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Climate Impacts in Scenarios: Time to Close the Loop?

Claudia Tebaldi[1], Brian O'Neill[1], and Edward Byers[2]

[1]University of Maryland, College Park, MD, USA, [2]International Institute for Applied Systems Analysis, Vienna, Austria

Key Points:

- We need to account for climate impacts when modeling scenarios of future emissions and land use to enhance consistency and plausibility
- Recent progress in understanding, data and modeling can help overcome long-standing obstacles in integrating emissions, climate and impacts
- We call for a coordinated multimodel comparison effort to foster critical progress, assess uncertainties, produce more plausible scenarios

Correspondence to:
C. Tebaldi,
claudia.tebaldi@pnnl.gov

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Author Contributions:
Conceptualization: Claudia Tebaldi, Brian O'Neill, Edward Byers
Writing – original draft: Claudia Tebaldi, Brian O'Neill, Edward Byers

Abstract Integrated modeling of Earth and human systems, accounting for feedbacks, is key to fully understand climate change consequences and ensuing adaptation needs. In some aspects of climate research, however, closing this loop has proved particularly challenging. A primary example is the generation and use of earth system model (ESM) simulations. Integrated assessment models (IAMs) are used to project socio-economic activities, emissions and land-use change. ESM projections, driven by these scenarios, are then used by impact models. According to this modeling chain, however, those impacts do not affect the emissions and land use driving ESMs. Whether this feedback is large enough to warrant explicitly accounting for, needs addressing. Two consequential possibilities, discussed in the literature, are that emissions and land-use scenarios representing the high and low ends of the plausible range might be too extreme: the high-end scenarios missing damaging impacts, which could reduce economic activity, therefore emissions; the low-end scenario ignoring climate feedbacks that make nature-based carbon removal less effective and hamper- the assumed mitigation. In this piece, we describe the challenges that implementing such feedbacks would face, while arguing that recent developments in impact research, data, human and Earth system modeling and emulation make the time ripe for a structured model intercomparison project (MIP). MIPs have benefitted climate modeling for decades. An IAM MIP focused on integrating impacts in emission and land-use change scenarios could enable testing these feedbacks' implications and assessing whether closing the loop would significantly change our outlook on future climate changes and their consequences.

Plain Language Summary Emission and land-use scenarios produced by Integrated Assessment Models (IAMs) drive projections of future climate by Earth System Models, which drive impact models in turn. This modeling chain, however, does not represent feedbacks from climate impacts on societal activities and emissions. Some have argued that climate change impacts on economic activity will be so large as to reduce emissions, making the highest emission scenarios not plausible. At the other end of the spectrum, wildfires, droughts, or other climatic changes associated with warming may undermine nature-based mitigation solutions assumed by the lowest scenarios, making them also implausible. Uncertainties in understanding and modeling affect our ability to measure the strength of these hypothesized but seldom-tested feedbacks. A coordinated model intercomparison exercise among IAMs can robustly assess these effects, especially thanks to recent progress in data, modeling and scientific understanding of many aspects of the interrelated systems at play.

1. Context

A wide variety of multidisciplinary efforts are contributing to a better understanding of future climate change risks and potential responses by considering the interactions between human and Earth systems. However, one major activity within this area—the production of emission and land-use scenarios by Integrated Assessment Models that drive Earth System Models—has so far largely represented critical interactions between systems in a one-way fashion. This activity (e.g., O'Neill et al., 2016; Riahi et al., 2017; van Vuuren et al., 2025) is arguably the cornerstone of our understanding of what future changes in the climate system will be like, as ESM projections are in turn used by impact models to assess consequences for ecosystems and societies. This chain of modeling, by construction, does not account for possibly significant feedbacks from impacts to emissions, through the alteration of those economic activities or natural systems responsible for generating or mitigating emissions.

As a result of these missing feedbacks, IAM emission and land-use scenarios could be criticized at both ends of the spectrum of what are presented as plausible emission scenarios: on the low end, scenarios may be too optimistic about the effectiveness of nature-based mitigation solutions. This is because while IAMs include the positive CO_2 fertilization effects on net primary productivity, they rarely include climate shocks like droughts or wildfires, endangering vegetation growth in the future as is already happening (Friedlingstein et al., 2025; Ke et al., 2024; Liang et al., 2025) and could happen even more in the future (Jager et al., 2024). On the high end, IAMs have also been viewed as too optimistic about economic development maintaining a high pace in the face of substantial climate change impacts, which could well damage economies, slowing their growth and therefore their emissions (Hausfather & Peters, 2020; Ho et al., 2019; Vinca, Andrijevic, et al., 2025; Vinca, Awais, et al., 2025; Waidelich et al., 2024).

