the baseline (NPi); (b) corresponding changes in global inequality relative to the baseline (NPi), measured as changes in the Gini coefficient (percentage points; 0 = perfect equality, 100 = perfect inequality). (c) net tax revenue as a share of gross domestic product, showing declining and eventually negative fiscal capacity under HO due to increasing reliance on CDR, with revenues measured from pricing GHG emissions in the energy system; and (d) climate damages under HO relative to LO, expressed as a share of GDP; two damage specifications are shown: a level damage function capturing contemporaneous temperature effects (lower bound), and a growth-plus-catastrophic specification incorporating persistent growth impacts and additional catastrophic risks, resulting in larger and more persistent damages (higher bound).

Another key characteristic of HO pathways is greater physical climate risk^{7,36,37}, with potentially persistent impacts beyond the peak. Figure 1d shows that projected global damages are higher in HO than in LO, highlighting the greater aggregate economic costs associated with the HO pathway. We use damage functions from the recent meta-analysis by Howard and Sterner³⁸, which synthesizes a still-unsettled literature by providing multiple estimates that control for key methodological differences, such as persistent growth effects and catastrophic risks. To illustrate this range, we report estimates from the lower bound (pure level effects) to the upper bound (including growth and catastrophic effects). This highlights the importance of including climate impacts in the overshoot discussion, but still falls short of capturing all relevant physical risk consequences, including effects on biodiversity and tipping-point risks.

To sum up, LO concentrates mitigation burdens in the near term, with higher welfare losses and rising inequality, but also avoids larger climate damages and generates substantial early tax revenues for redistribution. HO eases near-term pressures but shifts and amplifies risks to later periods, when higher inequality coincides with declining or negative fiscal capacity and greater climate damages. This temporal mismatch constrains governments’ fiscal ability to address distributional consequences, weakening the revenue-recycling channel often proposed to offset regressive mitigation impacts^{13,14,16,17}.

In the following sections, we trace how mitigation policy affects within-region household inequality through different consumption channels and assess how far tax revenues can offset these effects. We do not include climate impacts in the distributional analysis, although they are also likely to have important and regressive distributional effects^{13,39}.

Sectoral drivers of inequality dynamics

Mitigation, including carbon pricing, changes consumer prices through multiple channels, including carbon costs embedded in goods, energy taxes and subsidies, rising energy prices during the transition to low-carbon systems, and land-use competition. Our distributional framework examines how mitigation-induced consumption price changes across eight categories affect household welfare, measured in terms of real consumption. It is based on an empirically estimated Engel-curve demand system that projects decile-specific consumption baskets as a function of future expenditure levels. The system captures both regional heterogeneity and broader global patterns estimated from historical data, and is calibrated to match REMIND–MAGPIE aggregate consumption by category (ED Fig. 2).

We trace the transmission of these price shocks to regional distributional outcomes across four energy and four food categories by quantifying each category’s contribution to changes in the regional Gini coefficient. Using a Shapley decomposition, these category-level contributions sum to the total change in regional inequality.

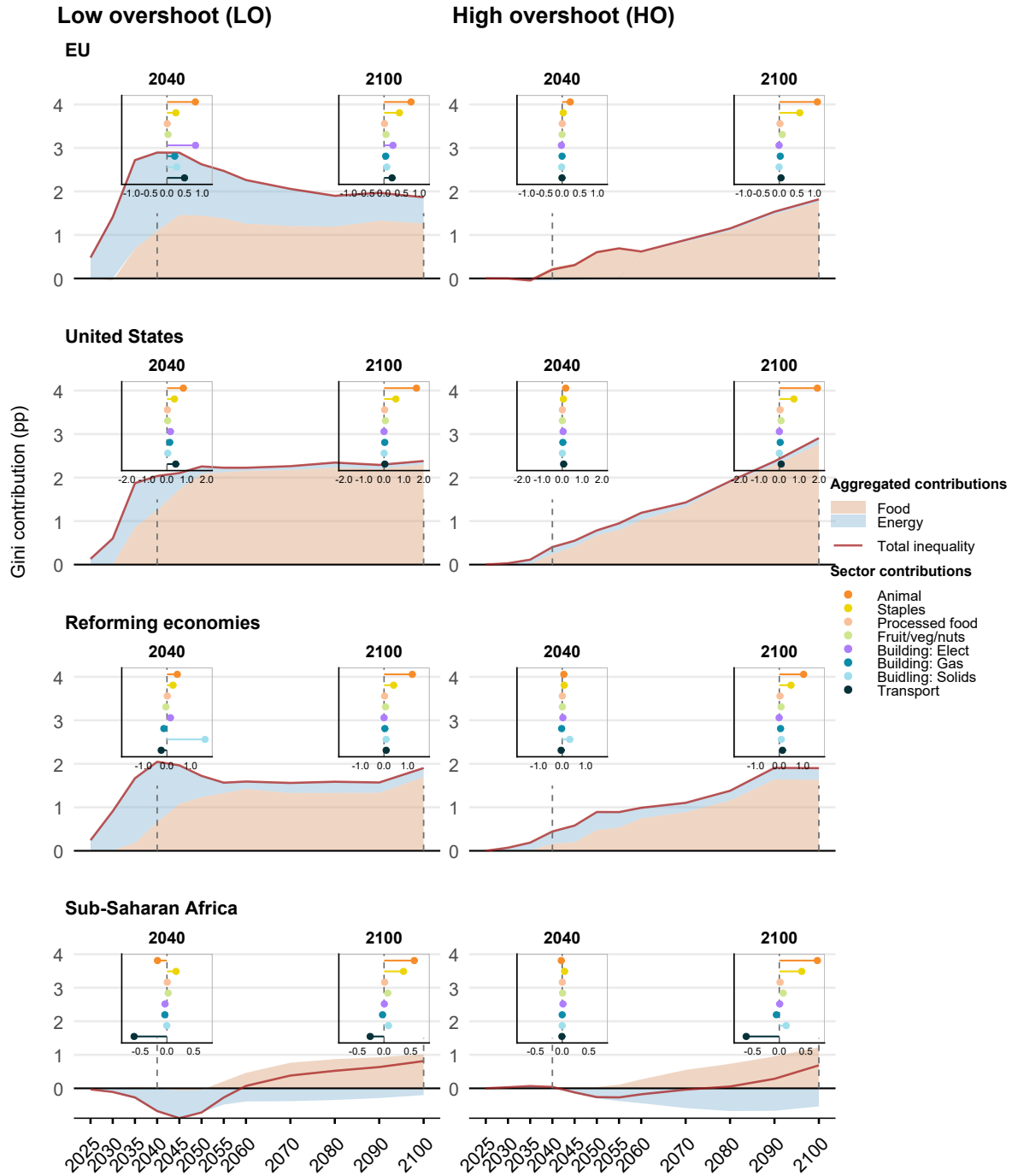


Figure 2: Food and energy price shocks shape regional inequality over time | Regional contributions to within-region inequality (Gini coefficient, percentage points, 0 = perfect equality, 100 = perfect inequality) from food and energy consumption categories under LO and HO scenarios. Rows show selected regions; columns compare LO and HO pathways. Stacked areas indicate the aggregate contribution of food and energy categories over time, with dashed lines showing total inequality change. Insets report the distribution of category-level contributions across consumption deciles in 2040 and 2100, highlighting heterogeneity across income groups.

In the LO pathway, a clear temporal shift emerges between energy- and food-driven inequality effects (Fig. 2). Energy price shocks dominate early, peaking around 2040, and increase inequality through regressive effects in most regions. An exception is Sub-Saharan Africa, where energy-related impacts are progressive because transport energy retains strong luxury characteristics at low income levels. This aligns with evidence that transport-fuel taxes tend to be less regressive, and in some developing-country contexts even progressive^{20,40}. India shows a similar pattern.

As energy systems decarbonize and emissions approach net zero, energy-related inequality effects fade, indicating that they are largely transient. Their magnitude and composition nevertheless vary across regions: Energy-driven risks are particularly pronounced in the EU, where electricity for buildings is a major driver of inequality, whereas solids used in the building sector play a more prominent role in reforming economies such as Russia.

In the HO pathway, energy-price-induced inequality is less pronounced because delayed mitigation moderates near-term price increases (ED Fig. 3). By contrast, food-related categories exert more persistent and increasingly dominant regressive effects once land-use mitigation intensifies. In LO, food prices remain elevated even after net zero, reflecting continued pricing of persistent agricultural emissions such as enteric fermentation and fertilizer-related N₂O (ED Fig. 3). In HO, these impacts build more gradually but reach higher levels because of higher late-century carbon prices and stronger pressure on land use and agricultural production from large-scale CDR deployment.

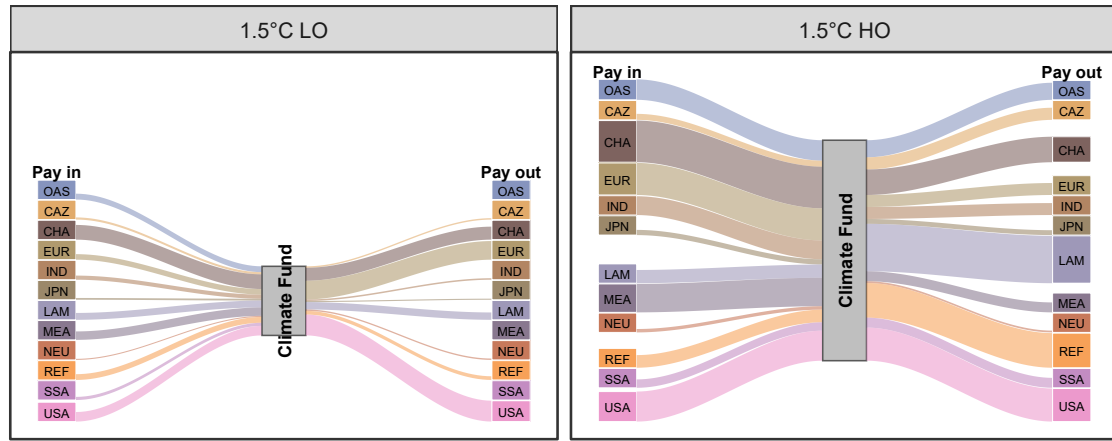
Across food categories, animal products and staple foods emerge as prominent drivers of inequality in most regions. This is consistent with literature highlighting the regressive effects of food price increases^{20,41,42}. Sub-Saharan Africa is again an exception: in the early 2040s, animal-product impacts are progressive because consumption is limited among poorer households and more concentrated among middle-income groups; this pattern fades as incomes rise.

