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Perspective

Solving science conundrums in the climate-nature-equity polycrisis with integrated transformative scenarios

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SUMMARY

Addressing the intertwined climate, biodiversity, and equity crises requires transformative societal change. Yet the scenario frameworks and models used to explore future pathways often reproduce existing institutions, governance systems, and social structures, limiting their ability to imagine more sustainable and just futures. A key gap is the lack of approaches that can identify and evaluate transformative actions while accounting for systemic inequities in implementation. Here, we argue that integrating climate and biodiversity knowledge

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across the natural sciences, social sciences, and humanities, together with stakeholders and diverse knowledge holders, can support the development of normative scenarios and models for just and sustainable Earth system futures. We outline a research agenda, highlight emerging examples of this shift, and identify the coalitions and institutional changes needed to advance it. More inclusive scenarios and modeling tools are essential for foregrounding equitable solution pathways and informing decisions about collective futures.

INTRODUCTION

The 2025 International Court of Justice (ICJ) ruling has emphasized the interconnectedness between the climate and environmental crises—"an existential problem of planetary proportions that imperils all forms of life and the very health of our planet" (para. 456).[1] With the Paris Agreement's 1.5°C goal increasingly unlikely to be met and less than 4 years left to achieve the 2030 Sustainable Development Agenda, failure to offer comprehensive solutions toward preferable futures at the science-policy interface risks science becoming marginalized in decision-making. While recognizing the existential risks that climate change and biodiversity loss pose, these solutions must account for the interconnected nature of climate and biodiversity challenges within societies, where interventions will have telecoupled and sometimes cascading impacts and transformative actions will look different in different contexts.[2,3] At the same time, dominant foresight approaches risk focusing on singular worldviews and marginalizing different understandings of reality in terms of the past, present, and future.[4,5] This underscores the need for improved modes of engagement and knowledge co-creation in setting a solution agenda that is more inspiring and inclusive for all involved.[6,7]

Many sustainability solutions are developed and tested within current global scenarios and models, but these largely reflect existing social structures and institutions, including fossil-fuel-dependent economic systems and growth-oriented paradigms.[8] As a result, current scenario frameworks often explore transitions within, rather than beyond, current dominant system configurations, which can lead to internal inconsistencies, for example, when trying to eliminate fossil fuels without breaking these same social structures and institutions and their underlying logics of extractivism. Disrupting these logics and imagining new ones is the starting point for developing new narratives and pathways toward preferable futures.[9] Scenarios and models are needed that illustrate transformed socioeconomic, political, and cultural systems—and their associated values and institutions—that enable pathways within a safe and just space. Gupta et al.[10] describe this in terms of avoiding 1.5°C overshoot and returning toward 1°C, meeting global biodiversity targets, minimizing human and nature's exposure to significant harm from Earth system change, and ensuring human needs are met equitably through Agenda 2030.

We draw on our diverse expertise and a review of the literature to highlight four critical gaps that the global scenario and modeling scientific communities need to address:

(1) Limited exploration of truly transformative pathways to achieve interconnected climate, biodiversity, and equity goals;
(2) Insufficient representation of transformations in underlying paradigms, values, institutions, and theories required to get onto "safe" and "just" trajectories;
(3) Inadequate treatment of how alternative transformation pathways might impact the diverse things society values—e.g., human rights, equity, conservation, or economic prosperity—thereby making trade-offs and co-benefits visible; and
(4) Underdeveloped methods for engaging with alternative futures in ways that are socially resonant and inclusive, including through new forms of knowledge co-creation, the arts, media, and design.

Addressing these four challenging tasks demands a fundamental reconfiguration of scenario and model development—centering justice and the inclusion of marginalized voices rather than treating them as afterthoughts.[11] Incremental extensions of existing frameworks are unlikely to capture the scale and nature of transformations required to address the underlying causes of biodiversity loss.[12] This urgency is underscored by stark global inequalities of the status quo[13–15]; the richest 20% of nations (15% of the global population) contribute to more than 40% of annual ecological overshoot, while the poorest 40% of countries (42% of the global population) face more than 60% of the social shortfall.[16] Climate and inequality research further highlights the uneven distribution of mitigation and impact burdens within and between countries (inter- and intragenerational inequalities).[17,18] These patterns point to the need for systemic transformations that integrate ecological integrity with distributive justice, including shifts toward regenerative practices and more equitable economic arrangements.