We need therefore to face these criticisms and ensure that IAMs produce scenarios of emissions and land-use change that are fully consistent with the impacts of climate change driven by those emissions and land-use changes.

The IAM community has been aware of the need to model impacts while developing emission scenarios, but many challenges have hampered implementation until now. We argue that recent progress on scientific, data and modeling fronts are making those challenges less daunting and allow us to take action on this problem.

2. Challenges and Recent Progress

There are many potential impacts of climate on human systems, acting through many channels. Which of them would feedback on emissions or land use change sufficiently to warrant an endogenous representation is still not clear, and possibly may not be until such endogenous representation is implemented (Tachiiri et al., 2021). Methodological developments may be of help here, including scenario discovery techniques relying on large ensembles of runs, where different inputs are tested and the outcomes of interest are linked to specific subsets of the input space (e.g., Dolan et al., 2021). Emulators of IAMs, which are also in a nascent phase, are being used to explore the models' sensitivities and the critical regions of their parameter space (Holmes et al., 2025) and could be deployed to explore the many sources of variability and uncertainty relevant to impact implementation within IAMs.

In many modeling implementations, impacts are represented only partially, and these challenges vary by the type of IAM. In Table 1 we categorize IAMs in this respect. Recursive models, in which decisions are based only on current and past information, are better suited to implement unanticipated climate shocks in individual years and also, since they are typically less computationally intensive, to run multiple simulations to test the sensitivity to assumptions and estimates of climate and impact forcing. Their downside is the lack of foresight in the decision making processes represented within the model, which prevents them from accounting for foreseeable chronic climate impacts. For example, these models may fail to invest in infrastructure that would be useful for coping with future impacts. In contrast, other IAMs are based on inter-temporal optimization with perfect foresight: decisions account for all future developments, such as climate impacts on crop productivity or cooling degree days. Thus decisions optimize the system while anticipating changing conditions over the whole time horizon. This is particularly important in the sizing and build-out of multi-decade infrastructure investments, such as in the energy and water sectors, where the operational performance and costs depend partly on climate conditions in the future. However, due to the deterministic nature of these methods, the representation of spatially and temporally stochastic climate variability and acute climate shocks, is difficult in comparison to simulation-based methods.

More generally, many IAMs can represent the impacts of longer-term climate trends on economic production (e.g., crop yields), but they don't yet include the consequences of extreme events such as floods, droughts, or heat waves (i.e., acute impacts). These shock-like, localized impacts, which can nonetheless be long-lasting, are also mismatched in scale compared to the typical IAM model resolution (usually subcontinental) and time step (multi-year to yearly in most cases). As another example, effects of heat stress on agricultural labor are starting to be incorporated (Sheng et al., 2025), but those on other types of outdoor labor are more challenging to represent, because these sectors may not be typically disaggregated in the economic modules of IAMs. Chronic climate impacts on the power sector are implemented through modifications to the supply curve of existing plants as hydro-, wind and water-cooled power plants may see their production decreasing or increasing because of adverse or favorable climate conditions (Hejazi et al., 2023; Liu et al., 2015), but extreme events and changes in the number and locations of such plants that may be triggered by climatological changes in the availability of the natural resources they rely on (runoff, winds, solar insolation, cooling water streams) are less commonly implemented. The roles of reservoirs and storage in buffering shortages in the supply of water or energy is expected to be significant, but IAM representation of the variability of these resources, particularly on sub-annual, that is, seasonal or shorter timescales, is in its infancy (Zhao et al., 2024).

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Table 1
Summary of Key Sectoral Components of IAMs, Different Types of IAM Frameworks, Their Implementation and Relation to How Climate Impacts Are Covered

Model category	Chronic impacts coverage	Acute impacts coverage	Timestep (years)	Temporal dynamics (optimization)	Endogenous adaptation	Example models	Notes
Broad sectoral focus							
Energy-Economy Optimization	☑ Detailed (energy supply potentials, demand etc.)	⚠ Needs scenario design	5–10 years	Inter-temporal (perfect foresight)	☑ Yes, foresight optimization	MESSAGEix, REMIND, TIAM, WITCH, MERGE, DNE21+, COFFEE	Full-horizon cost-optimal planning; good for anticipatory behavior
Land-Use and Agriculture	☑ Climate and hydrology impacting crop yield	⚠ Shocks modelable	5–10 years	Recursive dynamic (Myopic)	⚠ Limited and rule-based, not economically optimized	GLOBIOM, MAgPIE	Often coupled to energy models by relation of biomass supply; no endogenous foresight
Integrated approaches							
Recursive Dynamic Simulation	☑ Broad via inputs	☑ Exogenous shocks possible	5	Recursive dynamic (Myopic)	⚠ Limited and rule-based, not economically optimized	IMAGE, GCAM	Good for reacting to unanticipated impacts; lack foresight
Computable General Equilibrium (CGE)	☑ Productivity, labor, yield losses	☑ Capital/labor shocks	5	Recursive dynamic (Myopic)	⚠ Scenario-informed	AIM/Hub, GEM-E3, EPPA	Can capture economy-wide effects; can have foresight but typically myopic
Hybrid/Coupled Systems[a]	☑ Via combined strengths	⚠ Requires scenario linkage[b]	5	Mixed (perfect foresight + myopic)[c]	🔁 Partial, depending on framework	REMIND-MAgPIE, MESSAGEix-GLOBIOM	Balances perfect foresight optimized planning (REMIND/MESSAGEix) with a land use modeling feedback (MAgPIE/GLOBIOM)

