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Implications of climate change impacts for emission and land use scenario development

Claudia Tebaldi[1,*], Brian O'Neill[1], Di Sheng[2], Noah Prime[3], Mengqi Zhao[1], Kalyn Dorheim[1] and Joseph Brown[4]

[1] University of Maryland, College Park, MD, United States of America
[2] International Institute for Applied Systems Analysis, Vienna, Austria
[3] University of Vermont, Burlington, VT, United States of America
[4] Lake Forest College, Lake Forest, IL, United States of America
[*] Author to whom any correspondence should be addressed.

E-mail: claudia.tebaldi@pnnl.gov

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Abstract

Scenarios of future emissions and land use produced by integrated assessment models have traditionally been developed without accounting for how climate change impacts could affect the emissions and land use trajectories themselves. This omission risks skewing our assessments of the plausible range of future emission pathways and associated Earth system changes. Beyond the salience for emission scenario development, a better integrated representation of human and Earth system changes and feedbacks would enable better anticipation of the implications of alternative socio-economic development pathways. We use the Global Change Analysis Model to investigate whether endogenizing several impacts when generating its baseline emission scenario is warranted. We do so by comparing the emissions and land use change that result from the baseline scenario with and without impacts, where impacts are implemented as exogenous changes to water availability, crop and labor productivity, and energy demand and supply. Our results indicate that the effect on global emissions leads to less than 0.1 °C increase in warming by 2100 and therefore do not support endogenizing impacts. This conclusion is conditional on our modeling framework and the specific impact channels represented but is consistent with other studies that have addressed the magnitude of feedbacks by implementing a two-way coupling. However, we do find regional impacts indicating that local economies and well-being measures may be affected significantly.

1. Introduction

Traditionally, scenarios of future emissions and land use changes produced by integrated assessment models (IAMs) have not accounted for geophysical or socio-economic feedbacks from climate change impacts. The omission of such feedbacks, the failure of 'closing the loop', has the potential to skew our assessments of the plausible range of future emission pathways and Earth system changes. In fact, scenarios developed to force Earth system models' future climate simulations within the coupled model intercomparison project (CMIP) have recently been criticized. High emission scenarios, for example SSP5-8.5 (O'Neill *et al* 2016, Riahi *et al* 2017), hypothesize high economic growth with continued reliance on fossil fuels, but that growth could be significantly hampered by climate change impacts and damages. Low emission scenarios, for example SSP1-2.6, rely heavily on land-based mitigation options like reforestation, which could be made less effective by increases in heat, dryness and wildfires (Jäger *et al* 2024). Thus, scenarios at both ends of the emission spectrum have had their plausibility questioned for not accounting for climate impacts in their development (Hausfather and Peters 2020, Natali *et al* 2021, Ripple *et al* 2023).

Our study aims to test the relevance of endogenizing climate impacts in IAM emission scenario modeling. Recent studies investigate the significance of individual climate impacts for scenario development.

For example, Schultes *et al* (2021) use estimates of GDP damages from climate change to show that when accounted for, these would increase the cost of carbon and therefore change mitigation costs. Colelli *et al* (2022) show how accounting for adaptation (through the use of air conditioning in a warming climate) produces additional costs and emissions. Awais *et al* (2024) focus on the role of water availability in creating interdependencies and constraints across sectors, therefore influencing agriculture, land use, and energy supply. Byers *et al* (2024) examine changes in energy demand and therefore emissions caused by increased demand for cooling in a warming climate. However, these studies do not focus on the question of whether endogenizing impacts is necessary when generating emission scenarios and consider single rather than multiple impacts. We attempt a more comprehensive representation of different impact channels (energy demand for cooling and heating; water availability; energy supply changes due to hydropower generation changes and agriculture productivity of land and labor) and focus on whether it is warranted to fully couple the system. That is, do we need to model emissions and land use changes, their effects on climatic changes, the impacts of these changes on human systems, and finally, the effects of those impacts on emissions and land use changes (Van Vuuren *et al* 2012)?

An additional key aspect of our research relates to the type of IAMs we focus on. IAMs that model linkages between human and earth systems allowing representation of the feedbacks we are concerned with belong to two categories: 'benefit-cost' models, and 'process-based' models (Fisher-Vanden and Weyant 2020). The former are highly aggregated, represent impacts in a reduced-form as damage functions relating global average temperature directly to economic growth, usually through extrapolation of econometric estimates (see Howard and Sterner 2025), and are used to identify optimal emission pathways balancing costs and benefits (e.g. Barrage and Nordhaus 2024). We focus instead on process-based IAMs, which generate scenarios of emissions and land use driving Earth system model simulations. These models are regionally resolved, including a spatially detailed land surface representing different land uses, and rather than using damage functions, represent the specific processes through which climate affects socio-economic and natural systems. For example, they represent the response of agricultural productivity to changes in temperature, water availability or atmospheric CO_2 concentration, for individual regions and individual crops; they model the effects of heat and air pollution on human health, differentiating regional and in some cases demographic characteristics; they account for basin-scale changes in runoff and their effects on water supply in general, and hydropower production in particular, etc. These changes can in turn affect the economy and therefore emissions and land use changes (Tachiiri *et al* 2021). Other process models, besides the one we use in this study, the Global Change Analysis Model (GCAM, Calvin *et al* 2019), are MESSAGEix-GLOBIOM (Fricko *et al* 2017); REMIND-MAgPIE (Kriegler *et al* 2017); IMAGE (Stehfest *et al* 2014; AIM (Fujimori *et al* 2017); and WITCH (Bosetti *et al* 2007).

A major justification for the exclusion of climate impacts in scenario development is the need to avoid double counting, as these scenarios drive ESMs, whose output is then used to drive impact models. But fundamental challenges have also contributed to this exclusion, linked to the current state of science and modeling (Tebaldi *et al* 2026). IAMs' structure and process representation dictate which impacts can be reflected in the model dynamics. There are often mismatches of temporal and spatial scales between impacts (often driven by high frequency events, at fine regional scales) and the models' scales of aggregation (working at yearly, or multi-year time steps and resolving only large regional averages). The science underpinning our understanding of the channels through which economy, society and natural systems are affected by climatic changes, and the monetary value of climate impacts, is also uncertain (Chapagain *et al* 2022, Rising *et al* 2022, Srikrishnan *et al* 2022, Morris *et al* 2025, Wang *et al* 2024, Reinecke *et al* 2025).

Aware of these limitations, we do not claim a comprehensive and robust representation of climate impacts in emission scenarios in this study. Nonetheless, we investigate the potential urgency of the issue by measuring the effects of including a set of geophysical and economic impacts that our modeling system can represent. Specifically, we investigate whether accounting for these impacts alters GCAM's baseline scenario emission pathway enough to substantially affect the climate system evolution, which would call for endogenizing them. In the absence of such a finding, endogenization would not be supported.

In the remainder of the paper, we describe our experimental setup, outcomes, and interpretation, and compare GCAM outcomes from scenarios that incorporate all impact channels at once or a single channel at a time, to understand the origin of the changes we detect, for both global and regional scale dynamics. We conclude by discussing the main lessons learned by this exercise, its limitations, and what we consider the most promising and compelling ways forward.

2. Experimental setup

Figure 1 offers a schematic of our experimental setup, highlighting the components of our modeling chain. Text in the SM expands on the individual modeling components.