Here, we set out a research agenda to develop a more diverse, inclusive, and aspirational set of scenarios and pathways that demonstrate transformative options for the world. Current trends reaffirm the case for a complete reorientation toward regenerative practices and redistributive economic activities within and between nations that prioritize human needs and planetary integrity over growth,[16] recognize historical injustices and climate (and nature) coloniality,[19,20] and center the need for rebuilding trust and environmental justice.[21,22] This requires an ambitious collective effort that, to date, has only partially been mobilized in ad hoc ways to address specific questions, often at a regional scale, by science that largely remains based in and funded by the Global North.[23] Research needs a concerted effort to incorporate participatory approaches, including storylines and narratives that are co-developed with diverse stakeholders and, in particular, holders of Indigenous and local knowledge, to address historical injustices whilst paying special attention to the inclusion of marginalized voices in society as well as incorporating a broader set of modeling techniques, especially in cases of data scarcity.[24] While we focus on the failure to envision more transformative desired futures, we do acknowledge that thinking about the futures that we want to avoid can also be useful and powerful. There is a valid critique that we may be too sanguine in our counterfactual scenarios, where we do not fully appreciate the negative consequences and repercussions of the status quo or the surprises they may bring.[25,26]

We do not conclude with a "model of everything" but instead offer a suite of complementary approaches that embrace

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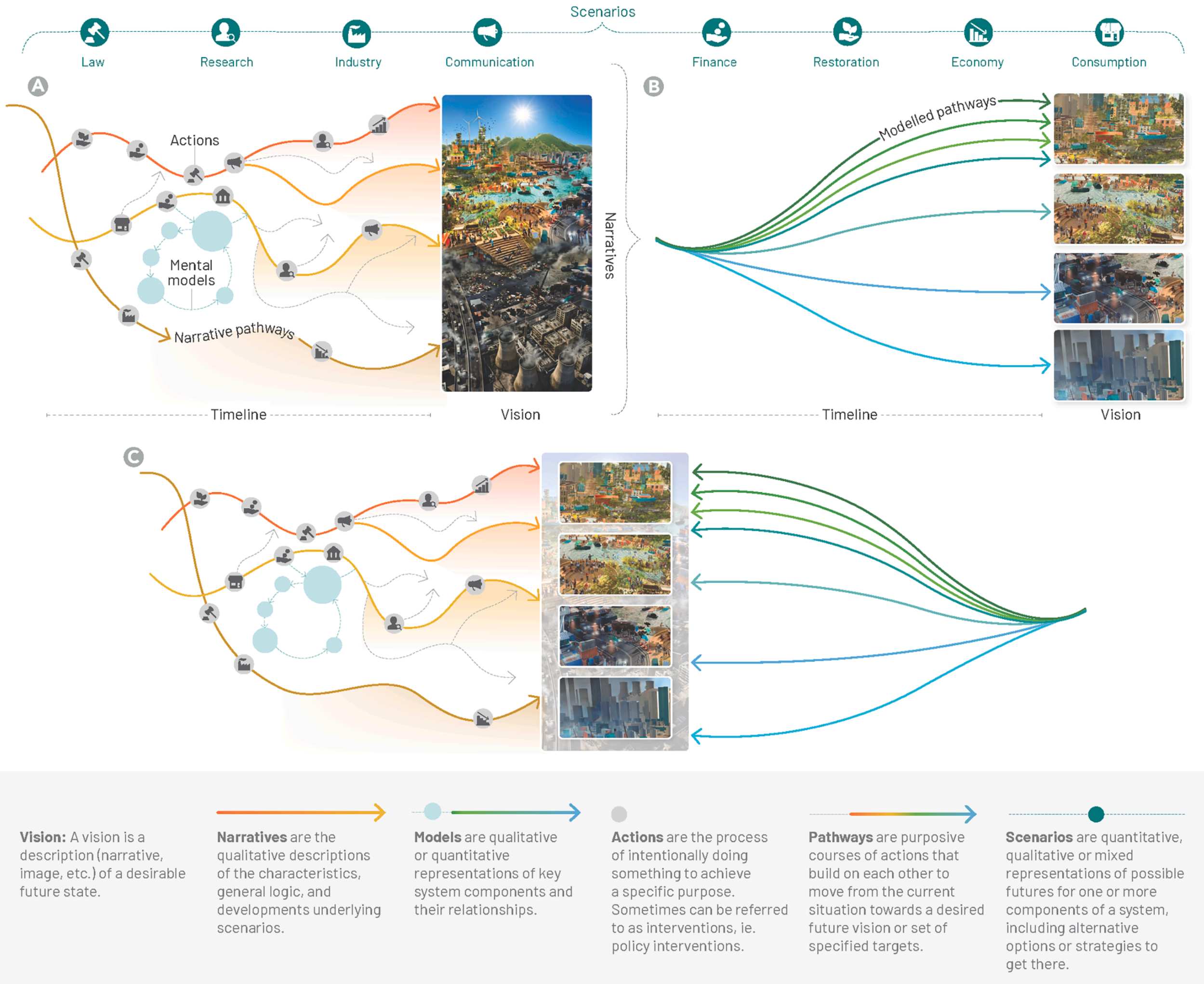