Taken together, these results show that the intertemporal evolution of inequality is driven by a structural shift from transient energy price effects early in the transition to persistent food price pressures later. These effects exhibit substantial regional heterogeneity in both magnitude and composition, shaped by differences in economic development, consumption structures, and socio-cultural preferences.

Intertemporal Fiscal Reallocation and Redistribution Effectiveness

While the literature suggests that climate policies combined with well-designed social transfers can achieve distributionally neutral outcomes, our analysis shows that this is challenged by declining revenues in the second half of the century. This constraint is more pronounced under HO, which requires additional financing to support large-scale net-negative CDR deployment.

a Who pays into and receives from the climate fund



b Regional cumulative net negative CDR, 2025-2100

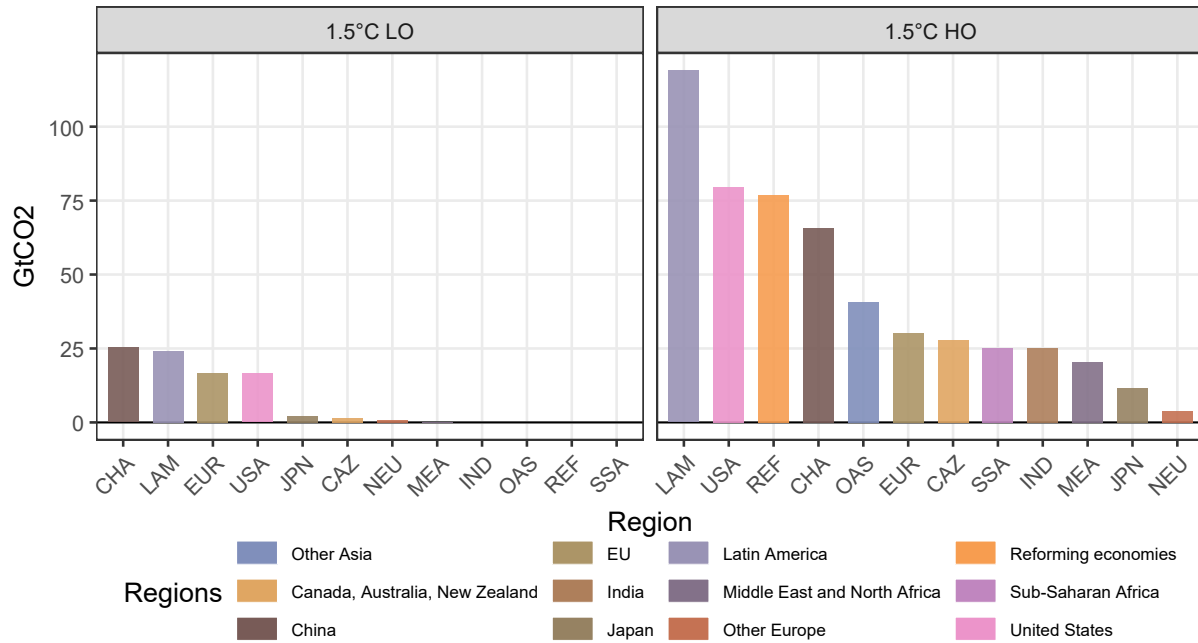


Figure 3: Regional contributions to and transfers from a global climate fund for net-negative emissions | (a) Regional contributions to (“pay in”) and transfers from (“pay out”) a stylized global climate fund under low-overshoot (LO) and high-overshoot (HO) 1.5 °C scenarios; flows indicate the net present value of financial transfers across regions, with the two plots in panel a using the same y-axis scale; (b) cumulative net CDR deployed in each region under each scenario over 2025–2100, ordered by magnitude.

In this section, we examine how far domestic tax revenue recycling can reduce distributional pressures. We begin with the financing challenge created by the regional concentration of net-negative CDR under HO (Fig. 3b). In cost-efficient IAMs such as REMIND–MAGPIE, large-scale CDR deployment is concentrated in a limited number of regions, particularly Latin America and reforming

economies, owing to their high CDR potential. Although this pattern reflects least-cost mitigation, it also concentrates the associated financing burden. Under HO, financing requirements for net-negative CDR, implemented as carbon-price-based subsidies, amount to around 14% of GDP in Latin America and about 50% in reforming economies, the latter because of the relatively small size of the economy (ED Fig. 4).

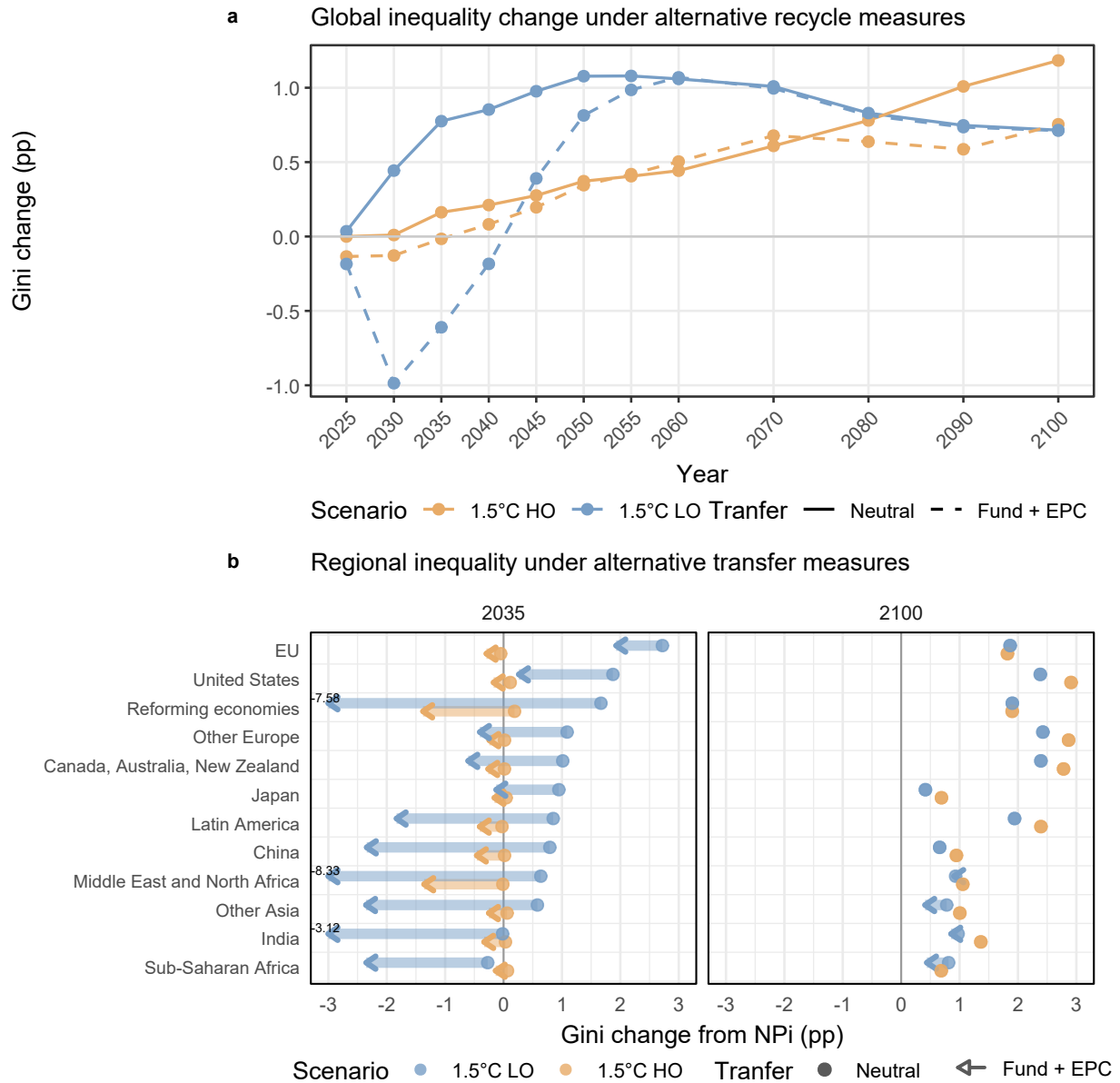
To illustrate a more intertemporally equitable approach to overshoot and CDR financing, we introduce a stylized global climate fund^{25,43}. Under this mechanism, a global fund allocates a fixed share of carbon tax revenues from all regions, which accumulates resources over time and finances net-negative CDR through 2100. This mechanism represents one possible way to address the intertemporal financing challenge posed by CDR and aligns with existing discussions of pricing-based instruments^{25,43}. It serves as a parsimonious illustration of a responsibility-based intertemporal transfer framework in which early generations that benefit from overshoot contribute to the carbon removal required thereafter.

Fig. 3a shows the net present value of regional contributions to and payouts from the fund. Compared with LO, HO requires a substantially larger fund and greater intertemporal coordination of financing and carbon budget management. Payouts are allocated according to regional net CDR deployment. Regions such as Latin America and reforming economies emerge as net recipients, with payouts exceeding their contributions.

Having addressed the intertemporal and cross-regional financing challenge through the climate fund, we next turn to within-region redistribution. Regions allocate the remaining net positive revenues (ED Fig. 4) to domestic equal-per-capita (EPC) transfers. Fig. 4b shows the resulting improvements in within-region consumption inequality relative to the inequality-neutral recycling benchmark (Neutral).

Despite a higher upfront increase in consumption inequality under LO, most regions are able to offset mitigation-induced inequality under EPC transfers and, in some cases, achieve better within-region outcomes than those observed under the HO pathway. By contrast, these gains become negligible late in the century, as net positive revenues disappear in most regions.

This erosion of domestic redistributive capacity makes it important to distinguish within-region from global inequality, because the climate fund continues to reallocate resources across regions even when EPC transfers fade. Fig. 4a therefore turns to global inequality under the combined climate-fund-plus-EPC scheme. In early decades (up to around 2040), LO achieves more favorable distributional outcomes because ample tax revenues support redistribution, whereas improvements under HO are more limited. Later in the century, however, HO shows stronger reductions in global inequality, driven mainly by intertemporal transfers through the climate fund that lower between-country inequality.



224 These results show that the effectiveness of redistribution depends not only on transfer design,

but also on the timing and scale of available fiscal resources. LO performs better in the near term because abundant early revenues support domestic compensation and contributions to the climate fund, but this advantage erodes after around 2040 as revenues decline. HO entails lower consumption-inequality effects early on, but it also offers much less scope for redistribution. Across the full period, revenues from the energy system provide an institutionally plausible but limited benchmark and are insufficient to fully offset these distributional pressures. As shown in the SI, broadening the revenue base to include agricultural emissions would substantially strengthen compensatory capacity, although doing so would likely face greater political and administrative constraints (SI Section 8).