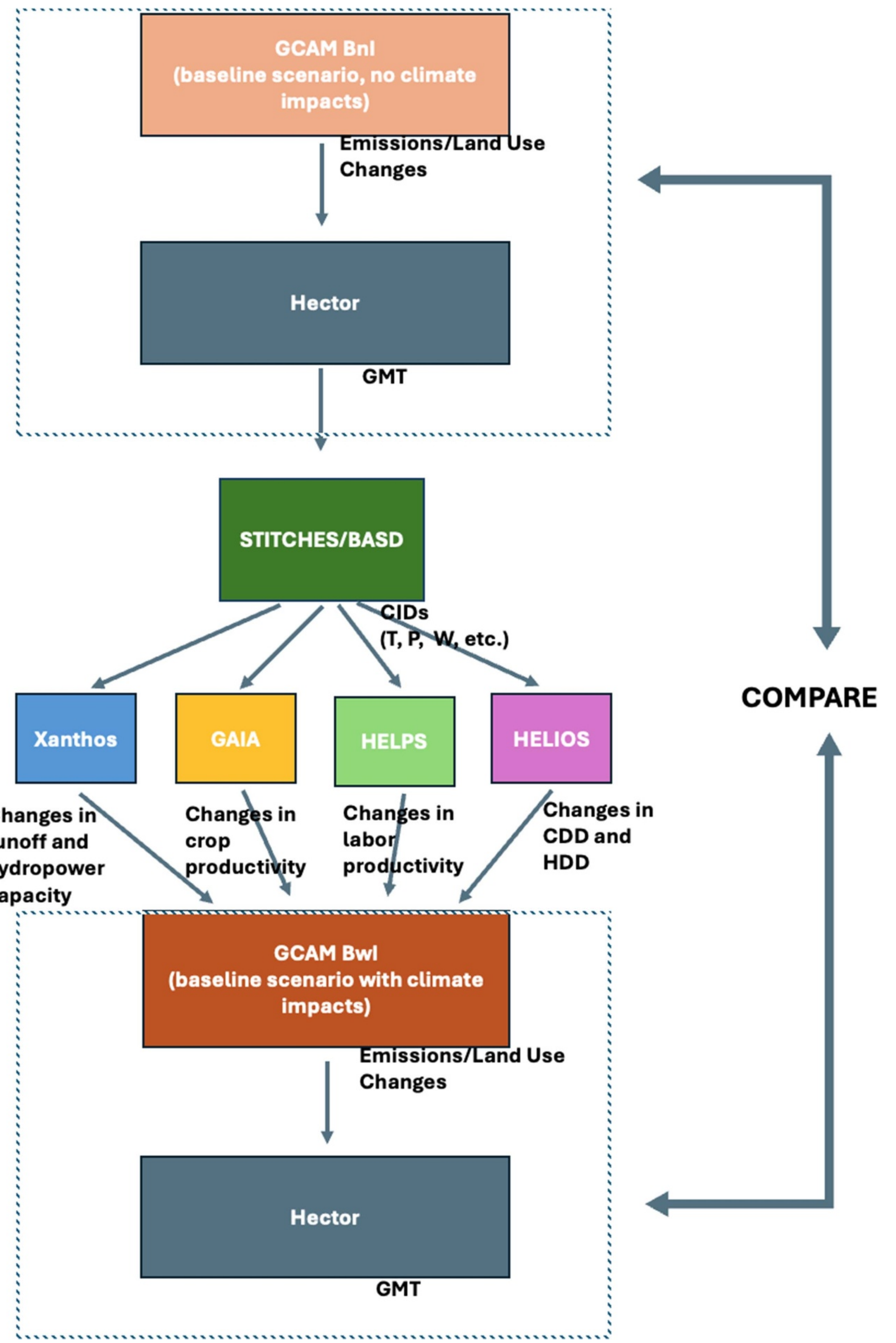

Figure 1. The modeling chain. Abbreviations: CIDs = climatic impact-drivers; T = temperature; P = precipitation; W = wind; CDD = cooling degree days; HDD = heating degree days; GMT = Global Mean Temperature; BnI = Baseline with no Impacts; BwI = Baseline with Impacts.

We run GCAM according to its baseline scenario, which covers the whole 21st century according to SSP2, and does not include mitigation policies. In its standard setup, the scenario is produced without reflecting any climate change impact. Outcomes from this scenario constitute the reference (labeled BnI in the following, i.e. Baseline with no Impacts).

To produce a version of the baseline scenario that accounts for impacts, we first generate climate outcomes consistent with the emissions and land use from the no-impacts baseline, then use these to drive a set of off-line impact models. We then introduce these impacts as exogenous forcers, or modifications, to some of the quantities that GCAM assumes at each time step, and regenerate the emission scenario, this time with the effects of climate impacts included (labeled BwI, Baseline with Impacts). Finally, we compare the BnI and BwI scenarios, including their implications for global mean temperature (GMT) change, to evaluate the importance of incorporating impacts in the baseline.

Generating climate outcomes consistent with the BnI scenario begins with translating the emissions and land-use changes from that scenario into GMT using Hector, a reduced complexity model (RCM; Dorheim *et al* 2024. See SM). We do so by using two parameterizations of the RCM: its default, having an equilibrium climate sensitivity (ECS) of 3 K, and a higher sensitivity version, with ECS of 5 K. The two time series of GMT reach by the end of the century a warming of 3.27 °C and 3.83 °C respectively (with reference to the 1850–1900 period). These two 21st century trajectories of GMT are then translated into time series of monthly and daily fields of several atmospheric variables (surface temperature, precipitation, surface winds, relative humidity, solar radiation) that are needed as input to a set of impact models. We do so by using STITCHES (Tebaldi *et al* 2022, Snyder *et al* 2024, see SM), a climate model output emulator, and by emulating two alternative Earth system models, CanESM5 (Swart *et al* 2019) and MRI-ESM2-0 (Yukimoto *et al* 2019). Together with the two parameterizations of Hector this allows us to test the sensitivity of our results to uncertainties in the climate response. The atmospheric variables, which we refer to as climatic impact-drivers (CIDs, Ruane *et al* 2022) in figure 1, are all downscaled to a common grid (0.5° in latitude/longitude) and bias-corrected, using the method developed for ISIMIPv3 (Lange 2019, Frieler *et al* 2024). With these four alternative realizations of CIDs as input, fully consistent with the emission trajectory of GCAM's baseline scenario without impacts, we proceed to model several climate impacts.

We use a set of impact models that are part of the GCAM ecosystem and have been used for previous studies of impacts (Graham *et al* 2020, Zhang *et al* 2023, Birnbaum *et al* 2024, Sampedro *et al* 2024, Sheng *et al* 2025a). In those cases, models relied on 'off the shelf' ESM output according to standard CMIP scenario experiments, while in this study we produce climate output by the Hector + STITCHES emulation. Also, those previous studies did not seek to model feedbacks on emissions and land use in the scenario development. We use the emulated climate variables to drive a hydrological model, Xanthos (Vernon *et al* 2019, see SM), that produces runoff projections and estimates hydropower potential; a heating and cooling degree days' emulator, Helios (Zhao *et al* 2024, see SM), that informs energy demand for both residential and commercial buildings; an econometric model, Gaia (Zhao *et al* 2025), estimating impacts on crop yields from climatic changes for the crops modeled in GCAM; and a physical work capacity emulator, HELPS (Sheng *et al* 2025b, see SM), that generates labor productivity shocks for crop production based on human heat stress level. All these models produce impacts at regional scales consistent with the spatial units at which GCAM operates (32 geopolitical/market regions; 235 hydrological basins and 396 land units resulting from the intersection of the two).

When producing the BwI scenario, we use the output of these impact models to exogenously inform the evolution of GCAM's energy, land, and water systems at each time step of the model integration, thus allowing the impacts to feedback on those activities that may change emissions and land use.

Specifically, at each time step:

- Water availability in GCAM's 235 hydrological basins, which would be constant over the century without climate impacts, is modified according to Xanthos' estimates of runoff.
- Hydropower capacity is changed consistently with these changes in runoff (note however that climate does not influence the opening of new plants, or retirement of old plants). This can lead to changes in the energy supply mix.
- Crop productivity of the various crops modeled by GCAM is modified by temperature and precipitation changes at the specific location where the crops are grown, thus affecting land use, emissions from agriculture, and, through effects on bioenergy feedstock production, emissions from energy as well.
- Labor productivity in the agricultural sector is negatively affected by heat stress, adding to the yield impacts of climatic changes on agricultural markets and the labor allocation across the economy.
- Energy demand for cooling and heating residential and commercial buildings is changed consistently with changing temperatures.