[a]Typically combine optimization and simulation models. [b]"Requires scenario linkage" means that integration of acute impacts (e.g., extreme weather shocks) needs to be imposed through shared scenario assumptions across the coupled models. Since REMIND or MESSAGEix are perfect foresight and MAgPIE/GLOBIOM are recursive, acute shocks must be fed into both sides carefully to simulate coordinated response or preparation. [c]"Mixed" refers to the fact that one model is based on perfect foresight inter-temporal optimization while another is myopic recursive dynamic.

Also typically missing from IAMs is the effect of sector impacts on the economy as a whole (e.g., as measured by GDP). In most IAMs, economic growth is exogenous, so sector impacts such as those on labor or land productivity, or damages to capital (through extreme events, for example), cannot in this modeling framework impact the scale of the economy. As a consequence, changes in emissions originating with climate impacts remain limited in size, with regional compensation through trade in many cases.

At an even more basic level, impact estimation remains a challenge for many types of climate impacts, and/or for many locations around the world, not just because they are difficult to represent in models, but because we lack the knowledge to capture the dynamics by which impacts operate or the data to carry out this estimation, or both. Examples spanning a range of challenges include our limited when not altogether absent ability to represent impacts from infrastructure damages; morbidity and mortality from air quality, heat and other climate stressors; and effects of climate stress on migration and crime, biodiversity loss, and ecosystem services (Rising et al., 2022).

Impacts act at temporal and spatial scales spanning sub-daily (the destructive effects of a tornado) to decadal (the agricultural impacts of mega droughts), and local (the shutdown of a power plant because of adverse weather conditions) to global (arctic sea ice disappearance and consequent changes in trade routes). How to translate them into quantities and effects that an IAM can represent and act upon necessitates bridging those scales.

Adaptation also complicates a realistic representation of impacts, including their magnitude, sphere of influence and persistence. Improved, more quantitative representation of the effect of adaptation (and its limits) is developing but still represents a frontier effort (Andrijevic et al., 2023; Van Maanen et al., 2023).

Like any additional modeling component or step applied to an existing system, adding the representation of climate impacts in IAMs comes with new sources of variability and uncertainty. Achieving a comprehensive representation will likely have to rely on the use of computationally efficient emulators, large ensembles and exploratory modeling (Giuliani et al., 2022).

Even as we strive to achieve results robust to sensitivities and variability, it remains to be seen if those results will be actionable, or if the ranges of uncertainty become so large as to confront us with the limits to predictability in this context.

3. Way Forward

We are witnessing substantial progress in scientific understanding, modeling tools, and data availability that are germane to this problem.

Climate models have become better able to represent salient phenomena (damaging extreme events like heat waves, tropical and extratropical cyclones, heavy rainfall and droughts) and their geophysical impacts (soil moisture deficits, vegetation dieback, flooded area, wildfires). Their experiments are providing "off the shelf" scenarios of climate change outcomes that can be used to implement impacts in IAMs and study their consequences (Dolan et al., 2021; Hejazi et al., 2014). In addition, the large data sets made available by concerted efforts like CMIP (Dunne et al., 2025; Van Vuuren et al., 2025) are used to train ESM emulators whose development facilitates the representation of the climate response precisely tailored to the aggregated, global scale pathway of emissions and land use change that the IAM is producing in a computationally efficient manner (Beusch et al., 2020, 2022; Mathison et al., 2025; Tebaldi et al., 2022). Local scale effects of changes in land-use and short lived forcers have not been found to generate a robust response in a multi-model context (Tebaldi et al., 2023; Westervelt et al., 2020) and we therefore see them as the object of future studies and emulator development.