Figure 1. Conceptual representation of the architecture of models and scenario terminology

This figure illustrates the relationships and overlaps between models, scenarios, and visions across qualitative (A) and quantitative (B) approaches and how they can be used complementarily (C), where qualitative narratives can provide a rich picture of potential futures and model outputs can bring greater clarity to what these futures entail, including seeing what is more or less feasible.

complexity and diversity and can deal with the radical reconfigurations that might be necessary to achieve interconnected goals. We outline examples of where some of this work is already starting to happen, offering building blocks for how this larger agenda might be achieved and what some key next steps would be, such as novel scenarios and new modeling configurations. Ultimately, science needs to start engaging with the complexity of transformative change if it is to provide actionable outputs for decision-making toward a more sustainable and equitable future.

CONTEXTUALIZING SCENARIOS AND MODELS

Scenarios and models are often used interchangeably, yet their definitions can be unclear. Here, we define them explicitly and visually represent them in Figure 1.

- Models are qualitative or quantitative representations of key system components and their relationships.
- Scenarios are quantitative, qualitative, or mixed representations of possible futures for one or more components of a system, including alternative options or strategies to get there.[27]
- Narratives (or storylines) are the qualitative descriptions of the characteristics, general logic, and developments underlying scenarios.
- Pathways are purposive courses of action that build on each other to move from the current situation toward a desired future vision or set of specified targets.[28–30]

Current approaches to these challenges remain sectorally and disciplinarily siloed, which constrains progress toward a shared agenda.[31] The climate community's shared socioeconomic pathway-representative concentration pathway (SSP-RCP) framework has organized modelers to explore possible climate futures based on adaptation and mitigation challenges.[32] The

Table 1. Description of main modeling approaches

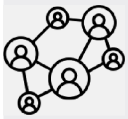
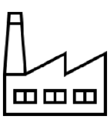
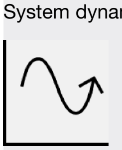
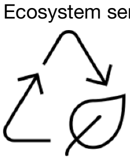
Model type	Description	Model count
Integrated assessment models (IAMs) 	Integrated assessment models are representations of complex physical and social systems, focusing on the interaction between economy, society, and the environment; the two main types are comprehensive or detailed process IAMs and cost-benefit IAMs.	27
Earth system models (ESMs) 	ESMs are climate models that incorporate biogeochemical and biophysical processes and cycles to evaluate the relationship between (primarily) emissions and climate change.	30
Computable general equilibrium (CGE) 	CGE models are macroeconomic simulations that employ mathematical equations to describe the whole economy and its interactions.	32
Sector 	These types of models tend to focus on agricultural production or energy systems modeling to give detailed sectoral representation (e.g., via partial equilibrium, gridded economic model approaches, and linear programming optimization).	19
Land-use change (LUC) 	LUC models reproduce the dynamics and spatial patterns of how land is used; they sit at an intermediate scale between (generally) fairly coarse global land-use change modeling of IAM and CGE models and the fine spatial resolution required by ecosystem services and biodiversity models.	15
Dynamic global vegetation model (DGVM) and crop models 	DGVM and crop models simulate the biosphere-climate dynamics between climate change, nutrient, water and carbon cycles and vegetation (crops and other vegetation types).	15
System dynamics 	Simulation modeling using differential equations to quantify complex feedbacks, stocks, and flows in system interactions over time.	11
Ecosystem services (ES) and biodiversity 	Ecosystem services models quantify, map, and economically value ecosystem services; these are distinct from ecosystem modeling, which represents a diverse set of approaches (see Geary et al.[45]) and were not explicitly considered here. Biodiversity models (e.g., macroecological and species distribution) are used to assess how environmental factors shape biodiversity and its different elements.	10