(In the SM we add a further description of our experiment rationale, step-by-step.)

In this version of the model, economic growth is generated endogenously as a function of capital accumulation, labor force (and productivity), and energy, agriculture and materials inputs (Edmonds *et al* 2025). Impacts on energy demand and supply and on land and labor productivity will therefore be reflected in changes in GDP as a bottom–up effect (see figure 2, panels (d) and (h)). This distinguishes our process-based approach from those studies that apply a damage function to GDP, assuming *a priori* a certain magnitude of climate impacts on GDP as a function of global average temperature change (see Morris *et al* 2025, Howard and Sterner 2025, and references therein). We run four separate GCAM simulations that include all impact channels, according to the four climate forcing alternatives. We expect the overall strength of the impacts to be larger when using the higher GMT trajectory (obtained by Hector parameterized by ECS = 5 K), and their geographic distribution to vary because the two ESMs have different geographic patterns of changes for temperature, precipitation and other CIDs, for the same global warming level. We point out however that differences in regional patterns may wash out because of the relatively coarse spatial aggregation required by GCAM, compared to an ESM grid resolution, and GCAM's low frequency time step (5 years). Furthermore, we also run simulations where only one of the impact channels is activated at a time, to help us attribute the compound result to the individual sources, and at least qualitatively assess the additivity of the individual effects.

In the following, we describe results in terms of time series of GMT, radiative forcing (RF), CO_2 emissions from industry and land use combined and GDP over the length of the GCAM simulation (the 21st century). We also show maps of differences of salient quantities from GCAM output at 2100 between the scenarios affected by impacts and the scenarios that are not. We could plot these geographic differences at other times during the 21st century, but we choose to display only the largest effects, at the time of the largest cumulative GHG emissions (the end of the century in this baseline scenario). In the SM we add a set of figures that help trace the results shown in the main text to individual impact channels.

3. Results

GCAM's output database contains thousands of metrics of the model's projections for all sectors, with detailed representation of subsectors, technologies, geographic units, and time steps. Our choice of outcomes to describe here is informed by the principal question we seek to answer, focusing on changes in global scale metrics which would indicate, or be associated with, a significant change in emissions (and therefore climate) due to the incorporation of impacts (GMT, RF, CO_2 emissions, GDP). Additionally, even if we do not see significant changes on emissions at the global scale, we document effects at regional scales related to changes in energy demand: we examine regional changes in demand for heating vs cooling services, document if changes in the fuel mix (hypothesized as possibly associated with a switch from heating to cooling demand, the former usually reliant on natural gas consumption, while the latter usually provided by electricity) change emissions of methane and sulfates significantly. We conclude with an assessment of changes in the regional prices of agricultural products (crops and meat) and energy sources, which are relevant to food and energy security.

3.1. Global scales

As discussed, emission changes large enough to change climate significantly in the BwI scenario (relative to BnI) would call for endogenizing impacts in emission scenario generation. Thus, we compare the GMT trajectories that Hector produces based on the BwI and BnI emission outcomes. As figure 2(a) shows, the difference is positive (i.e. incorporating impacts leads to more warming) but does not reach a tenth of a degree at 2100 even when using the stronger climate system response from Hector (we recall that warming with respect to the 1850–1900 baseline under BnI is 3.27 °C when Hector's ECS is set to its default value (3 K) and 3.83 °C if ECS is set to 5 K). This result suggests that in this modeling framework, with the implementation as described of these five impact channels, differences in emissions do not amount to a magnitude that changes climate significantly. Here we use the study of Tebaldi *et al* (2015) to justify our use of 'significant.' The study, accounting for uncertainties across climate models and the effects of internal climate variability, demonstrates that with a global warming difference of 0.1 °C, less than 10% of land regions experience changes in temperature that are larger than internal variability, and no significant land fraction is affected by changes in precipitation above internal variability.

The corresponding lower panel 2(e) distinguishes the contribution of the individual impact channels for the climate experiment setup having the largest response (Hector with ECS = 5 K and STITCHES using MRI, see panel 2(a), solid red line, corresponding to the same line in the lower panel). The largest (and positive) contribution comes from the representation of changes in energy demand (line labeled HDCD) through changes in heating and cooling degree days with climate change, with impacts from changes in yields and hydropower capacity also contributing to increased warming. The effects of changes in runoff stay close to zero, while the effects of changes in labor productivity are negative. The total (net) effect seems consistent with an additive behavior of the individual channels. Panels 2(b) and (f) show the differences in RF between the various climate experiments and the various impact channels, and are fully consistent with the behavior of temperature, as expected. Differences in RF amount to at most 0.2 Wm^{-2} by the end of the century. Two additional panels 2(c) and (g), document one of the sources of these RF and GMT changes, global CO_2 emission increases, which amount to at most slightly over 1% increase compared to the reference at some times during the century, with the various impact channels offsetting one another. The resulting changes in cumulative emissions at the end of the century are only on the order

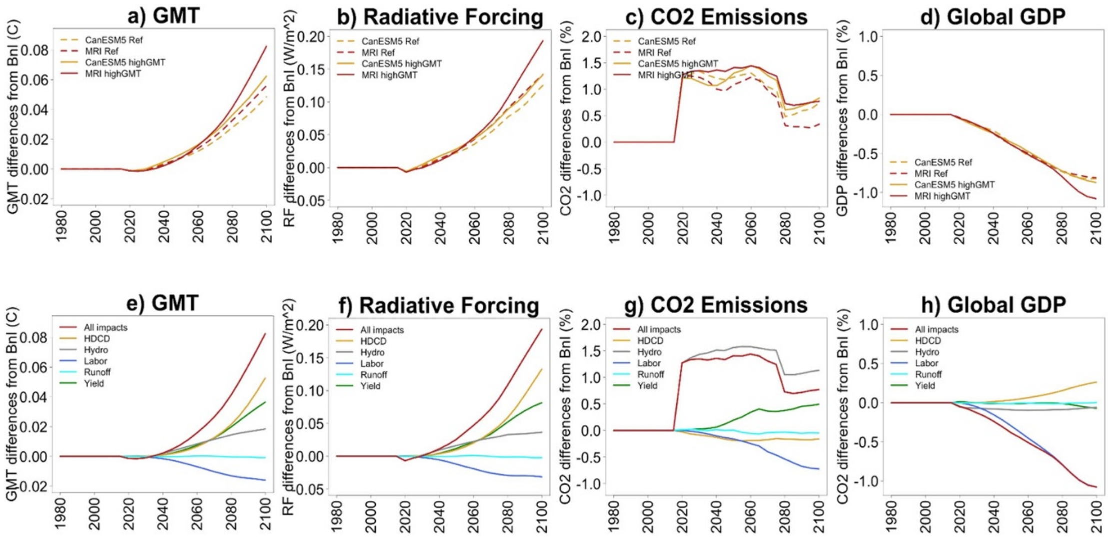

Figure 2. Differences in global mean temperature (a), (e), radiative forcing (b), (f), CO_2 emissions (c), (g) and GDP (d), (h) trajectories resulting from GCAM simulations with and without impacts. First row (panels (a)–(d)) shows a comparison among the alternative climate drivers implemented, the second row (panels (e)–(h)) shows a comparison between the simulation with the larger climate drivers (STITCHES emulating MRI—Hector using ECS = 5 K) and all impacts represented, and simulations with the same climate drivers but each impact channel implemented in isolation. All time series are differences from the reference scenario without impacts (BnI), absolute differences in the case of GMT and RF, percent differences in the case of CO_2 emissions and GDP. In each pair of plots for a given quantity, the solid red line (MRI highGMT/all impacts) is the same.

of 2.7 GtC in the experiment that includes all impacts (not shown). The rank of the contributions of the various channels is consistent between changes in RFs and changes in GMT, but not between those and changes in CO_2 emissions, suggesting the presence of effects from other active gases on the total RF in these experiments. In fact, an investigation of the individual contributions to the total RF confirms that other gases with positive or negative effects show disparate behavior across the experiments, with methane forcing, for example, increasing over the century in the yield-only single impact experiments, but not in the hydro-only impact experiment.