Impact modeling is also benefiting from increasing data availability; more advanced process models, algorithms and computational techniques; and efforts at coordination and intercomparison. The econometric approach is making use of observed data to estimate response functions through which warming affects individual socio-economic sectors or assets and geographies, or aggregated outcomes, like gross domestic product (GDP; Bilal & Kanzig, 2024; Howard & Sterner, 2025; Waidelich et al., 2024). Process-based models representing mechanisms and dynamics by which climate phenomena determine socio-economic outcomes "from the bottom up" are addressing an increasingly wide range of impacts. Coordinated efforts at modeling and comparing outcomes (Frieler et al., 2024; Warszawski et al., 2014), and making results available through open archives, are supporting more robust projections, uncertainty quantification and even impact emulation. For example, RIME (Byers et al., 2025) emulates climate system impacts by building on available scenarios to "stratify" outcomes according to global temperature levels.

IAMs are also beginning to represent damage functions directly affecting GDP and therefore energy demand, production and ensuing emissions. The resulting changes in emission levels, compared to a baseline scenario without climate impacts, appear significant, in the sense of affecting climate beyond the noise of internal variability (Vinca, Andrijevic, et al., 2025; Vinca, Awais, et al., 2025). Other approaches attempt to model impacts at the process level, at present focusing primarily on impact channels like water availability, land and labor productivity, and energy demand due to changing heating or cooling needs (Awais et al., 2024; Birnbaum et al., 2024; Byers et al., 2024; Colelli et al., 2022; Graham et al., 2020; Hartin et al., 2021; Sampedro et al., 2024; Zhang et al., 2023).

In summary, each IAM effort individually can benefit from progress being achieved by a multi-disciplinary community of scientists, data-analysts and modelers. Methodological development like emulators and scenario discovery methods (Lamontagne et al., 2018) can also facilitate those efforts.

3.1. Beyond Individual Models' Efforts, a Model Intercomparison Project

We believe that a coordinated effort, bringing together different IAM teams, to attack the problem of representing climate impacts in emission and land use scenarios and thus attempting to close the loop, is achievable now, and will be critical in highlighting areas of robust understanding and areas most in need of improvement.

The priority should be to identify impact channels that have significant effects on global emissions, compared to an implementation without impacts, since such effects would have major implications for how we produce projections of future conditions.

We may want to start with a top-down approach, by which modeling teams are asked to implement common damage functions mapping global warming levels to impacts to the scale of production, often measured in GDP losses, from the literature. A central estimate of such damage functions as well as uncertainty bounds should be implemented to test the sensitivity of the outcomes, which the literature characterizes as highly uncertain (Howard & Sterner, 2025; Morris et al., 2025). Exogenous changes in temperature (or other climatic impact drivers) driving the damage functions can be obtained by a simple climate model calculation based on the emissions and land use changes that the IAM produced in the absence of the climate impacts representation. In this case the climate outcome will not be consistent with the emission and land-uses scenario (as impacted by damages), but it will constitute a first "sanity check" that will test the relevance of climate-driven damages to the emission pathway produced by the model at the global level. If the test returns a significant change in emissions, a follow-up experiment could ensue: endogenizing the climate outcome by modifying it step-by-step as the model simulation evolves, so that emissions, land use change, climate, and impacts are all endogenous and consistent with each other.

More complex is the implementation of process-level, bottom up impacts. We see the possibility of coordinating some initial stylized experiments, starting from a set of impacts commonly "approachable" by IAM teams. The implemented impacts could be initially those closest to (geo)physical outcomes, assuming that the degree of variation and uncertainty would only increase when moving toward impacts more largely affected by socio-economic dynamics. The list could include impacts on water availability, crop and labor productivity, energy demand, and renewable energy production, on which various IAMs have made progress in recent years (Awais et al., 2024; Byers et al., 2024; Colelli et al., 2022; Schmidt et al., 2024; Vinca, Andrijevic, et al., 2025; Vinca, Awais, et al., 2025). Coordination across the modeling teams would ensure that the set of impacts were representable by all models. For this case, the use of climate model emulators will be key (Tebaldi et al., 2025), as process-level impacts will need multivariate climate drivers as inputs that simple climate models cannot provide. As in the case of top-down damage function implementation, a first experiment would exogenously impose these climate impacts on the model dynamics driving emissions and land use. If such an experiment indicates a substantial change in emissions at the global scale, implementing these impacts endogenously would be warranted, so that climate outcomes are consistent with the effects of impacts on emissions.

Importantly, we do not propose that scenarios accounting for impacts substitute completely for scenarios that do not. The latter should be still produced and fed to ESMs, and the results to IAV models, to allow for a comparison between the two approaches to modeling scenarios and their impacts.

Establishing a protocol and common metrics of evaluation will be challenged by the diversity of the IAMs participating, but this obstacle can be overcome through communication and common planning. We believe a model intercomparison is the only way to achieve a robust characterization of the effects of climate impacts on emission scenarios, thus improving our understanding of the plausible range of future emission pathways the world may experience and guiding further exploration of this critical multi-system dynamics.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

Data were not used, nor created for this research.

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