Discussion

Our analysis shows that choosing a temperature-overshoot pathway is not only a question of technological feasibility or long-run cost minimization, but also one of distribution. Although low- and high-overshoot pathways meet the same long-term climate objective, they differ in the timing of mitigation, the evolution of fiscal conditions, and the transmission of price shocks to households, producing distinct welfare and distributional outcomes.

This creates a clear trade-off between LO and HO pathways. Across scenarios, mitigation-induced price changes tend to increase within-region consumption inequality, consistent with previous findings on the regressive effects of carbon pricing^{13,16,17,20,41}. LO brings mitigation burdens forward and can therefore generate stronger near-term and more persistent within-region distributional consequences. Yet these pressures emerge while governments still collect substantial carbon revenues, leaving greater scope for progressive recycling. HO, by contrast, moderates near-term price pressures but makes distributional outcomes more dependent on how late-century compensation is financed.

This mismatch between late-century compensation needs and a shrinking or negative carbon-revenue base is the central challenge of high overshoot. Under HO, mitigation is delayed until net emissions are already low, while the subsequent expansion of CDR further erodes or even reverses the carbon-revenue base. As a result, redistribution needs are greatest precisely when fiscal space is most constrained. An intertemporal global transfer mechanism could help alleviate late-century CDR financing pressures, but would require substantial global coordination and effective fund management⁴³. Our analysis therefore echoes intergenerational concerns about high overshoot³⁷ while adding a within-country dimension: overshoot not only defers costs across generations, but also intensifies adverse distributional effects within countries when compensatory capacity is weakest. Equitable CDR financing remains part of a broader debate about equity, normative principles, and financing efficiency. For reasons of scope, we focus on a responsibility-based approach and encourage future studies to examine these issues in greater depth.

When broad revenue recycling is insufficient to address mitigation-induced consumption-inequality impacts over time, revenues need to be used more selectively. Our sectoral decomposition shows that compensating prices in selected consumption categories might yield larger distributional benefits than uniform recycling. By mapping the intertemporal and regional heterogeneity of inequality drivers, we identify where policy can be more effective. In particular, revenues could reduce excise taxes on goods associated with substantial distributional risks, such as animal products and electricity. Governments could also exempt hard-to-abate residual emissions, such as the share of N_2O emissions from fertilization, in later periods. This perspective aligns with a growing literature on alternative policy designs to address distributional concerns^{44,45}. Finally, using policies to encourage dietary shifts towards lower meat consumption could also help households adapt to rising food prices.

While these results point to gains from more targeted compensation, evaluating specific compensation instruments is beyond the scope of this paper. Our analysis is also limited in that it focuses only on price-mediated effects and abstracts from income effects, climate damages, and adaptation needs, all of which matter for a comprehensive cost–benefit assessment. This omission may be more consequential under higher overshoot, where larger climate damages are likely to increase adaptation needs and may add further distributional effects beyond the price-mediated channels examined here. Another limitation is that we focus on vertical (income-based) inequality within countries and do not consider horizontal dimensions of inequality, such as gender, ethnicity, sectoral affiliation, or urban–rural location, which are also important in distributional analysis^{46–48}. Finally, we consider only the one-way effects of climate change and mitigation on inequality; feedbacks from inequality, which have also been shown to be important in the literature⁴⁹, are left for future work.

Looking ahead, delayed mitigation would make high-overshoot pathways and large-scale CDR increasingly salient. Our results suggest that in such a context, greater attention must be paid to heterogeneous welfare effects across and within countries when evaluating overshoot pathways and designing feasible climate policy.

Methods

We develop a micro-distributional framework that downscales regional macroeconomic consumption changes to ten within-region expenditure deciles by translating mitigation-induced price shocks into decile-specific welfare effects. The approach combines (i) a parametric representation of within-region expenditure distributions, (ii) empirically estimated Engel curves to construct decile-specific consumption baskets, and (iii) a cost-of-living index that maps category-level price changes into welfare impacts. This structure allows us to assess the distributional effects of mitigation policies while remaining consistent with aggregate consumption dynamics from the IAM framework.

Macro model

The scenario data used in this study are generated with the coupled REMIND–MAGPIE modelling framework, which integrates a global multi-regional energy–economy model with a detailed land-use model. REMIND represents the energy system and macroeconomic dynamics, determining optimal investment, technology deployment, and energy use under climate policy constraints. It operates as an intertemporal optimisation model, capturing trade-offs between near-term mitigation efforts and long-term costs^{30,32,33}.

MAGPIE, a recursive dynamics model, complements this representation by modelling land-use dynamics, including agricultural production, land competition, and land-based mitigation options. It explicitly accounts for constraints on land availability, productivity, and trade, and determines the allocation of land across food, feed, bioenergy, and carbon sequestration purposes³¹.

The two models are soft-linked through an iterative exchange of information⁵⁰. REMIND provides bioenergy demand and GHG prices, which MAGPIE applies to CO₂ emissions from land-use change and to agricultural non-CO₂ emissions, thereby informing land-use decisions. In turn, MAGPIE returns land-use emissions, bioenergy prices, and mitigation costs, which are incorporated into the REMIND optimisation. This coupling ensures internal consistency between the energy system and land-use responses under different policy scenarios.

The resulting scenarios provide internally consistent projections of emissions, energy use, land-use change, and prices, which serve as inputs to the distributional analysis conducted in this study.

Scenario setup

We consider three scenarios in this study: National Policies implemented (NPI), low overshoot (LO), and high overshoot (HO). The LO and HO scenarios are Tier 2 scenarios developed in the RESCUE project to represent more plausible near-term mitigation trends³⁵. All scenarios are based

on Shared Socioeconomic Pathway 2 (SSP2)⁵¹, the “Middle of the Road” pathway.

The baseline scenario used in this study corresponds to a current policies pathway (NPi2025), which reflects national climate policies that are implemented as of around 2025, without assuming any further strengthening of mitigation ambition over time. As such, it represents a continuation of existing policy frameworks rather than a no-policy counterfactual³³.

The low-overshoot (LO) and high-overshoot (HO) pathways considered in this study represent alternative intertemporal strategies to meet the same cumulative CO₂ budget by 2100. Both pathways allow for endogenous adjustment of the energy system, land use, and carbon dioxide removal (CDR), and ensure that cumulative emissions return to the prescribed budget at the end of the century. As a result, even pathways with limited overshoot may exhibit temporary exceedance of the carbon budget, while maintaining a smooth decline in emissions and non-CO₂ greenhouse gases over time.

Mitigation is implemented through regionally differentiated carbon prices that converge over time toward a common global level, which determines abatement effort and technology deployment endogenously. Despite this shared temperature goal, the two pathways differ fundamentally in the timing of mitigation efforts. In LO pathways, earlier and more rapid increases in carbon prices induce a front-loaded transition of the energy system, limiting the need for large-scale CDR deployment later on. In contrast, HO pathways delay mitigation in the near term, resulting in higher cumulative emissions and a stronger reliance on CDR in the second half of the century to return to the same carbon budget. In the LO scenarios, GHG prices are designed to increase until cumulative CO₂ emissions reach their peak, after which they remain constant. In the HO scenario, prices increase exponentially throughout the century and reach their maximum in 2100.

CDR is realized through a portfolio of different CDR options, namely Bioenergy with Carbon Capture and Storage (BECCS), Direct Air Carbon Capture and Storage (DACCS), Ocean Alkalinity Enhancement (OAE), Enhanced Weathering of rocks (EW), Afforestation and Reforestation (AE), and carbon storage in long-lived materials. A key feature of the scenario design is the inclusion of system-level constraints on CDR deployment. In particular, the total final energy use associated with CDR is limited relative to regional energy demand (around 10% at the regional level and 17% at the global level), and geological CO₂ storage is subject to an upper bound on annual injection rates. These constraints restrict the large-scale expansion of energy-intensive options such as direct air capture with carbon storage (DACCS), and shape the composition of the CDR portfolio. As a result, CDR deployment emerges from the interaction between mitigation demand, resource availability, and system constraints.

These differences imply distinct system responses across pathways. In LO, earlier mitigation requires a faster transformation of the energy system and a faster scale-up of CDR. In return, it reduces the overall scale of required CDR and thereby limits pressure on energy and land systems

in the long run. In HO, delayed mitigation shifts adjustment to later periods, leading to substantially higher reliance on land-based and lower-energy CDR options, particularly BECCS, as well as tighter interactions with energy and resource constraints. At the same time, the feasible magnitude of overshoot is limited by the maximum deployable CDR capacity and scale-up speed, rather than being freely determined.

Comparing the LO and HO pathways to the NPi baseline provides a counterfactual framework to isolate the effects of strengthening mitigation ambition. The NPi scenario reflects a continuation of currently implemented and announced policies, without additional scaling-up of mitigation efforts over time. In contrast, both LO and HO pathways introduce policy trajectories consistent with a 1.5 °C carbon budget, implying substantially stronger and more coordinated mitigation.

The comparison therefore captures the economic and distributional consequences of increasing mitigation ambition relative to a current-policy baseline, while differences between LO and HO isolate how the timing of mitigation effort redistributes these impacts over time.

Decile welfare measure and analytic framework

We operationalize distributional impacts through a consumption-based welfare measure, real consumption, which provides a transparent link between sectoral price changes and household-level welfare. The analysis is conducted at the level of household expenditure deciles within each RE-MIND-MAgPIE region.

For region r , household expenditure decile h , and year t , real consumption is defined as

$$c_{r,h,t} \equiv \frac{E_{r,h,t} + T_{r,h,t}}{P_{r,h,t}}, \quad (1)$$

where $E_{r,h,t}$ denotes nominal consumption expenditure, $T_{r,h,t}$ net fiscal transfers, and $P_{r,h,t}$ a decile-specific cost-of-living index (COLI).

Let primes denote the policy scenario and assume no carbon-tax recycling in the baseline ($T_{r,h,t} = 0$). The log change in real consumption between the policy and baseline scenarios can be written in closed form as

$$\Delta \ln c_{r,h,t} = \ln \left(\frac{E'_{r,h,t}}{E_{r,h,t}} \right) + \ln \left(1 + \frac{T'_{r,h,t}}{E'_{r,h,t}} \right) - \Delta \ln P_{r,h,t}. \quad (2)$$

This decomposition provides the organizing framework of the analysis. Distributional impacts of mitigation on within-region household deciles arise through three channels: changes in nominal resources, fiscal transfers, and changes in the COLI driven by category-level price changes.