Last, we plot global GDP in panels 2(d) and (h). To first order, in a baseline scenario without mitigation, the size of the economy will have a strong imprint on emissions, and the results from our experiments confirm that the overall impacts on GDP amount to at most 1% by the end of the century when using the stronger climate response. The evaluation of these results suggests that a fully coupled representation of the Earth and human system components with feedbacks implemented as the model integrates forward would not be warranted, as those feedbacks would not be large enough to alter the evolution of the coupled system, compared to simply imposing the effects of climate impacts exogenously onto GCAM as we are doing in this exercise.

3.2. Regional scales

Even if the global scale response is not affected significantly by the representation of these impacts, it is still worth asking if interesting regional dynamics emerge. Regional changes in GHG emissions can still have relevance for regional climate policy targets and carbon and other goods' prices.

We consider absolute and percent differences in 2100 when comparing BwI and BnI for outcomes of a number of metrics (related to energy, land and water), focusing on those simulations that used the largest climate forcings (Hector with ECS of 5 K, STITCHES emulating the MRI model) to compute impacts. We find that regional patterns are similar when using GMT derived by the lower ECS of 3 K, and when using the alternative climate model (CanESM5) in the emulation.

Figure 3 shows changes in emissions of CO_2 from energy and industry production, and, separately, those from land use change, in absolute and percentage difference from the BnI baseline. The units of the absolute differences (MtC, panels (a) and (b)) make it clear that these values, also considering the offsetting effects across regions of changes opposite in sign, are a minuscule fraction of annual global emissions (about 37GtCO_2 in 2023 from energy and industry use, and increasing thereafter in this baseline scenario without mitigation). Nevertheless, in terms of percent changes, some regions experience large changes between BwI and BnI, and these changes could mean more strain in meeting mitigation targets. The Amazon region stands out and invites an in-depth analysis to trace the source of a sizeable increase of about 10% in energy and industry emissions, which are not reflected in changes in energy demand for cooling (see figure 4). A one-at-a-time-impact analysis that we

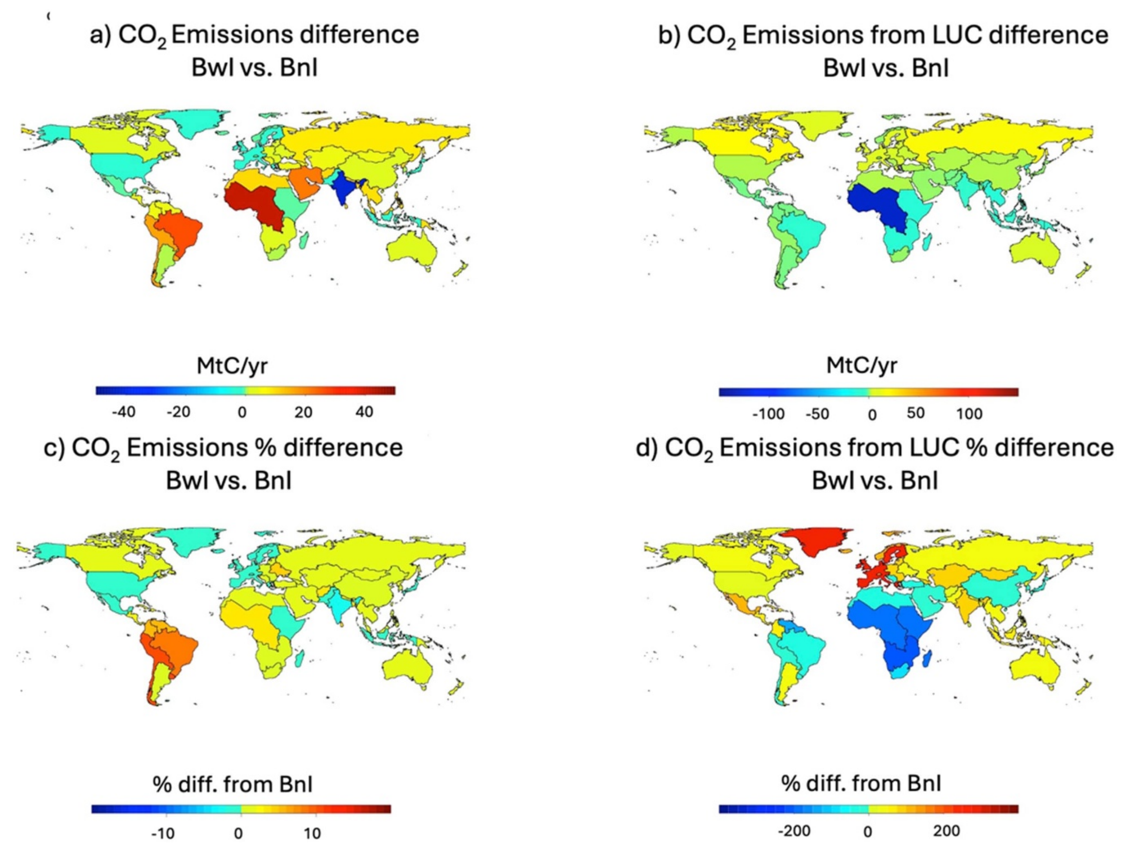

Figure 3. Absolute (a), (b) and percent of BnI (c), (d) changes at 2100 in regional emissions of CO_2 from energy and industry (a), (c) and land use changes (b), (d) when comparing BwI to BnI. The experiment showing the largest impacts is shown, which uses an estimate of GMT by Hector parameterized by ECS = 5 K, and STITCHES emulating the MRI model. Results from those experiments with other climate forcing implementation are qualitatively similar, if overall reduced in size.

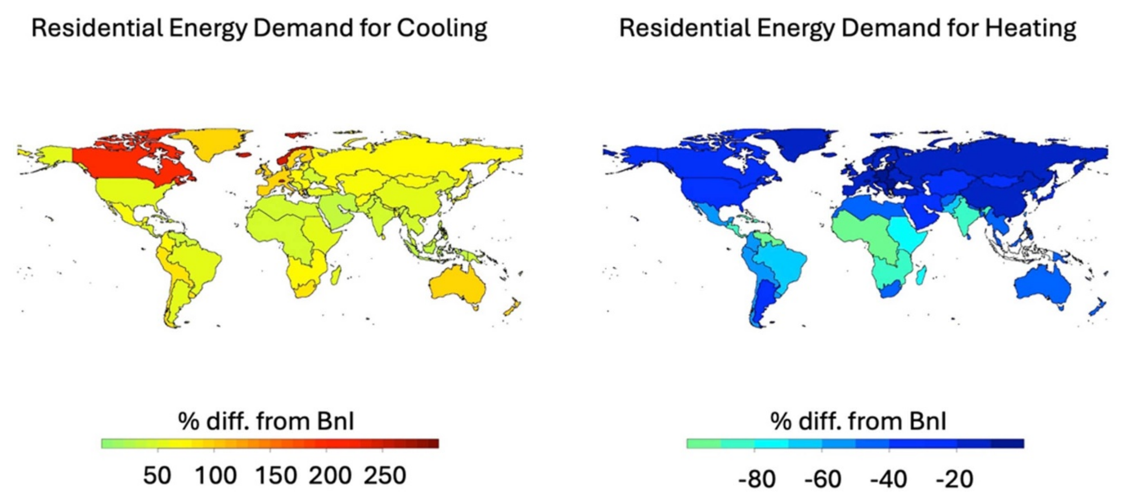

Figure 4. Percent changes at 2100 in final energy use for residential building cooling (left) and heating (right). See figure S3 for absolute terms and the break-down among individual impact channels, showing that HDD/CDD implementation is sufficient to explain these changes. The experiment showing the largest impacts is shown, which uses an estimate of GMT by Hector parameterized by ECS = 5 K, and STITCHES emulating the MRI model. Results from those experiments with other climate forcing implementation are qualitatively similar, if overall reduced in size.

conducted for this purpose (figure S1) identifies the main source of increased emissions as a change in hydropower production due to changes in runoff, projected to decrease over the century because of drier future climate conditions. This region, which relies heavily on hydropower generation, would be forced to adopt more carbon-intensive sources of energy when the impacts of lower river flow on the production of hydropower plants is represented in GCAM.