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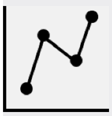
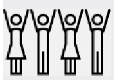
Table 1. *Continued*

Model type	Description	Model count
Econometric 	sSatistical modeling to approximate relationships between economic variables; used in some IAMs and sector models.	7
Input-output (IO) 	Macroeconomic approach to link and understand the interdependencies between different sectors of the economy, with extensions for environmental indicators.	6
Agent-based modeling (ABM) 	Simulation models of heterogeneous agents that interact with each other and their environment under a set of rules/goals with individual micro-level behavior and decision-making that results in emergent macro level outcomes.	4

This table describes the various types of models and how many of each kind were included in the analysis.

biodiversity community, through IPBES, identified the need for nature-centered, multi-level scenarios considering diverse worldviews,[33,34] leading to the Nature Futures Framework (NFF)[24] with methodological approaches for further applications.[35] Alternative economic frameworks, such as ecological economics,[36] Doughnut economics,[37] and post-growth economics,[38] provide novel economic framings that emphasize equity rather than centering economic growth. However, in isolation, these frameworks cannot provide the integrated guidance decision-makers need for transformative change, and moreover, radical post- and degrowth policy proposals are underrepresented in modeling.[39] Recognizing that transformations are inherently uncertain, sustainability frameworks must be able to identify the assumptions and uncertainties in scenarios and models to effectively support decision-making.[40]

Model synthesis

An important contextual starting point is understanding the current modeling approaches and outputs that have attempted to provide guidance for decision-making toward sustainability objectives. To this end, we mapped 197 models (see Table S1 for details) across different disciplines and methodological approaches to capture the current breadth of futures-related modeling. The mapping drew on recent reviews of food system transformation modeling,[41] macroeconomic modeling of energy systems and industrial transformation,[42] earth-economy modeling,[43] and modeling of environmental limits and social outcomes.[44] This was complemented by searching models listed with the Integrated Assessment Modeling Consortium (IAMC), IPCC AR6 WGI and WGIII Annex models (IPCC Annex II), and author knowledge of specific models not captured by the above but deemed relevant. The model name, main reference publication (given by the review articles examined and in IPCC Annexes), and modeling type were recorded.

Table 1 presents a synopsis of some of the key modeling approaches in coupled human and environmental systems. Table 2 gives examples of models under each approach, outlining their core features, what they primarily do, and some important assumptions they make. The categorizations and distinctions between modeling approaches are based on recent review papers.[41–44] We recognize this exercise is inexact, with overlapping and blurred boundaries between different types of models, but it is nonetheless a useful starting point. The generalities we report here cannot, and are not intended to, capture the heterogeneity of capability across the 197 models that were mapped. For example, integrated assessment models (IAMs) represent a highly diverse set of models that have tended to dominate discussions of scenarios and policy analysis of integrated climate and economy modeling.[43] Conventionally, IAMs have operated at fairly coarse spatial resolution, but some modeling frameworks have land-use modules with fine spatial scale (e.g., IMAGE, MESSAGE-GLOBIOM, and REMIND-MAgPIE). As some of these comprehensive IAMs now have the same submodels as some Earth system models (ESMs), it is no longer a matter of spatial resolution but rather how they represent systems or processes that is the defining characteristic.

Figure 2 gives a conceptual representation of the 11 main modeling approaches used in futures and scenario research. Model approaches are qualitatively positioned based on their orientation, with model types more commonly involved with IPCC processes and employing SSP scenarios positioned toward the center. The relative size of each model circle corresponds to the number of specific models found within the mapping exercise (given in Table S1). IAM, ESM, and computable general equilibrium (CGE) models account for around 50% of all models that were mapped (see Table S1) and collectively represent the core tools used in much conducted of the scenario research.