While this framework allows us to examine the relative exposure of different household deciles across channels, our objective is not to re-estimate aggregate welfare effects. Because regional real consumption in REMIND–MAGPIE already reflects general-equilibrium price and quantity adjustments, we use the micro model only to characterize heterogeneity in relative impacts across income groups. Specifically, real consumption changes at the decile-group level derived from the post-processing micro model are used as weights to anchor group-specific losses to the aggregate real consumption change, thereby avoiding double counting of aggregate welfare effects while preserving the IAM-consistent welfare level.

Consumption across expenditure deciles

For each region r and year t , REMIND provides aggregate regional consumption expenditure. To introduce within-region heterogeneity, we assume that household-level nominal consumption expenditure follows a lognormal distribution, which provides a parsimonious representation of empirical expenditure distributions⁵².

Specifically, nominal household expenditure satisfies

$$\ln E_{r,t}^{(i)} \sim \mathcal{N}(\mu_{r,t}, \sigma_{r,t}^2), \quad (3)$$

where parameters $\mu_{r,t}$ and $\sigma_{r,t}$ are calibrated to match regional mean expenditure and the corresponding Gini coefficient. The calibrated lognormal distribution is subsequently integrated over ten equal-population expenditure deciles, which serve as the representative household groups in the analysis.

Because REMIND does not provide projections of within-region inequality, we rely on exogenous Gini projections for the Shared Socioeconomic Pathways (SSPs)^{51,53,54}. Focusing on consumption-side distributional consequences of mitigation pathways, we hold the regional Gini coefficient fixed across scenarios within a given year. This implies that policy-induced changes in aggregate nominal expenditure are passed through proportionally across deciles in our framework.

Decile-specific cost-of-living index

Distributional impacts of mitigation arise through heterogeneous exposure to price changes across consumption categories. To capture this, we construct decile-specific changes in the cost-of-living index (COLI) using a superlative Törnqvist price index over a set of energy, food, and residual consumption categories.

411 For region r , decile h , and year t , the change in the COLI is given by

$$412 \quad \Delta \ln P_{r,h,t} = \sum_g \bar{w}_{g,r,h,t} (\ln p'_{g,r,t} - \ln p_{g,r,t}), \quad (4)$$

$$413 \quad \bar{w}_{g,r,h,t} = \frac{1}{2} (w_{g,r,h,t} + w'_{g,r,h,t}), \quad (5)$$

414 where g indexes consumption categories; $p_{g,r,t}$ and $p'_{g,r,t}$ denote category-level prices in the baseline
 415 and policy scenarios, respectively; and $w_{g,r,h,t}$ and $w'_{g,r,h,t}$ denote the corresponding decile-specific
 416 expenditure shares. Using the average of baseline and policy expenditure shares ensures symmetric
 417 treatment of both states and provides a second-order approximation to changes in the cost of living,
 418 thereby avoiding bias from relying solely on base-period or policy-period weights.

419 Differences in COLI across deciles are therefore driven by heterogeneity in consumption baskets.
 420 To represent these baskets, we use empirically estimated Engel curves that map expenditure levels
 421 to category-specific budget shares, allowing price changes to translate into heterogeneous welfare
 422 effects across income groups.

423 Consumption baskets and Engel curves

424 We estimate Engel curves using cross-sectional household expenditure survey data aggregated to
 425 country-by-expenditure-decile cells. Regional estimation is performed separately by region, pooling
 426 all countries within each region and including country fixed effects to absorb country-specific price
 427 levels and measurement differences. For each consumption category g , we estimate:

$$428 \quad \text{logit}(w_{r,c,h,g}) = \alpha_{r,g} + \beta_{r,g,1} \ln E_{r,c,h} + \beta_{r,g,2} (\ln E_{r,c,h})^2 + \delta_{r,c} + \varepsilon_{r,c,h,g}. \quad (6)$$

429 Here $w_{r,c,h,g}$ is the expenditure share of category g for expenditure decile h in country c (within
 430 region r), $E_{r,c,h}$ is total expenditure for the corresponding cell, and $\delta_{r,c}$ denotes country fixed effects.
 431 The estimated regional Engel curves are then used to project decile-specific consumption shares
 432 under future scenarios, conditional on their projected expenditure levels.

433 To project consumption baskets beyond observed data, we extend these Engel curves using a two-
 434 stage extrapolation procedure. First, regional Engel curves are used where projected expenditures
 435 remain within historical support. When projections extend beyond this range, predicted shares are
 436 gradually shifted toward pooled (global) Engel curves, which provide a more stable representation
 437 of consumption patterns at higher income levels. This transition is defined at the region-year level
 438 based on exceedance of empirical lower or upper support and is implemented smoothly to avoid
 439 discontinuities.

440 Second, to prevent implausible upper-tail behavior, we impose shape restrictions on a subset of

pooled Engel curves. For categories where historical evidence supports saturation rather than declining absolute consumption at high income levels (e.g., electricity, transport energy, and food categories), we constrain the upper-tail response to rule out excessively steep declines in expenditure shares. These restrictions apply only when projections extend beyond the empirical support of the pooled data, preserving fit within observed ranges while ensuring economically plausible extrapolation (see SI).

Finally, projected consumption shares are reconciled with IAM-implied aggregate consumption patterns through a matrix-balancing (RAS-type) calibration step. This adjustment ensures consistency with aggregate category-level consumption while preserving the relative consumption patterns across expenditure deciles within each category (see SI).

Global climate fund and revenue recycling schemes

Our framework distinguishes between (i) the IAM-consistent baseline allocation of emission-tax revenues, (ii) a global fund that governs the financing of net-negative emissions, and (iii) alternative within-region redistribution schemes.

REMIND treats carbon pricing revenues as revenue-neutral, such that aggregate consumption paths already reflect recycling in general equilibrium. In our analysis, this implies that the baseline allocation of tax revenues is effectively distribution-neutral across expenditure deciles. We therefore interpret the downscaled decile-level consumption as reflecting an inequality-neutral recycling benchmark.

In overshoot pathways, net-negative emissions can generate negative carbon pricing revenues, effectively implying a subsidy requirement for carbon dioxide removal (CDR) activities. In cost-efficient IAM pathways such as REMIND, CDR is deployed where it is cheapest, leading to a strong geographic concentration of net-negative emissions. This implies that the associated financing burden would fall disproportionately on a small number of regions, although such an allocation does not reflect plausible real-world burden-sharing. To account for international and intertemporal equity considerations, we introduce a global climate fund that pools carbon pricing revenues across regions and over time. Regions with positive tax revenues contribute a uniform share of their revenues to the fund each period, while the fund covers the financing requirement associated with net-negative emissions in later periods. The fund is designed to remain solvent over time and does not require borrowing, ensuring consistency with the underlying IAM framework.

To examine how alternative revenue recycling designs shape distributional outcomes, we consider an equal-per-capita (EPC) recycling scheme as a redistributive perturbation that leaves aggregate consumption unchanged but redistributes tax revenues across deciles. This allows us to isolate the distributional effects of alternative recycling designs while preserving IAM-consistent aggregate

outcomes.

In the main analysis, recycled revenue is defined as carbon pricing revenue from GHG emissions in the energy system, reflecting an institutionally plausible tax base for redistribution. Broader tax bases, including agricultural emissions, are considered in the Supplementary Information.

Data and macro–micro interface

We take the macroeconomic environment from REMIND–MAGPIE and use regional aggregate consumption expenditure $E_{r,t}$, category-level price indices $p_{g,r,t}$, representative household expenditure shares $w_{g,r,t}^{\text{IAM}}$, and regional carbon pricing revenues $T_{r,t}$.

Within-region expenditure distributions are parameterized using SSP2-consistent Gini projections⁵³.

Micro-level consumption behavior is captured using a harmonized household expenditure database covering 88 countries⁴⁸. The data are aggregated to expenditure deciles and used to estimate region-specific and pooled Engel curves linking total expenditure to category-level budget shares.

Data and code availability

Data and code supporting the findings of this study will be made publicly available upon acceptance.

Acknowledgement

We thank Nico Bauer, Miodrag Stevanović and Sijmen Adrianus Duineveld for helpful discussions. We thank Falk Benke for technical assistance and Simon Feindt for helpful comments on the manuscript.

Funding statements

B.L.B. discloses the European Union’s Horizon Europe Research and innovation programme provided funding under grant no 101135512 (LegumES). B.L.B. further acknowledges support from PIK core funding, and the project NitroDynamics funded by the Seeding The Future Foundation. R.H. discloses support from the Kopernikus-Ariadne project (FKZ 3SFK5A0-2) funded by the German Federal Ministry of Research, Technology and Space. L.Me. discloses funding from the EU’s Horizon Europe research and innovation programme under grant numbers 101056939 (RESCUE)

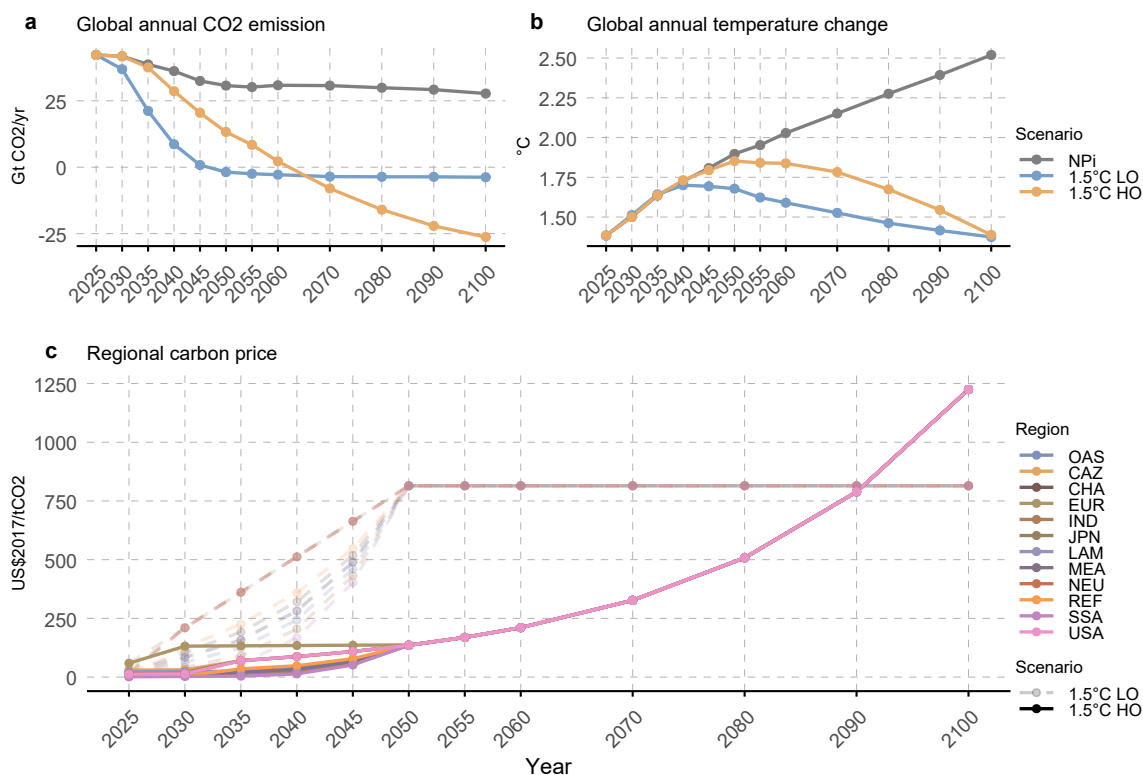
and 101081193 (OptimESM). A.M. discloses funding from European Union’s Horizon Europe research and innovation program under grant no. 101081521 (UPTAKE). T.D. acknowledges funding from the CDRSynTra2 project funded by the Federal Ministry of Research, Technology and Space (BMFTR) under grant number 01LS2501G. B.P. discloses support from the GeoClimRisk Project (of the Potsdam Institute for Climate Impact Research), funded by the International Climate Initiative (IKI) on behalf of the German Federal Foreign Office as part of the Climate Diplomacy Action Programme (CDAP), and implemented by the Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH.