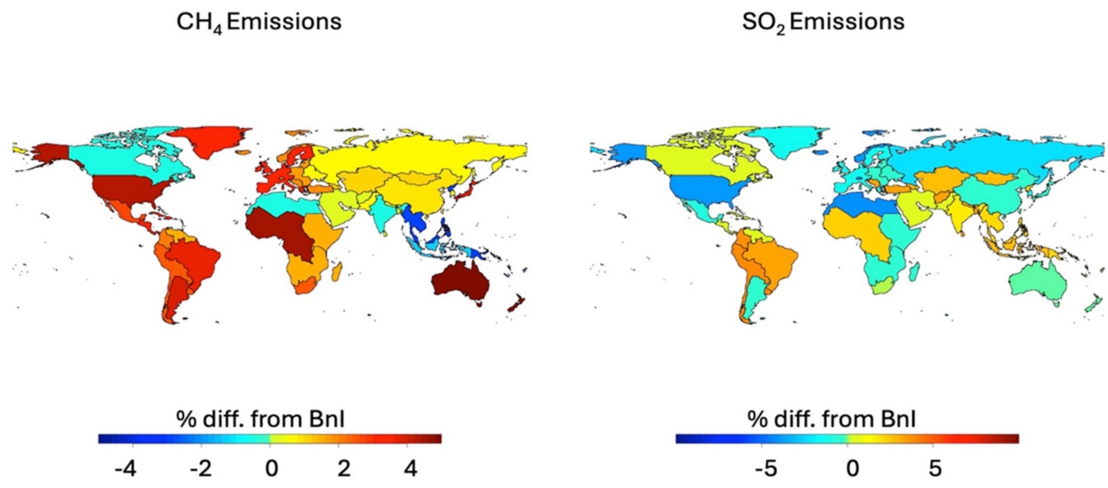

Figure 5. Percent changes at 2100 in non-CO2 emissions across scenarios. See figure S4 for absolute terms and the break-down among individual impact channels. The experiment showing the largest impacts is shown, which uses an estimate of GMT by Hector parameterized by ECS = 5 K, and STITCHES emulating the MRI model. Results from those experiments with other climate forcing implementation are qualitatively similar, if overall reduced in size.

Increases in LU emissions, largest in absolute terms over Northern Eurasia, are attributable to the effects of agricultural impacts through changes in labor and crop productivity, inducing cultivated land expansion and deforestation in this region as well as in all other regions of the world. Figure S2 documents this effect, and a one-at-a-time implementation of these impacts confirms that it is attributable to changes in labor productivity and the productivity of land for the different crops that GCAM represents: as climate diminishes yields per hectare across the globe, more land is put to production to compensate for the detrimental impact. The same figure also displays the corresponding loss of forested land, responsible for increased carbon emissions in figures 3(b) and (d).

Previous work has tested the effects in GCAM of making energy demand endogenously driven by changes in heating and cooling degree days consistent with GCAM emissions (Hartin *et al* 2021). That work found that, in a warming climate, the effects on emissions of the increased demand for cooling was offset by the lower demand for heating, so that the globally aggregated emissions, and therefore climate itself, did not change significantly by implementing this feedback. Our results confirm that finding: figure 4 shows that there are changes, as expected, in the final energy use for cooling and heating, significant (more than doubling, in some cases) for some regions, but, as we already discussed, the aggregated effect is not significant (figure 2). Interestingly, the regional pattern of differential energy use does not correspond to the regional pattern of overall changes in regional CO_2 emissions (figure 3), pointing at the compounding effects of different impact channels. As we already described, the largest changes in regional emissions in figure 3, which express themselves in particular over South America, are attributable to changes in runoff specifically through changes in capacity for hydropower generation (figure S1), rather than changes in energy demand. We also assessed changes in methane and sulfate emissions, which could result from the new balance between heating demand (predominantly for natural gas) and cooling demand (predominantly for electricity). If we found large changes at regional scales, implications for short lived climate forcers could be significant and may affect regional climate, even if the lack of robust signals across different earth system models documented in the literature (Westervelt *et al* 2020, Tebaldi *et al* 2023) hampers our ability to quantify their feedback potential in a robust way. Figure 5, however, shows that changes are small, and their patterns are not obviously consistent with the patterns in figure 4.

GCAM is an economic model, whose dynamics are driven by the need to balance, at each time steps, supply and demand for hundreds of markets across sectors and geographies. Thus, its output not only includes hundreds of physical quantities related to the energy, land and water sectors, but also their prices. We can therefore explore if the changes at the regional scale just described affect prices, particularly for energy and food. We focus on tendencies and the order of magnitude of changes, and we stress that ours is always a comparative perspective, between outcomes under scenarios accounting for climate impacts and those that do not. While we do not trace causes of price changes in detail, in general terms, impacts either affect the cost of production of goods (e.g. food production through yield impacts) or affect demand (e.g. for cooling), either of which will lead to a change in price.

We find that the price of fuels for primary energy production do not show significant increases; the difference at 2100 between BwI and BnI is within 1

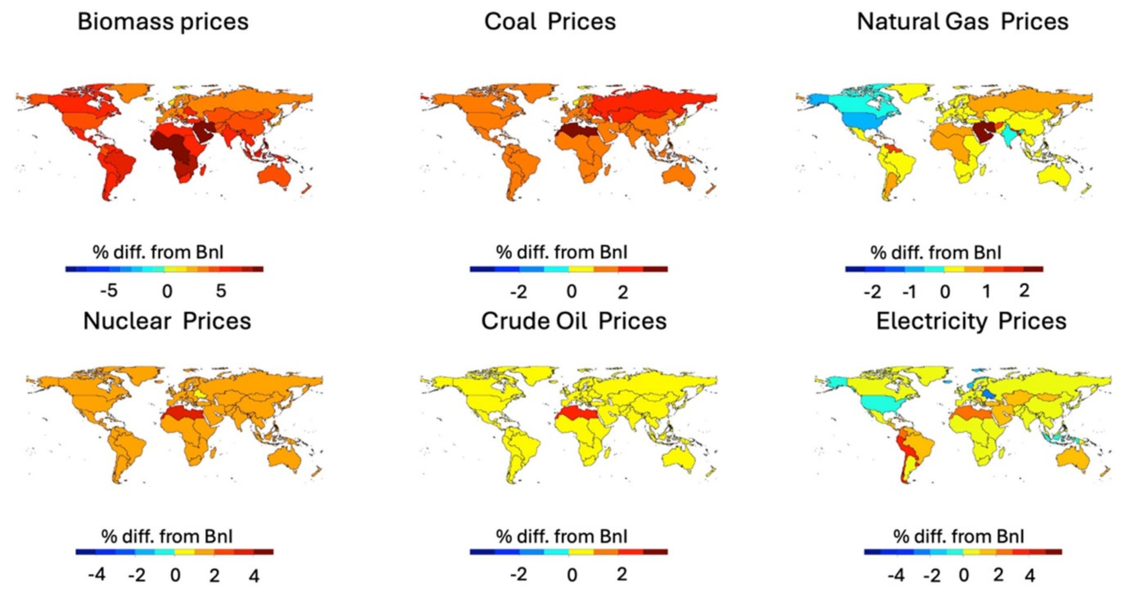

Figure 6. Percent changes at 2100 in prices of fuels used for primary energy production, comparing BwI to BnI. The experiment showing the largest impacts are shown, which use an estimate of GMT by Hector parameterized by ECS = 5 K, and STITCHES emulating the MRI model. Results from those experiments with other climate forcing implementation are qualitatively similar, if overall reduced in size.