Limitations of current climate scenarios for modeling

The science of projecting climate and ecological outcomes has made substantial progress through increasingly comprehensive models, scenarios, and decision-support frameworks. Decision-making processes for achieving sustainable development globally and regionally increasingly have projections generated from them

Table. 2. Summary of main modeling approaches involved in futures-related modeling

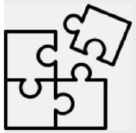
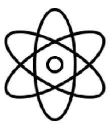
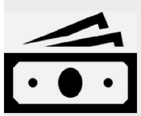
Main orientation	Type	Example models	Core features, areas of focus	Assumptions and limitations
Biophysical-socioeconomic 	IAM (integrated assessment model)	IMAGE, WITCH, REMIND-MAgPIE, MESSAGE-GLOBIOM, AIM, GCAM, DICE	• computational frameworks that couple human (e.g., land use, energy, and economics) and natural (water and climate) systems to varying degrees; often combine models of different orientations • numerical models that simulate system behavior under constraints (climate, environment, social costs, etc.) to find lowest cost solutions • extensive use in IPCC and climate policy • high spatial, social, and technological aggregation • tend to run over long time horizons (decadal +)	• different modeling methods: optimization, recursive dynamic, equilibrium, etc. • largely assume neoclassical economic behavior with representative agents, e.g., economic components typically assume perfect markets and foresight (i.e., if the model solves all years simultaneously, not if it runs year by year/recursive dynamics) • single representative economic rationalizing agent (i.e., profit/utility maximizing) by region/country • limited capacity to simulate non-linear behaviors
Biophysical-biogeochemical 	ESM (Earth system model)	CESM2, UKESM1-0-LL, GFDL-ESM4, E3SM-1-1	• process-based simulation of atmosphere-ocean-biosphere-cryosphere interactions; used for climate projections under emission scenarios • atmosphere, ocean, and biosphere are well represented, cryosphere is moderately well represented • generally used for analysis of monodirectional interaction between human activities as drivers of Earth system changes	• climate and biogeochemistry are governed by physical laws and observed processes (e.g., energy, mass, and momentum conservation) • incomplete representation of forcings and feedback involving the lithosphere (slow processes) and anthroposphere (contemporary processes), e.g., limited explicit socioeconomic feedback where human activities usually treated as exogenous forcings (emissions and land use (LU))
Socioeconomic 	CGE (computable general equilibrium)	ENVISAGE, EPPA, MAGNET, GTAP, AIM/Hub, GEM-E3	• represents the economy in an initial equilibrium condition, which is perturbed by the introduction of a "shock" (e.g., tax or climate policy), which then solves for a new general equilibrium (i.e., across all sectors and factor markets) • can be run for single years (e.g., comparative statics) or multiple years (recursive dynamics), where the solution for year 1 is that starting point for year 2 • data intensive requiring complete coverage of input-output relationships, technical coefficients, and trade flows • comprehensive economy-wide representation, capturing detailed sectoral and market disaggregation	• based on neoclassical economic theory that assumes perfect markets and information, with rational profit-maximizing firms and utility-maximizing consumers, where the model finds market prices where supply equals demand • the equilibrium focus limits dynamic transitions • CGEs do not generally assume perfect foresight—if run in recursive dynamics (solved 1 year after another), the models are myopic • preferences are static (e.g., consumer preferences) • key drivers of change (i.e., shocks) population growth, technological progress