Author contributions

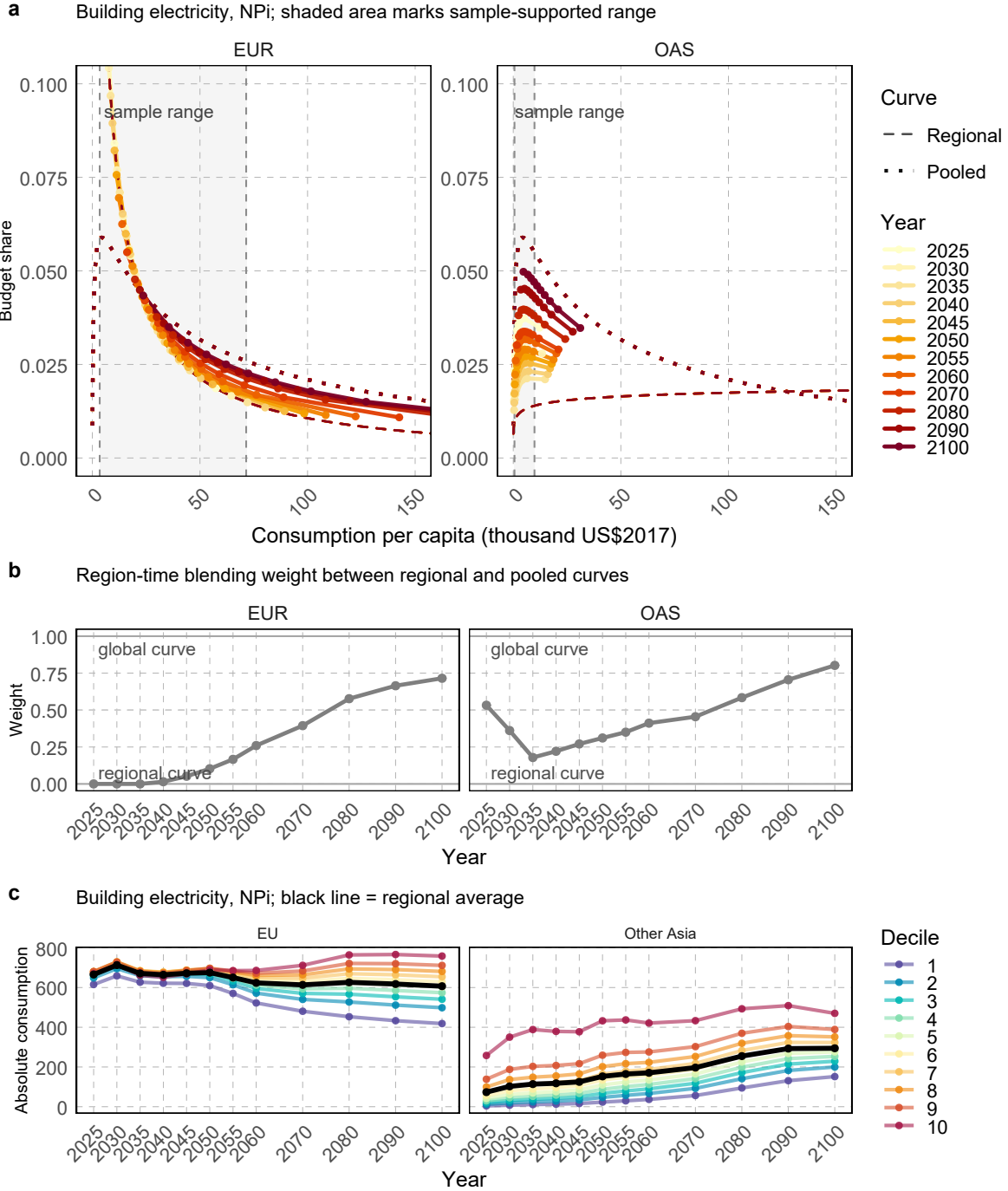
J.Z., F.P. and E.K. conceptualized the study with contributions from B.L.B., D.M.D. and L.Mi. J.Z. developed the methodology, performed the analysis, implemented the distributional framework and data processing pipeline, and created the visualizations. L.Mi. contributed to the preparation and aggregation of the global decile consumption data. L.Me., T.D. and A.M. contributed to REMIND model development for the overshoot scenarios and discussions related to the scenarios. J.Z. wrote the paper. All authors discussed the results, reviewed and edited the manuscript.

Competing interests

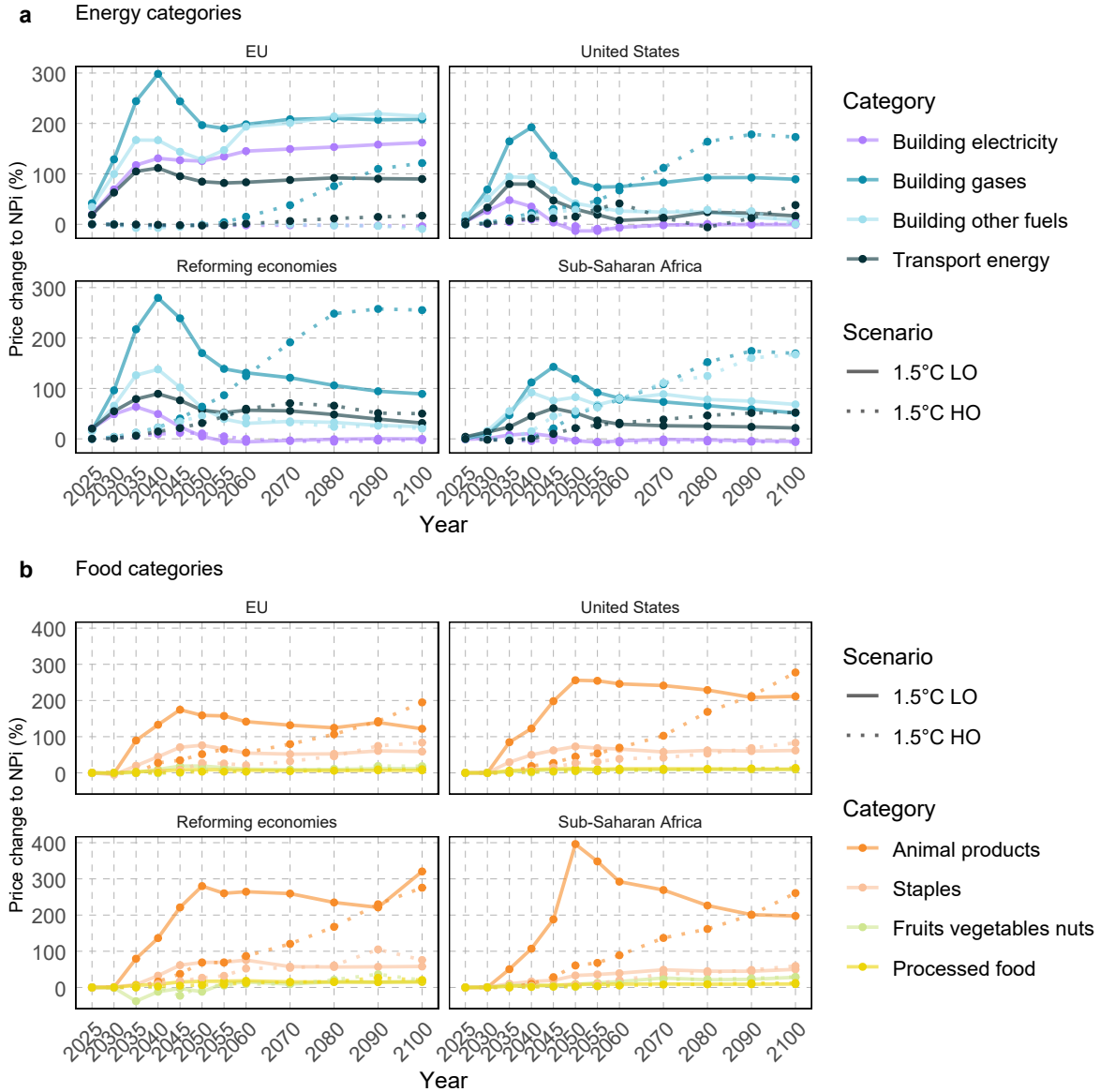
The authors declare no conflicts of interest.



Extended Data Figure 1. Intertemporal dynamics of emissions, temperature, and carbon prices across scenarios | (a) Annual CO₂ emissions under a current-policy scenario (NPi), a low-overshoot 1.5°C pathway (LO), and a high-overshoot 1.5°C pathway (HO). The LO pathway achieves rapid emissions reductions and reaches net zero around mid-century, whereas the HO pathway delays mitigation and relies on substantial net-negative emissions in the second half of the century; (b) global mean surface temperature change relative to pre-industrial levels. The LO pathway limits peak warming and returns to 1.5°C earlier, whereas the HO pathway exhibits a higher and more prolonged temperature overshoot before declining by 2100; and (c) regional carbon prices across scenarios. In the low-overshoot (LO) pathway, carbon prices rise rapidly and stabilize after mid-century, whereas in the high-overshoot (HO) pathway they increase more gradually at first before escalating sharply in the second half of the century. Regional differentiation is present in early years, with prices converging across regions by around 2050.