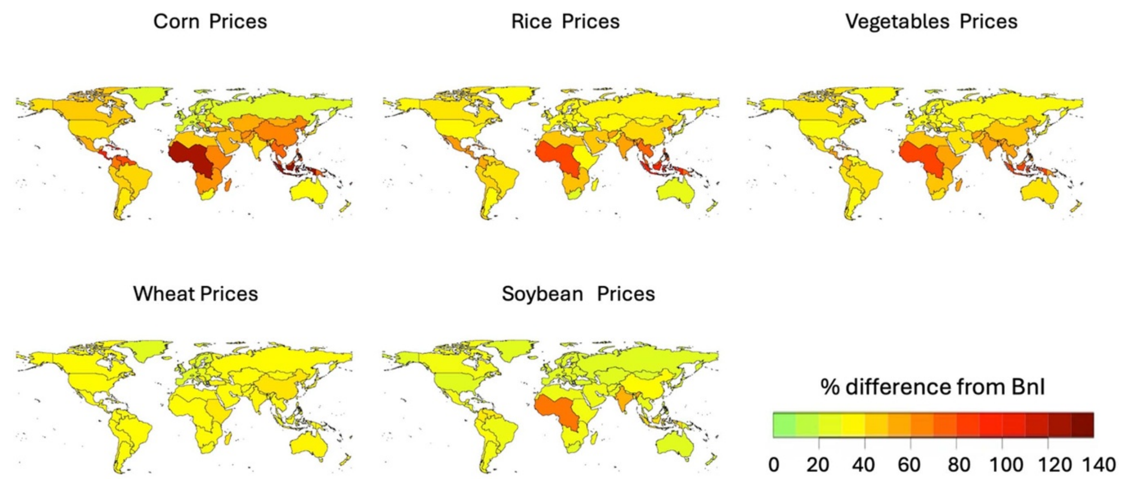

Figure 7. Percent changes at 2100 in food prices (agricultural products), comparing BwI to BnI. The experiment showing the largest impacts is shown, which uses an estimate of GMT by Hector parameterized by ECS = 5 K, and STITCHES emulating the MRI model. Results from those experiments with other climate forcing implementation are qualitatively similar, if overall reduced in size.

or 1.5% of one another for coal, oil, natural gas and nuclear. The only source showing increases on the order of 5%–10% is biomass (figure 6). The cost of electricity also remains close between the two experiments, with all regions experiencing increases less than 4%.

The same behavior is found for other energy-related prices, like those of fuels for final energy use for buildings, transportation and industry. All fuel price changes remain substantially below 5% (decreasing or increasing regionally), with the exception of prices of biomass for building and industry use, which are however not much larger than 5%.

The price of food, however, changes significantly between scenarios, with corn, rice and vegetables becoming more costly by up to 50%–60% in some regions, wheat up to 30% and soybean up to 15% (figure 7). These results are a reminder that even though impacts may not substantially affect emissions, they can still have important socio-economic consequences.

Meat and dairy products as well show increasing costs, but changes remain between 5% and 15% in most regions (figure 8).

The analysis of single impact experiments (figures S5 and S6) reveals that the larger changes can be explained mainly by intra-sectoral impacts: as those

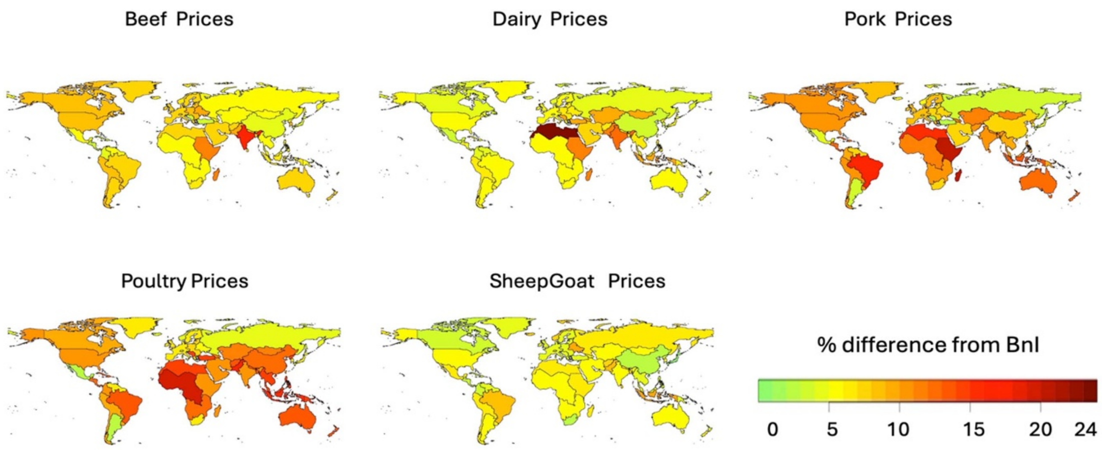

Figure 8. Percent changes at 2100 in food prices (meat and dairy products), comparing BwI to BnI. The experiment showing the largest impacts is shown, which uses an estimate of GMT by Hector parameterized by ECS = 5 K, and STITCHES emulating the MRI model. Results from those experiments with other climate forcing implementation are qualitatively similar, if overall reduced in size.

figures show, the compound change experienced by the simulations that accounts for all impact channels appears equivalent to the sum of the changes experienced when accounting individually for impacts on yields and on agricultural labor productivity.

4. Conclusions

We examined how representing climate impacts in GCAM's baseline scenario affects emissions and climate outcomes. Our core question was whether IAMs should include climate impacts when producing emission and land-use scenarios, what error results if they do not, and whether the size of the error indicates the necessity of implementing a fully coupled, endogenized representation of climate impacts.

To test this, we translated GCAM's baseline emissions and land use into climate responses and impacts, applied those impacts exogenously to produce a new GCAM baseline scenario, and compared the results. If this approach had significantly altered human-system dynamics and emissions—enough to meaningfully change climate outcomes—it would have indicated that impacts need to be modeled endogenously when emission scenarios are produced.

Our results, however, indicate that the effects on the global economy and global emissions lead to less than 0.1 °C difference in warming by 2100, from a baseline scenario warming of almost 4 °C, and therefore do not support endogenizing these impacts. This conclusion is conditional on our modeling framework and the specific impact channels represented but is consistent with other studies finding modest-scale impacts on emissions (Hartin *et al* 2021; Matsumoto *et al* 2021, both of which implemented a two-way coupling but found only regionally significant changes). Of course, the value of a better integrated representation of human and Earth system changes and feedbacks goes beyond our focus, as it could enable more accurate anticipation of the consequences of alternative socio-economic development pathways. In fact, we do see sizable regional outcomes emerging in several metrics (emissions from both industrial and land use activities, food prices) which indicate that local economies and well-being measures may be affected significantly.

We have addressed climate projection uncertainty by using different global temperature responses to the same scenario and two climate models' regional responses for the same level of global warming. But many other sources of limitations and uncertainty call for continued exploration of the issue, in order to draw robust conclusions on the size of impacts and therefore the potential need to endogenize them in scenario development.