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Table. *Continued*

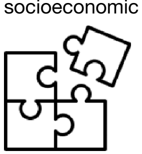
Main orientation	Type	Example models	Core features, areas of focus	Assumptions and limitations
			• can represent complex bilateral trade relationships • models markets in as monetary flows, which requires translation to natural units (e.g., kg)	(TFP), and consumer preference shifts are treated as exogenous inputs
Biophysical 	LUC (land-use change)	CLUE-S, DynaCLUE, SEALS, Dinamica	• downscale aggregated land-use projections (e.g., from IAMs) to finer spatial resolutions • can translate changes in economic models (e.g., CGEs) to land-use change • when paired with economic models, can assess key factors driving land-use change • high-resolution spatial and temporal data required	• can sometimes incorporate a range of biophysical assumptions on vegetation growth and ecosystem functioning based on observed data and biophysical theories • assumptions on land-use transition matrices determine the feasibility of converting between land-use categories • often lack integration of multiple drivers or social processes • if they include behavioral assumptions, then they tend to optimize land-use around cost-minimizing or profit-maximizing assumptions
Biophysical 	DGVM and crop models	EPIC, ORCHIDEE, LPJml, LPJ-GUESS, JULES	• typically process-based vegetation and crop growth modeling sensitive to climate variables; can assess impacts on yields and carbon cycles • can have high spatial resolution (e.g., km or farm scale)—often also point/plot models • challenges to represent extreme events • representation is most advanced for major crop commodities and a number of plant-functional types	• limited to no behavioral components; farmer actions are treated as exogenous inputs to biophysical modeling • calibrated to historical data, therefore sensitivity to changes in biophysical conditions on plant growth (e.g., CO_2 fertilization) is based on observed data • challenges with representing extreme events and novel climates
Biophysical-socioeconomic 	sector/partial equilibrium	GLOBIOM, MAgPIE, IMPACT, GENeSYS-MOD, PLUM, DIVERSE	• detailed supply-side representation (e.g., agricultural productivity and energy technologies) • simulates markets in natural units, facilitating coupling with biophysical models (e.g., crop and land-use models)	• based on neoclassical economic theory assumes perfect markets and information, with rational profit-maximizing producers and utility-maximizing consumers, where the model finds market prices where supply equals demand • partial equilibrium models omit interaction and limit feedbacks with broader economy

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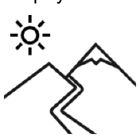
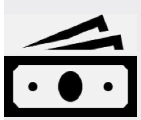
Table. ***Continued***

Main orientation	Type	Example models	Core features, areas of focus	Assumptions and limitations
				● often cost optimizing without social or behavioral dynamics, i.e., preferences are static (e.g., consumer preferences) ● key drivers of change (i.e., shocks) population growth, technological progress , and consumer preference shifts are treated as exogenous inputs
System behavior 	system dynamics (SD)	Eurogreen, iSDG, MEDEAS, IFs	● stock-and-flow representations capturing feedbacks, delays, and non-linearities in social-ecological systems ● can capture non-linear interactions but requires deliberate structural choices, as default is often smooth response functions	● no assumption of equilibrium or optimization—less standardized than IAMs ● highly sensitive to model structure and parameterization: model design determines which feedback loops are the driving mechanism(s) of system change ● difficult to capture full causal loop and define the scope of what is included (i.e., what feedbacks are omitted) ● in general, either detailed single country parametrization or highly aggregated global scale; lack of detailed multi-region multi-sector SD modeling ● validated over historical data, can lead to unexpected shifts if subjected to novel conditions (i.e., scenarios), as they are particularly sensitive to choices in which causal loops are involved
Biophysical 	ecosystem services and biodiversity	GLOBIO-Biodiv, PREDICTS, InVEST, BOATS, DPBM, FEISTY, EcoOcean Ecopath with Ecosim, Ecospace, OSMOSE, MICE, DBEM	● ranging from local, to regional, to global scales ● calibrated and parameterized using scientific survey data and/or section-specific statistics ● can capture context-specific factors ● often parameterized via systematic literature review and expert elicitation	ecosystem services: ● assumption of (or heavy emphasis on) instrumental economic value paradigm (i.e., monetizing ecosystem and biodiversity) biodiversity: ● assumption that calibration parameters from field-based studies can be used in other contexts ● data limitations from costly fieldwork measurement requirements ● often highly spatially specific
Socioeconomic 	econometric	E3MG, NEMESIS, MFMod	● used to forecast (predict) future changes (e.g., in response to policies) based on historically observed relationships between variables ● better for shorter time horizons, where there is a relevant historical domain of data	● general assumption of linearity and normality ● static coefficients that do not capture dynamic feedbacks