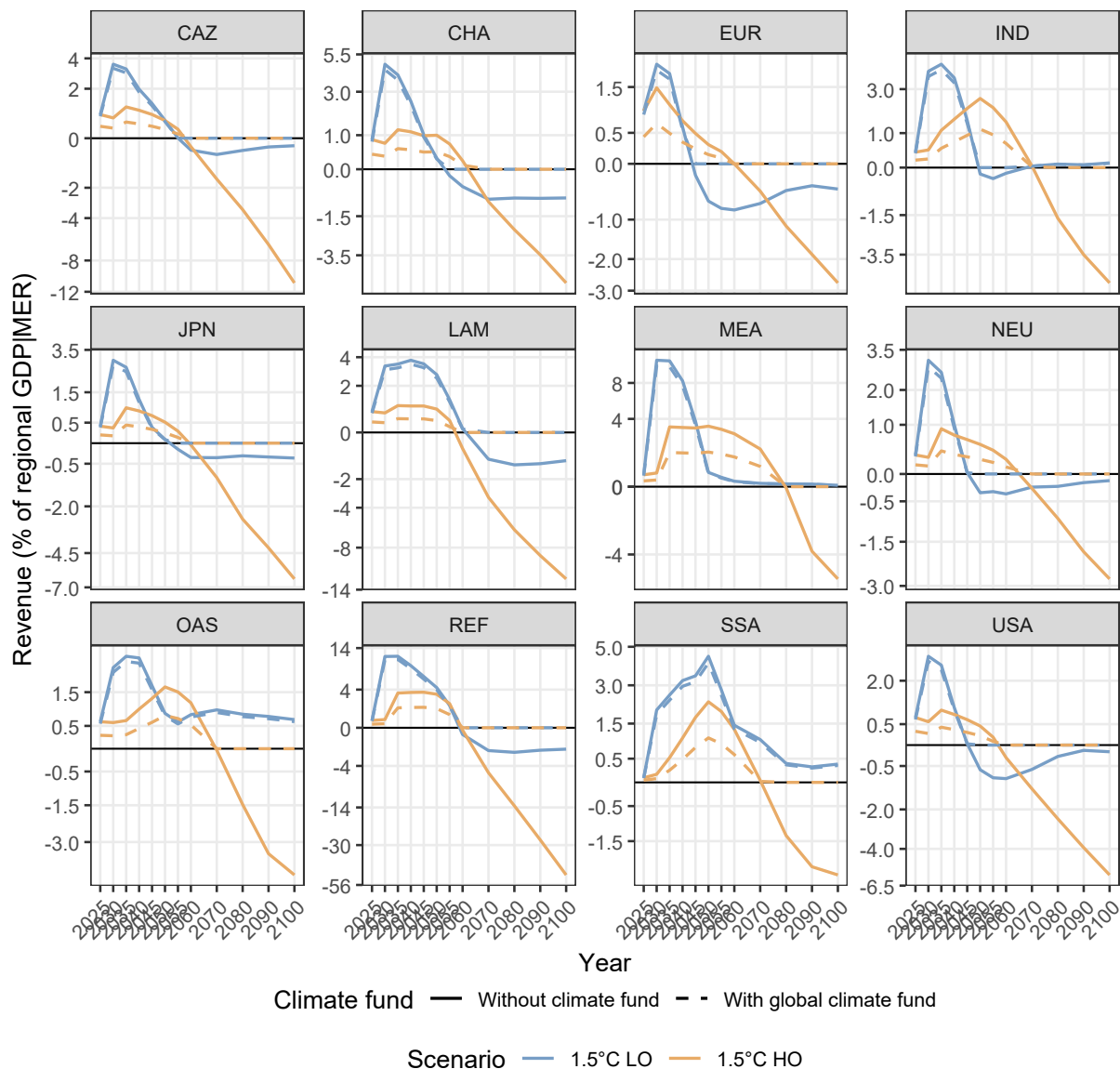


Extended Data Figure 2. From Engel curve estimation to projected consumption: regional–global blending | (a) Engel curves for building electricity (EUR and OAS); shaded areas indicate data support, dashed and dotted lines show regional and pooled estimates, and colored lines represent blended curves used for projection each year; (b) time-varying blending weights between regional and pooled curves (0 = using fully regional estimates, 1 = fully using global pooled); and (c) projected absolute consumption across deciles, with the black line denoting the regional mean.



Extended Data Figure 3. Price changes relative to the NPi scenario across energy and food categories | (a) Energy-related prices (% change relative to NPi) across regions, showing earlier and stronger increases under LO and more delayed but persistent increases under HO; and (b) food-related prices, with substantially larger and more persistent increases than energy prices, particularly for animal products. Price responses exhibit strong regional heterogeneity, with especially large increases in Latin America and Sub-Saharan Africa, while solid lines denote the LO pathway and dotted lines denote the HO pathway.

Uniform saving rate α^* : 1.5°C HO=0.542; Uniform saving rate α^* : 1.5°C LO=0.081



Extended Data Figure 4. Intertemporal burden sharing through carbon revenues and a global climate fund | Carbon revenues and climate fund transfers over time across regions under LO and HO pathways. Positive carbon revenues in early decades are partially allocated to a global climate fund, which accumulates resources and finances net-negative emissions in later periods. The uniform saving rate is 0.542 in HO and 0.81 in LO, applied to all regions in all periods with positive carbon revenues. In later periods, the fund finances all net-negative CDR, so that negative revenue flows are offset by corresponding fund payouts.

References

- [1] Myles Allen, Mustafa Babiker, Yang Chen, Heleen de Coninck, Sarah Connors, and Renée van Diemen. Summary for Policymakers. In: Global Warming of 1.5 °C an IPCC special report. Technical report, IPCC, 2018.
- [2] IEA. Net Zero Roadmap: A Global Pathway to Keep the 1.5 °C Goal in Reach – Analysis. <https://www.iea.org/reports/net-zero-roadmap-a-global-pathway-to-keep-the-15-c-goal-in-reach>, September 2023.
- [3] Calvin Katherine, Dasgupta Dipak, Krinner Gerhard, Mukherji Aditi, Peter W. Thorne, Trisos Christopher, Romero José, Aldunce Paulina, Barrett Ko, Blanco Gabriel, William W. L. Cheung, Connors Sarah, Denton Fatima, Diongue-Niang Aïda, Dodman David, Garschagen Matthias, Geden Oliver, Hayward Bronwyn, Jones Christopher, Jotzo Frank, Krug Thelma, Lasco Rodel, Lee Yune-Yi, Masson-Delmotte Valérie, Meinshausen Malte, Mintenbeck Katja, Mokssit Abdalah, Friederike E. L. Otto, Pathak Minal, Pirani Anna, Poloczanska Elvira, Pörtner Hans-Otto, Revi Aromar, Debra C. Roberts, Roy Joyashree, Alex C. Ruane, Skea Jim, Priyadarshi R. Shukla, Slade Raphael, Slangen Aimée, Sokona Youba, Anna A. Sörensson, Tignor Melinda, Detlef van Vuuren, Wei Yi-Ming, Winkler Harald, Zhai Panmao, Zommers Zinta, Hourcade Jean-Charles, Francis X. Johnson, Pachauri Shonali, Nicholas P. Simpson, Singh Chandni, Thomas Adelle, Totin Edmond, Alegría Andrés, Armour Kyle, Bednar-Friedl Birgit, Blok Kornelis, Cissé Guéladio, Dentener Frank, Eriksen Siri, Fischer Erich, Garner Gregory, Guivarch Céline, Haasnoot Marjolijn, Hansen Gerrit, Hauser Mathias, Hawkins Ed, Hermans Tim, Kopp Robert, Leprince-Ringuet Noémie, Lewis Jared, Ley Debora, Ludden Chloé, Niamir Leila, Nicholls Zebedee, Some Shreya, Szopa Sophie, Trewin Blair, Kaj-Ivar van der Wijst, Winter Gundula, Witting Maximilian, Birt Arlene, and Ha Meeyoung. IPCC, 2023: Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (eds.)]. IPCC, Geneva, Switzerland. July 2023. doi: 10.59327/ipcc/ar6-9789291691647.
- [4] Massimo Tavoni, Nico Bauer, Laurent Drouet, Shinichiro Fujimori, Sergey Paltsev, Anna Pirani, Keywan Riahi, Joeri Rogelj, Roberto Schaeffer, Detlef van Vuuren, Matthias Weitzel, and Elmar Kriegler. Implications of overshoot for climate mitigation strategies. *Nature Climate Change*, 16(3):261–272, March 2026. ISSN 1758-6798. doi: 10.1038/s41558-026-02563-7.
- [5] Andy Reisinger, Jan S. Fuglestedt, Anna Pirani, Oliver Geden, Chris D. Jones, Shobha Maharaj, Elvira S. Poloczanska, Angela Morelli, Tom Gabriel Johansen, Carolina Adler, Richard A. Betts, and Sonia I. Seneviratne. Overshoot: A Conceptual Review of Exceeding and Returning to Global Warming of 1.5°C. *Annual Review of Environment and Resources*, April 2025. ISSN 1543-5938, 1545-2050. doi: 10.1146/annurev-environ-111523-102029.