Studies similar to ours are needed across IAMs given structural limitations, diversity in representation and assumptions, and a variety of approaches to representing the dynamics and drivers of the human system (e.g. partial vs general equilibrium, intertemporal optimization vs recursive-dynamics models, different scales of regional disaggregation and temporal steps, different sectoral details) (Tebaldi *et al* 2026). Studies should also include additional impact channels, such as damages from a wider range of extremes to productivity, infrastructure, and assets which could affect GDP more significantly and even cause persistent growth effects when accounted for; the effects of wildfire on emissions and natural carbon sinks could strongly affect mitigation scenarios, which we have not tackled in this investigation limited to a baseline scenario without mitigation measures; the interaction of air pollutants and heat on human health could further affect labor productivity and public health; and the encroaching sea level on coastal settlements and populations could cause not only losses to assets and infrastructures but also redistribute population. Notably, however, labor-productivity losses—represented here, albeit only in agriculture—remain among the most significant impact channels (Tachiiri *et al* 2021).

A more comprehensive exploration of uncertainties is also needed. Any choice of impact model carries with it uncertainties both within the model itself, and in comparison to alternative models (a different parameterization of Xanthos would probably produce different estimates of runoff, but so would a different hydrological model). Perhaps even more strikingly, there is a wide range of estimates of damage functions of the type typically used in benefit-cost models (Morris *et al* 2025). The effect of climate impacts on GDP in the kind of process-based models we focus on here tends to align with the low end of the range of damage function estimates (Piontek *et al* 2021). The higher end of this range implies much larger potential for climate change impacts to feed back on emissions. Many of these damage functions are econometrically derived from historical observations, but the validity of high damage estimates is contested (Newell *et al* 2021). Nonetheless, a wider consideration of uncertainties than is presented here is warranted.

A parallel track of research, modeling, and analysis in coupling human and earth systems has approached the problem from the perspective of Earth system modeling. In that framework, the representation of human activities relevant to Earth system dynamics (for example, water management and agricultural land use, besides, of course, emissions) are endogenized and the human component is coupled on par with the other geophysical components of the Earth system model (atmosphere, ocean, land, cryosphere, biosphere) (Calvin and Bond-Lamberty 2018, Tan *et al* 2023, Bjordal *et al* 2025, Di Vittorio *et al* 2025). At least a few experiments documented in the literature have suggested that the strength of socio-economic feedbacks justifies the endogenization, as they affect the model evolution. For example, Thornton *et al* (2017) document feedbacks of climate on land productivity and ensuing effects on decisions about land allocation to crops or forest, on prices, and on emissions. More recently, it has been shown that carbon prices necessary to meet a steep decarbonization goal for China would increase in a net-zero scenario if warming impacts on energy demand were accounted for (Wang *et al* 2025).

The computational demands of Earth system models, however, further increased by the addition of human systems' process representations, challenge a full exploration of the uncertainties and sensitivities that the coupling introduces. In this work, we take the alternative approach of representing a simplified and computationally efficient Earth system response (through emulation) and its translation in impacts as external forcing to an IAM. This allowed us to quantify how much these climatic changes affect the IAM dynamics, and therefore the potential to alter its emissions and land use path if those forcings were endogenized. By choosing models—and emulators—that preserve computational tractability, we explored several dimensions of uncertainties and variability affecting our results. We hope this work informs both IAM development and decisions about coupling human and Earth systems within ESMs.

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Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://doi.org/10.5281/zenodo.16576194 (Sheng 2025); https://github.com/dsheng1026/climate_impact_CT/tree/master (Sheng 2026).

ORCID iDs

Claudia Tebaldi 0000-0001-9233-8903
Brian O'Neill 0000-0001-7505-8897
Di Sheng 0009-0006-7567-380X
Noah Prime 0000-0003-0150-2590
Mengqi Zhao 0000-0001-5385-2758
Kalyn Dorheim 0000-0001-8093-8397
Joseph Brown 0000-0002-3828-4729

References

Awais M *et al* 2024 MESSAGEix-GLOBIOM nexus module: integrating water sector and climate impacts *Geosci. Model. Dev.* **17** 2447–69

Barrage L and Nordhaus W 2024 Policies, projections, and the social cost of carbon: results from the DICE—2023 model *Proc. Natl Acad. Sci. USA* **121** e2312030121

Birnbaum A N, Shabestanipour G, Zhao M, Snyder A, Wild T and Lamontagne J 2024 Characterizing the multisectoral impacts of future global hydrologic variability *Environ. Res. Lett.* **19** 074014

Bjordal J *et al* 2025 NorESM2–DIAM: a coupled model for investigating global and regional climate-economy interactions *EGUsphere* [preprint] (https://doi.org/10.5194/egusphere-2025-4660)

Bosetti V, Massetti E and Tavoni M 2007 The WITCH Model: structure, baseline, solutions *Fondazione Eni Enrico Mattei Working Papers. Paper 71* (available at: https://services.bepress.com/feem/paper71)

Byers E, Meng M, Mastrucci A, van Ruijven B and Krey V 2024 Flexible emulation of the climate warming cooling feedback to globally assess the maladaptation implications of future air conditioning use *Environ. Resour.* **1** 035011

Calvin K *et al* 2019 GCAM v5.1: representing the linkages between energy, water, land, climate, and economic systems *Geosci. Model. Dev.* **12** 677–98