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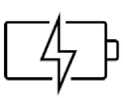
Main orientation	Type	Example models	Core features, areas of focus	Assumptions and limitations
Socioeconomic-biophysical 	input-output (IO)	EORA-based, EXIOBASE, DEFINE, MRIO	● represent interindustry flows across regions/sectors with environmental extensions tracking emissions and resource use ● comprehensive detailed internally consistent interactions between different economic sectors ● can be "environmentally extended" to include diverse impact categories	● assume homogeneous products (goods and services) and static price structures ● assumption of static technical coefficients (i.e., production and input use scales linearly)
Systems behavior 	agent-based modeling (ABM)	CRAFTY, DSK, MUSE, SMILI, SmallTrade, POSEIDON	● seeks to capture emergent behavior of a systems(s) ● can incorporate heterogeneous agents/actors with diverse goals and realistic behaviors ● usually highly specific and difficult to generalize	● modelers determine what the agents are (e.g., firms, governments, consumers, etc.) ● agent and boundary definitions determine cross-scale interactions that drive model results ● agent behavior defined by simple rules that are inferred from observed data, as opposed to optimization ● agents are bounded rational agents and tend to be assumed to follow general rules based on social science theory (e.g., satisficing, imitation, learning, etc.) ● challenges with calibration and validation
Social-metabolic 	world Earth model	copan:CORE	● a kind of Earth system model but with a socio-metabolic component that allows it to function more like an IAM	● a key difference from global system dynamics models is that its "Earth" representation is pretty much an emulator of biophysical Earth system models

This table outlines in detail the main modeling approaches used in futures research with some key examples, outlines their core features and areas of focus, and discusses their main assumptions and limitations.

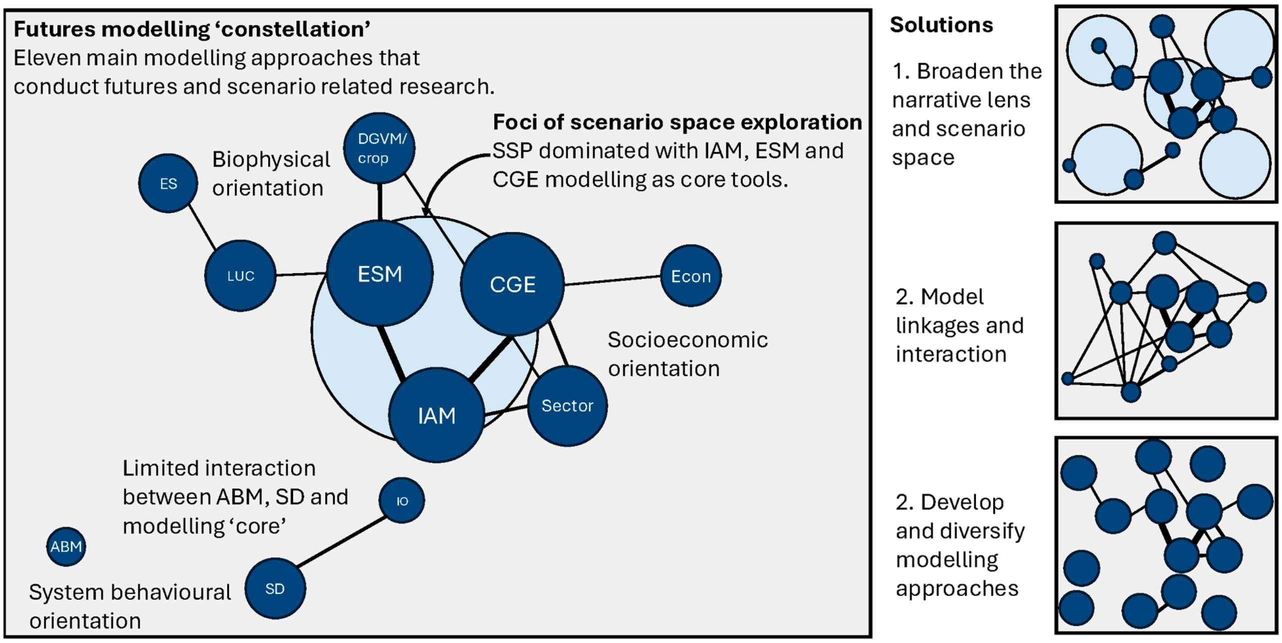


Figure 2. Main approaches employed in futures- and scenario-related research
This is a conceptual representation of the main modeling approaches employed in futures- and scenario-related research and possible solutions to address the challenge of projecting futures for transformative change. The size of the circle is scaled to represent the number of individual models mapped in each model category (see the supplemental information for the full list and mapping). Lines between circles represent linkages (e.g., inputs) between model types, with line thickness indicating greater interaction. The categories are as follows: IAM, integrated assessment model; ESM, Earth-system model; CGE, computable general equilibrium; Sector, sectoral-focused models (e.g., agriculture and energy systems); LUC, land-use change model; DGVM/crop, dynamic global vegetation models/crop models; SD, systems dynamics; ES, ecosystem services and/or biodiversity models; Econ, econometric based; IO, input-output models; ABM, agent-based models.