- [6] Andy Reisinger and Oliver Geden. Temporary overshoot: Origins, prospects, and a long path ahead. *One Earth*, 6(12):1631–1637, December 2023. ISSN 25903322. doi: 10.1016/j.oneear.2023.11.008.
- [7] Nico Bauer, David P Keller, Julius Garbe, Kristine Karstens, Franziska Piontek, Werner von Bloh, Wim Thiery, Maria Zeitz, Matthias Mengel, Jessica Strefler, Kirsten Thonicke, and Ricarda Winkelmann. Exploring risks and benefits of overshooting a 1.5 °C carbon budget over space and time. *Environmental Research Letters*, 18(5):054015, May 2023. ISSN 1748-9326. doi: 10.1088/1748-9326/accd83.
- [8] Kaj-Ivar van der Wijst, Andries F Hof, and Detlef P van Vuuren. Costs of avoiding net negative emissions under a carbon budget. *Environmental Research Letters*, 16(6):064071, June 2021. ISSN 1748-9326. doi: 10.1088/1748-9326/ac03d9.
- [9] Laurent Drouet, Valentina Bosetti, Simone A. Padoan, Lara Aleluia Reis, Christoph Bertram, Francesco Dalla Longa, Jacques Després, Johannes Emmerling, Florian Fosse, Kostas Fragkiadakis, Stefan Frank, Oliver Fricko, Shinichiro Fujimori, Mathijs Harmsen, Volker Krey, Ken Oshiro, Larissa P. Nogueira, Leonidas Paroussos, Franziska Piontek, Keywan Riahi, Pedro R. R. Rochedo, Roberto Schaeffer, Jun’ya Takakura, Kaj-Ivar van der Wijst, Bob van der Zwaan, Detlef van Vuuren, Zoi Vrontisi, Matthias Weitzel, Behnam Zakeri, and Massimo Tavoni. Net zero-emission pathways reduce the physical and economic risks of climate change. *Nature Climate Change*, 11(12):1070–1076, December 2021. ISSN 1758-6798. doi: 10.1038/s41558-021-01218-z.
- [10] Jessica Strefler, Nico Bauer, Florian Humpenöder, David Klein, Alexander Popp, and Elmar Kriegler. Carbon dioxide removal technologies are not born equal. *Environmental Research Letters*, 16(7):074021, July 2021. ISSN 1748-9326. doi: 10.1088/1748-9326/ac0a11.
- [11] Johannes Emmerling and Massimo Tavoni. Representing inequalities in integrated assessment modeling of climate change. *One Earth*, 4(2):177–180, February 2021. ISSN 2590-3330, 2590-3322. doi: 10.1016/j.oneear.2021.01.013.
- [12] Mark Budolfson, Francis Dennig, Frank Errickson, Simon Feindt, Maddalena Ferranna, Marc Fleurbaey, David Klenert, Ulrike Kornek, Kevin Kuruc, Aurélie Méjean, Wei Peng, Noah Scovronick, Dean Spears, Fabian Wagner, and Stéphane Zuber. Climate action with revenue recycling has benefits for poverty, inequality and well-being. *Nature Climate Change*, 11(12):1111–1116, December 2021. ISSN 1758-6798. doi: 10.1038/s41558-021-01217-0.
- [13] Johannes Emmerling, Pietro Andreoni, Ioannis Charalampidis, Shouro Dasgupta, Francis Dennig, Simon Feindt, Dimitris Fragkiadakis, Panagiotis Fragkos, Shinichiro Fujimori, Martino Gilli, Carolina Grottera, Celine Guivarch, Ulrike Kornek, Elmar Kriegler, Daniele Malerba, Giacomo Marangoni, Aurélie Méjean, Femke Nijse, Franziska Piontek, Yeliz Simsek, Björn Soergel, Nicolas Taconet, Toon Vandyck, Marie Young-Brun, Shiya Zhao, Yu Zheng, and

- Massimo Tavoni. A multi-model assessment of inequality and climate change. *Nature Climate Change*, 14(12):1254–1260, December 2024. ISSN 1758-6798. doi: 10.1038/s41558-024-02151-7.
- [14] Johannes Emmerling, Pietro Andreoni, and Massimo Tavoni. Global inequality consequences of climate policies when accounting for avoided climate impacts. *Cell Reports Sustainability*, 1(1), January 2024. ISSN 2949-7906. doi: 10.1016/j.crsus.2023.100008.
- [15] Paolo Gazzotti, Johannes Emmerling, Giacomo Marangoni, Andrea Castelletti, Kaj-Ivar van der Wijst, Andries Hof, and Massimo Tavoni. Persistent inequality in economically optimal climate policies. *Nature Communications*, 12(1):3421, June 2021. ISSN 2041-1723. doi: 10.1038/s41467-021-23613-y.
- [16] Marie Young-Brun, Francis Dennig, Frank Errickson, Simon Feindt, Aurélie Méjean, and Stéphane Zuber. Within-country inequality and the shaping of a just global climate policy. *Proceedings of the National Academy of Sciences*, 122(39):e2505239122, September 2025. doi: 10.1073/pnas.2505239122.
- [17] Shiya Zhao, Shinichiro Fujimori, Jihoon Min, Jarmo S. Kikstra, Tomoko Hasegawa, Ken Oshiro, and Saritha Sudharmma Vishwanathan. The multi-faceted global poverty and income inequality landscape in a decarbonizing world. *Cell Reports Sustainability*, 2(10), October 2025. ISSN 2949-7906. doi: 10.1016/j.crsus.2025.100487.
- [18] Yiyi Bai and Samuel J. Okullo. Drivers and pass-through of the EU ETS price: Evidence from the power sector. *Energy Economics*, 123:106698, July 2023. ISSN 0140-9883. doi: 10.1016/j.eneco.2023.106698.
- [19] Sylvain Charlebois, Gumataw Abebe, Tony R. Walker, Vlado Keselj, Janet Music, Keshava Pallavi Gone, Karim Tuffaha, Janele Vezeau, Bibhuti Sarker, and Stacey Taylor. Implications of carbon Taxing policies on the food supply chain in Canada. *Transportation Research Interdisciplinary Perspectives*, 28:101276, November 2024. ISSN 2590-1982. doi: 10.1016/j.trip.2024.101276.
- [20] Ira Irina Dorband, Michael Jakob, Matthias Kalkuhl, and Jan Christoph Steckel. Poverty and distributional effects of carbon pricing in low- and middle-income countries – A global comparative analysis. *World Development*, 115:246–257, March 2019. ISSN 0305-750X. doi: 10.1016/j.worlddev.2018.11.015.
- [21] Shinichiro Fujimori, Tomoko Hasegawa, Ken Oshiro, Shiya Zhao, Katsuya Sasaki, Junya Takakura, and Kiyoshi Takahashi. Potential side effects of climate change mitigation on poverty and countermeasures. *Sustainability Science*, 18(5):2245–2257, September 2023. ISSN 1862-4057. doi: 10.1007/s11625-023-01369-2.

- [22] Julian Schaper, Max Franks, Nicolas Koch, Charlotte Plinke, and Michael Sureth. On the emission and distributional effects of a CO₂-tax on agricultural goods—The case of Germany. *Food Policy*, 130:102794, January 2025. ISSN 03069192. doi: 10.1016/j.foodpol.2024.102794.
- [23] Jan C. Steckel, Ira I. Dorband, Lorenzo Montrone, Hauke Ward, Leonard Missbach, Fabian Hafner, Michael Jakob, and Sebastian Renner. Distributional impacts of carbon pricing in developing Asia. *Nature Sustainability*, 4(11):1005–1014, November 2021. ISSN 2398-9629. doi: 10.1038/s41893-021-00758-8.
- [24] Johannes Többen, Peter-Paul Pichler, Ingram S Jaccard, Kurt Kratena, Daniel Moran, Heran Zheng, and Helga Weisz. Unequal carbon tax impacts on 38 million German households: Assessing spatial and socio-economic hotspots. *Environmental Research: Climate*, 2(4):045006, October 2023. ISSN 2752-5295. doi: 10.1088/2752-5295/aceea0.
- [25] Ottmar Edenhofer, Max Franks, Friedemann Gruner, Matthias Kalkuhl, and Kai Lessmann. The Economics of Carbon Dioxide Removal. *Annual Review of Resource Economics*, 17(Volume 17, 2025):301–321, October 2025. ISSN 1941-1340, 1941-1359. doi: 10.1146/annurev-resource-010224-094505.
- [26] Gunnar Luderer, Silvia Madeddu, Leon Merfort, Falko Ueckerdt, Michaja Pehl, Robert Pietzcker, Marianna Rottoli, Felix Schreyer, Nico Bauer, Lavinia Baumstark, Christoph Bertram, Alois Dirnhaichner, Florian Humpenöder, Antoine Levesque, Alexander Popp, Renato Rodrigues, Jessica Strefler, and Elmar Kriegler. Impact of declining renewable energy costs on electrification in low-emission scenarios. *Nature Energy*, 7(1):32–42, January 2022. ISSN 2058-7546. doi: 10.1038/s41560-021-00937-z.
- [27] Shinichiro Fujimori, Wenchao Wu, Jonathan Doelman, Stefan Frank, Jordan Hristov, Page Kyle, Ronald Sands, Willem-Jan van Zeist, Petr Havlik, Ignacio Pérez Domínguez, Amarendra Sahoo, Elke Stehfest, Andrzej Tabeau, Hugo Valin, Hans van Meijl, Tomoko Hasegawa, and Kiyoshi Takahashi. Land-based climate change mitigation measures can affect agricultural markets and food security. *Nature Food*, 3(2):110–121, February 2022. ISSN 2662-1355. doi: 10.1038/s43016-022-00464-4.
- [28] David Meng-Chuen Chen, Benjamin Bodirsky, Xiaoxi Wang, Jiaqi Xuan, Jan Philipp Dietrich, Alexander Popp, and Hermann Lotze-Campen. Future food prices will become less sensitive to agricultural market prices and mitigation costs. *Nature Food*, 6(1):85–96, January 2025. ISSN 2662-1355. doi: 10.1038/s43016-024-01099-3.
- [29] Pietro Andreoni, Johannes Emmerling, and Massimo Tavoni. Inequality repercussions of financing negative emissions. *Nature Climate Change*, 14(1):48–54, January 2024. ISSN 1758-6798. doi: 10.1038/s41558-023-01870-7.
- [30] Nico Bauer, Lavinia Baumstark, Markus Haller, Jerome Hilaire, Marian Leimbach, Gunnar Luderer, Michael Lueken, Robert Pietzcker, Jessica Strefler, Sylvie Ludig, Alexander Koerner,

Anastasis Giannousakis, David Klein, Michaja Pehl, Christoph Bertram, and Anselm Schultes. REMIND:TheEquations. 2017.

[31] Jan Philipp Dietrich, Benjamin Leon Bodirsky, Isabelle Weindl, Florian Humpenöder, Miodrag Stevanovic, Ulrich Kreidenweis, Xiaoxi Wang, Kristine Karstens, Abhijeet Mishra, Felicitas Dorothea Beier, Edna Johanna Molina Bacca, Patrick von Jeetze, Michael Windisch, Michael Scott Crawford, Debbora Leip, David Klein, Vartika Singh, Geanderson Ambrósio, Ewerton Araujo, Anne Biewald, Pascal Sauer, Alexandre Köberle, Jan Steinhäuser, David Hötten, Hermann Lotze-Campen, and Alexander Popp. MAGPIE - An Open Source land-use modeling framework. Zenodo, April 2025.

[32] Gunnar Luderer, Marian Leimbach, Nico Bauer, and Elmar Kriegler. *Description of the ReMIND-R Model*. Technical Report, Potsdam Institute for Climate Impact Research, 2010.