Calvin K and Bond-Lamberty B 2018 Integrated human-earth system modeling—state of the science and future directions *Environ. Res. Lett.* **13** 063006
Chapagain R, Remenyi T A, Harris R M B, Mohammed C L, Huth N, Wallach D, Rezaei E E and Ojeda J J 2022 Decomposing crop model uncertainty: a systematic review *Field Crops Res.* **279** 108448
Colelli F P, Emmerling J, Marangoni G, Mistry M N and De Cian E 2022 Increased energy use for adaptation significantly impacts mitigation pathways *Nat. Commun.* **13** 4964
Di Vittorio A V, Sinha E, Hao D, Singh B, Calvin K V, Shippert T, Patel P and Bond-Lamberty B 2025 E3SM-GCAM: a synchronously coupled human component in the E3SM Earth system model enables novel human-earth feedback research *J. Adv. Model. Earth Syst.* **17** e2024MS004806
Dorheim K, Gering S, Gieseke R, Hartin C, Pressburger L, Shiklomanov A N, Smith S J, Tebaldi C, Woodard D L and Bond-Lamberty B 2024 Hector V3.2.0: functionality and performance of a reduced-complexity climate model *Geosci. Model. Dev.* **17** 4855–69
Edmonds J, Zhao X, Patel P, Sheng D, Lochner E, Bertram C, Iyer G, Westphal M, Fawcett A and Waldhoff S 2025 Sensitivity of future regional and global energy markets and macroeconomic activity to a hypothetical global energy market disruption *iScience* **28** 111449
Fisher-Vanden K and Weyant J 2020 The evolution of integrated assessment: developing the next generation of use-inspired integrated assessment tools *Annu. Rev. Resour. Econ.* **12** 471–87
Fricko O *et al* 2017 The marker quantification of the Shared Socioeconomic Pathway 2: a middle-of-the-road scenario for the 21st century *Glob. Environ. Change* **42** 251–67
Frieler K *et al* 2024 Scenario setup and forcing data for impact model evaluation and impact attribution within the third round of the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP3a) *Geosci. Model. Dev.* **17** 1–51
Fujimori S, Hasegawa T, Masui T, Takahashi K, Herran D S, Dai H, Hijioka Y and Kainuma M 2017 SSP3: AIM implementation of shared socioeconomic pathways *Glob. Environ. Change* **42** 268–83
Graham N *et al* 2020 Humans drive future water scarcity changes across all shared socioeconomic pathways *Environ. Res. Lett.* **15** 014007
Hartin C, Link R, Patel P, Mundra A, Horowitz R, Dorheim K and Clarke L 2021 Integrated modeling of human-earth system interactions: an application of GCAM-fusion *Energy Econ.* **103** 105566
Hausfather Z and Peters G 2020 Emissions—the 'business as usual' story is misleading *Nature* **577** 618–20
Howard P and Sterner T 2025 Methodology matters: a careful meta-analysis of climate damages *Environ. Resour. Econ.* **88** 3289–327
Jäger F *et al* 2024 Fire weather compromises forestation-reliant climate mitigation pathways *Earth Syst. Dyn.* **15** 1055–71
Kriegler E *et al* 2017 Fossil-fueled development (SSP5): an energy and resource intensive scenario for the 21st century *Glob. Environ. Change* **42** 297–315
Lange S 2019 Trend-preserving bias adjustment and statistical downscaling with ISIMIP3BASD (v1.0) *Geosci. Model. Dev.* **12** 3055–70
Matsumoto K, Tachiiri K and Su X 2021 Heat stress, labor productivity, and economic impacts: analysis of climate change impacts using two-way coupled modeling *Environ. Res. Commun.* **3** 12
Morris J, Rose S K, Reilly J, Gurgel A, Paltsev S and Schlosser C A 2025 Reconciling widely varying estimates of the global economic impacts from climate change *Nat. Clim. Change* **15** 124–7
Natali S M, Holdren J P, Rogers B M, Treharne R, Duffy P B, Pomerance R and MacDonald E 2021 Permafrost carbon feedbacks threaten global climate goals *Proc. Natl Acad. Sci. USA* **118** e2100163118
Newell R G, Prest B C and Sexton S E 2021 The GDP-temperature relationship: implications for climate change damages *J. Environ. Econ. Manage.* **108** 102445
O'Neill B C *et al* 2016 The scenario model intercomparison project (ScenarioMIP) for CMIP6 *Geosci. Model. Dev.* **9** 3461–82
Piontek F, Drouet L, Emmerling J, Kompas T, Mejean A, Otto C, Rising J, Soergel B, Taconet N and Tavoni M 2021 Integrated perspective on translating biophysical to economic impacts of climate change *Nat. Clim. Change* **11** 563–72
Reinecke R *et al* 2025 Uncertainties as a guide for global water model advancement *WIREs Water* **12** e70025
Riahi K *et al* 2017 The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: an overview *Glob. Environ. Change* **42** 153–68
Ripple W J, Wolf C, Lenton T M, Gregg J W, Natali S M, Duffy P B, Rockström J and Schellnhuber H J 2023 Many risky feedback loops amplify the need for climate action *One Earth* **6** 86–91
Rising J, Tedesco M, Piontek F and Stainforth D A 2022 The missing risks of climate change *Nature* **610** 643–51
Ruane A C *et al* 2022 The climatic impact-driver framework for assessment of risk-relevant climate information *Earth's Future* **10** e2022EF002803
Sampedro J, Waldhoff S T, Edmonds J A, Iyer G, Msangi S, Narayan K B, Patel P and Wise M 2024 Residential energy demand, emissions, and expenditures at regional and income-decile level for alternative futures *Environ. Res. Lett.* **19** 084031
Schultes A, Piontek F, Soergel B, Rogelj J, Baumstark L, Kriegler E, Edenhofer O and Luderer G 2021 Economic damages from on-going climate change imply deeper near-term emission cuts *Environ. Res. Lett.* **16** 104053
Sheng D 2025 GCAM outputs for Closing The Loop, a First Exploration (preliminary) [Data set] *Zenodo* (https://doi.org/10.5281/zenodo.16576194)
Sheng D 2026 Code to generate figures *Zenodo* (available at: https://github.com/dsheng1026/climate_impact_CT/tree/master)
Sheng D, Zhao X, Edmonds J A, Morris S T, Patel P, O'Neill B C and Tebaldi C 2025a Omitting labor responses underestimates the effects of future heat stress on agriculture *Commun. Earth Environ.* **6** 400
Sheng D, Zhao X, Snyder A, Morris S and Vernon C 2025b HELPS: an R package to project future heat effects on labor productivity by sector *J. Open Source Softw.* **10** 8415
Snyder A C, Dorheim K R, Tebaldi C and Vernon C R 2024 STITCHES: a Python package to amalgamate existing Earth system model output into new scenario realizations *J. Open Source Softw.* **9** 5525
Srikrishnan V *et al* 2022 Uncertainty analysis in multi-sector systems: considerations for risk analysis, projection, and planning for complex systems *Earth's Future* **10** e2021EF002644
Stehfest E *et al* 2014 Integrated Assessment of Global Environmental Change with IMAGE 3.0. Model description and policy applications (PBL Netherlands Environmental Assessment Agency) (available at: https://www.pbl.nl/sites/default/files/downloads/pbl-2014-integrated_assessment_of_global_environmental_change_with_image30_735.pdf)
Swart N C *et al* 2019 The Canadian earth system model version 5 (CanESM5.0.3) *Geosci. Model. Dev.* **12** 4823–73
Tachiiri K, Su X and Matsumoto K 2021 Identifying key processes and sectors in the interaction between climate and socio-economic systems: a review toward integrating Earth–human systems *Prog. Earth Planet. Sci.* **8** 24
Tan J, Duan Q, Xiao C, He C and Yan X 2023 A brief review of the coupled human-Earth system modeling: current state and challenges *Anthropocene Rev.* **10** 664–84
Tebaldi C, O'Neill B and Byers E 2026 Climate impacts in scenarios: time to close the loop? *Earth's Future* **14** e2025EF007622

Tebaldi C, O'Neill B and Lamarque J-F 2015 Sensitivity of regional climate to global temperature and forcing *Environ. Res. Lett.* **10** 074001

Tebaldi C, Snyder A and Dorheim K 2022 STITCHES: creating new scenarios of climate model output by stitching together pieces of existing simulations *Earth Syst. Dyn.* **13** 1557–609

Tebaldi C, Wehner M, Leung R and Lawrence D 2023 Is land use producing robust signals in future projections from Earth system models, all else being equal? *Environ. Res. Lett.* **18** 084009

Thornton P *et al* 2017 Biospheric feedback effects in a synchronously coupled model of human and Earth systems *Nat. Clim. Change* **7** 496–500

Van Vuuren D P, Batlle Bayer L, Chuwah C, Ganzeveld L, Hazeleger W, van den Hurk B, van Noije T, O'Neill B and Strengers B J 2012 A comprehensive view on climate change: coupling of earth system and integrated assessment models *Environ. Res. Lett.* **7** 024012

Vernon C R, Hejazi M I, Turner S W D, Liu Y, Braun C J, Li X and Link R P 2019 A global hydrologic framework to accelerate scientific discovery *J. Open Res. Softw.* **7** 1

Wang B *et al* 2024 Pathways to identify and reduce uncertainties in agricultural climate impact assessments *Nat. Food* **5** 550–6

Wang T, Lu Y, Teng F, Zhang X, Zhang X, Wei M, Wu T, Wang D, Sun J and Zhong J 2025 Coupling natural-social models can better quantify the interactions in achieving carbon neutrality in China *Environ. Res. Lett.* **20** 024026

Westervelt D M, Mascioli N R, Fiore A M, Conley A J, Lamarque J-F, Shindell D T, Faluvegi G, Previdi M, Correa G and Horowitz L W 2020 Local and remote mean and extreme temperature response to regional aerosol emissions reductions *Atmos. Chem. Phys.* **20** 3009–27

Yukimoto S *et al* 2019 The meteorological research institute earth system model version 2.0, MRI-ESM2.0: description and basic evaluation of the physical component *J. Meteorol. Soc. Japan* **97** 931–65

Zhang Y, Waldhoff S, Wise M, Edmonds J and Patel P 2023 Agriculture, bioenergy, and water implications of constrained cereal trade and climate change impacts *PLoS One* **18** e0291577

Zhao M, Khan Z, Dorheim K and Vernon C 2024 Helios: an R package to process heating and cooling degrees for GCAM *J. Open Source Softw.* **9** 6033

Zhao M, Morris S T, Tebaldi C and Snyder A 2025 Gaia: an R package to estimate crop yield responses to temperature and precipitation *J. Open Source Softw.* **10** 7538