[33] Gunnar Luderer, Nico Bauer, Lavinia Baumstark, Christoph Bertram, Marian Leimbach, Robert Pietzcker, Jessica Strefler, Tino Aboumahboub, Gabriel Abrahão, Cornelia Auer, David Bantje, Felicitas Beier, Falk Benke, Stephen Bi, Jan Philipp Dietrich, Alois Dirnhaichner, Tabea Dorndorf, Jakob Duerrwaechter, Sophie Fuchs, Pascal Führlich, Anastasis Giannousakis, Chen Chris Gong, Alex Hagen, Markus Haller, Robin Hasse, Léa Hayez, Jerome Hilaire, Verena Hofbauer, Johanna Hoppe, David Klein, Johannes Koch, Laurin Köhler-Schindler, Alexander Körner, Katarzyna Kowalczyk, Elmar Kriegler, Fabrice Lécuyer, Antoine Levesque, Alexander Lorenz, Sylvie Ludig, Michael Lüken, Aman Malik, Rahel Mandaroux, Susanne Manger, Anne Merfort, Leon Merfort, Simón Moreno-Leiva, Ioanna Mouratiadou, Jarusch Müfel, Adrian Odenweller, Michaja Pehl, Mika Pflüger, Franziska Piontek, Laura Popin, Sebastian Rauner, Oliver Richters, Renato Rodrigues, Niklas Roming, Ricarda Rosemann, Marianna Rottoli, Tonn Rüter, Robert Salzwedel, Pascal Sauer, Eva Schmidt, Christof Schötz, Felix Schreyer, Anselm Schultes, Joanna Sitarz, Björn Sörgel, Falko Ueckerdt, Philipp Verpoort, Pascal Weigmann, and Bennet Weiss. REMIND - REgional Model of INvestments and Development. Zenodo, April 2025.

[34] Lavinia Baumstark, Nico Bauer, Falk Benke, Christoph Bertram, Stephen Bi, Chen Chris Gong, Jan Philipp Dietrich, Alois Dirnhaichner, Anastasis Giannousakis, Jérôme Hilaire, David Klein, Johannes Koch, Marian Leimbach, Antoine Levesque, Silvia Madeddu, Aman Malik, Anne Merfort, Leon Merfort, Adrian Odenweller, Michaja Pehl, Robert C. Pietzcker, Franziska Piontek, Sebastian Rauner, Renato Rodrigues, Marianna Rottoli, Felix Schreyer, Anselm Schultes, Bjoern Soergel, Dominika Soergel, Jessica Strefler, Falko Ueckerdt, Elmar Kriegler, and Gunnar Luderer. REMIND2.1: Transformation and innovation dynamics of the energy-economic system within climate and sustainability limits. *Geoscientific Model Development*, 14(10):6571–6603, October 2021. ISSN 1991-959X. doi: 10.5194/gmd-14-6571-2021.

[35] Leon Merfort, Nico Bauer, Pascal Sauer, Jan Philipp Dietrich, Weiwei Xiong, Katsumasa Tanaka, Jarmo Kikstra, and Marco Zecchetto. Report on CDR portfolio climate neutrality

scenarios with and without overshoot including sensitivity analysis, gridding and extensions. Technical Report D1.2 of the Rescue project, 2025.

- [36] Andrew Kruczkiewicz, Zinta Zommers, Joyce Kimutai, Matthias Garschagen, and Joshua Fisher. The human and social impacts of climate overshoot. *PNAS Nexus*, 4(11):pgaf332, November 2025. ISSN 2752-6542. doi: 10.1093/pnasnexus/pgaf332.
- [37] Carl-Friedrich Schleussner, Gaurav Ganti, Quentin Lejeune, Biqing Zhu, Peter Pfleiderer, Ruben Prütz, Philippe Ciais, Thomas L. Frölicher, Sabine Fuss, Thomas Gasser, Matthew J. Gidden, Chahan M. Kropf, Fabrice Lacroix, Robin Lamboll, Rosanne Martyr, Fabien Maussion, Jamie W. McCaughey, Malte Meinshausen, Matthias Mengel, Zebedee Nicholls, Yann Quilcaille, Benjamin Sanderson, Sonia I. Seneviratne, Jana Sillmann, Christopher J. Smith, Norman J. Steinert, Emily Theokritoff, Rachel Warren, Jeff Price, and Joeri Rogelj. Overconfidence in climate overshoot. *Nature*, 634(8033):366–373, October 2024. ISSN 1476-4687. doi: 10.1038/s41586-024-08020-9.
- [38] Peter H. Howard and Thomas Sterner. Methodology Matters: A Careful Meta-Analysis of Climate Damages. *Environmental and Resource Economics*, 88(12):3289–3327, December 2025. ISSN 1573-1502. doi: 10.1007/s10640-025-01016-7.
- [39] Martino Gilli, Matteo Calcaterra, Johannes Emmerling, and Francesco Granella. Climate change impacts on the within-country income distributions. *Journal of Environmental Economics and Management*, 127:103012, September 2024. ISSN 0095-0696. doi: 10.1016/j.jeem.2024.103012.
- [40] Don Fullerton. Net Burdens of Carbon Policy Vary within Each Income Group – and within Each Nation. In *CESifo Forum*, volume 22, pages 20–25, München, 2021. ifo Institut - Leibniz-Institut für Wirtschaftsforschung an der Universität München.
- [41] Bjoern Soergel, Elmar Kriegler, Benjamin Leon Bodirsky, Nico Bauer, Marian Leimbach, and Alexander Popp. Combining ambitious climate policies with efforts to eradicate poverty. *Nature Communications*, 12(1):2342, April 2021. ISSN 2041-1723. doi: 10.1038/s41467-021-22315-9.
- [42] Benjamin Leon Bodirsky, Felicitas Beier, Florian Humpenöder, Debbora Leip, Michael S. Crawford, David Meng-Chuen Chen, Patrick von Jeetze, Marco Springmann, Bjoern Soergel, Zebedee Nicholls, Jessica Streffer, Jared Lewis, Jens Heinke, Christoph Müller, Kristine Karstens, Isabelle Weindl, Miodrag Stevanović, Patrick Rein, Pascal Sauer, Abhijeet Mishra, Edna Johanna Molina Bacca, Alexandre C. Köberle, Xiaoxi Wang, Vartika Singh, Claudia Hunecke, Quitterie Collignon, Pepijn Schreinemachers, Simon Dietz, Ravi Kanbur, Jan Philipp Dietrich, Hermann Lotze-Campen, and Alexander Popp. A food system transformation pathway reconciles 1.5 °C global warming with improved health, environment and social inclusion. *Nature Food*, 6(12):1133–1152, December 2025. ISSN 2662-1355. doi: 10.1038/s43016-025-01268-y.

- [43] Johannes Bednar, Michael Obersteiner, and Fabian Wagner. On the financial viability of negative emissions. *Nature Communications*, 10(1):1783, April 2019. ISSN 2041-1723. doi: 10.1038/s41467-019-09782-x.
- [44] Jules Linden, Cathal O’Donoghue, and Denisa M. Sologon. The many faces of carbon tax regressivity—Why carbon taxes are not always regressive for the same reason. *Energy Policy*, 192:114210, September 2024. ISSN 0301-4215. doi: 10.1016/j.enpol.2024.114210.
- [45] David Klenert, Linus Mattauch, Emmanuel Combet, Ottmar Edenhofer, Cameron Hepburn, Ryan Rafaty, and Nicholas Stern. Making carbon pricing work for citizens. *Nature Climate Change*, 8(8):669–677, August 2018. ISSN 1758-6798. doi: 10.1038/s41558-018-0201-2.
- [46] Julie Anne Cronin, Don Fullerton, and Steven Sexton. Vertical and Horizontal Redistributions from a Carbon Tax and Rebate. *Journal of the Association of Environmental and Resource Economists*, 6(S1):S169–S208, March 2019. ISSN 2333-5955. doi: 10.1086/701191.
- [47] Martin C. Hänsel, Max Franks, Matthias Kalkuhl, and Ottmar Edenhofer. Optimal carbon taxation and horizontal equity: A welfare-theoretic approach with application to German household data. *Journal of Environmental Economics and Management*, 116:102730, October 2022. ISSN 0095-0696. doi: 10.1016/j.jeem.2022.102730.
- [48] Leonard Missbach and Jan Steckel. Compensation Design for Carbon Pricing with Horizontal Heterogeneity: Evidence from 88 Countries, 2025.
- [49] Moritz A. Drupp, Ulrike Kornek, Jasper N. Meya, and Lutz Sager. The Economics of Inequality and the Environment. *Journal of Economic Literature*, 63(3):840–874, September 2025. ISSN 0022-0515. doi: 10.1257/jel.20241696.
- [50] Nico Bauer, David Klein, Florian Humpenöder, Elmar Kriegler, Gunnar Luderer, Alexander Popp, and Jessica Strefler. Bio-energy and CO2 emission reductions: An integrated land-use and energy sector perspective. *Climatic Change*, 163(3):1675–1693, December 2020. ISSN 1573-1480. doi: 10.1007/s10584-020-02895-z.
- [51] Keywan Riahi, Detlef P. van Vuuren, Elmar Kriegler, Jae Edmonds, Brian C. O’Neill, Shinichiro Fujimori, Nico Bauer, Katherine Calvin, Rob Dellink, Oliver Fricko, Wolfgang Lutz, Alexander Popp, Jesus Crespo Cuaresma, Samir Kc, Marian Leimbach, Leiwen Jiang, Tom Kram, Shilpa Rao, Johannes Emmerling, Kristie Ebi, Tomoko Hasegawa, Petr Havlik, Florian Humpenöder, Lara Aleluia Da Silva, Steve Smith, Elke Stehfest, Valentina Bosetti, Jiyong Eom, David Gernaat, Toshihiko Masui, Joeri Rogelj, Jessica Strefler, Laurent Drouet, Volker Krey, Gunnar Luderer, Mathijs Harmsen, Kiyoshi Takahashi, Lavinia Baumstark, Jonathan C. Doelman, Mikiko Kainuma, Zbigniew Klimont, Giacomo Marangoni, Hermann Lotze-Campen, Michael Obersteiner, Andrzej Tabeau, and Massimo Tavoni. The Shared

Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. *Global Environmental Change*, 42:153–168, 2017. ISSN 09593780. doi: 10.1016/j.gloenvcha.2016.05.009.

[52] Erich Battistin, Richard Blundell, and Arthur Lewbel. Why Is Consumption More Log Normal than Income? Gibrat’s Law Revisited. *Journal of Political Economy*, December 2009. ISSN 0022-3808. doi: 10.1086/648995.

[53] Narasimha D. Rao, Petra Sauer, Matthew Gidden, and Keywan Riahi. Income inequality projections for the Shared Socioeconomic Pathways (SSPs). *Futures*, 105:27–39, January 2019. ISSN 0016-3287. doi: 10.1016/j.futures.2018.07.001.

[54] S. K. C., M. Dhakad, M. Potančoková, S. Adhikari, D. Yildiz, M. Mamolo, T. Sobotka, K. Zeman, G. Abel, W. Lutz, and A. Goujon. Updating the Shared Socioeconomic Pathways (SSPs) Global Population and Human Capital Projections. February 2024.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- [Sl.pdf](#)