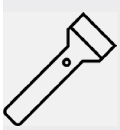
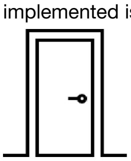
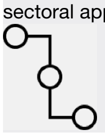
at their disposal. However, while these projections are invaluable for anticipating risks and guiding incremental climate interventions, they are often ill-equipped to inform or inspire transformative action. There is a fundamental disconnect between scenarios and models, which are driven largely by extrapolations from present trends and assumptions, and simulating transformative change, which is inherently disruptive and uncertain.[9,26] In these instances, methods such as visioning and backcasting are more appropriate and can also be applied in participatory ways, although methodological innovations are also required.[46]

The IAMs that have dominated discussions of climate scenarios and policy analysis rely on socioeconomic, technological, and biophysical assumptions to sketch future outcomes. These assumptions, embedded in emission scenarios and pathways since the inception of the IPCC, provide essential inputs for climate system models and ESMs while underpinning most biodiversity and land-use change modeling.[34] The most recent of these inputs, SSPs refer to five standard trajectories that represent possible ways that global society, demographics, and economics might change over the next century, focusing on the dual challenges of adaptation and mitigation.[32,47] See Note S1 for a brief history of climate scenarios. The SSPs brought coherence to IPCC AR6's literature but offered limited options for transformative change, with only one preferable "sustainability" pathway (SSP1) in which challenges to both adaptation and mitigation are overcome. Yet, these remain the primary global narratives through which most environment-related modeling is done. For instance, the Biodiversity and Ecosystem Services Simulation (BES-SIM) project that was conducted for the IPBES's first global assessment[48] had to rely on the SSP-RCP framework for modeling, despite findings that SSP1 was still not a "desirable" storyline for nature.[49]

The IAMs that are largely used to model the impacts of climate change have also been critiqued themselves.[50] Firstly, socioeconomic assumptions (for example, how the economy works, how trade clears in the market, or the relationship between economic growth and energy consumption) are "baked into" IAMs and have parameters or relationships that cannot be changed easily, thereby often precluding transformative economic and development trajectories. While there have been recent attempts to address these shortcomings (Table 3), it is nevertheless important to note some specific concerns.

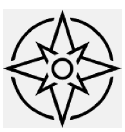
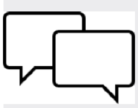
First, while IAM outputs can be used for some development indicators such as poverty rates or food security, they do not adequately represent crucial factors, including gender impacts, inequality, governance quality, conflict and security, and cultural values.[58] While not always feasible or desirable to incorporate all these factors into models, their absence means that these aspects can be left unaccounted for when model outputs are used for informing decision-making. Recent efforts to incorporate degrowth scenarios[96] and alternative economic frameworks represent progress but require further development to fully understand the implications of such transitions through improved economic modeling (Table 3). Recent advances in post-growth research focus on five core principles: well-being, sufficiency, reduced inequalities, repurposing of the economy, and north-south convergence, but

Table 3. How some limitations in IAMs have been addressed

Limitation	Area of focus	Selected references
There is a primary focus on growth-oriented economic models without sufficient attention given to alternative economic models like degrowth and post-growth[51,52] 	degrowth in Australia	Kikstra et al.,[53] Li et al.[54]
	degrowth in the food system	Bodirsky et al.[55]
	stronger interregional GDP convergence	Min et al.,[56] Soergel et al.[57]
The inclusion of diverse governance mechanisms as well as different policy options and their implications is not well captured in scenarios[58] 	ambitious policy to reduce CDR	Edelenbosch et al.,[59] Fuhrman et al.,[60] van Vuuren et al.[61]
	costs and benefits of limiting overshoot	Riahi et al.[62]
	governance and fairness of CDR	Gidden et al.[63]
Foregrounding fairness and the implications of what a fair allocation of burdens is has not been fully explored, and this can sometimes lead to an over-reliance on CDR for mitigation rather than interventions to reduce carbon emissions now[64,65] 	demand-side mitigation: avoid, shift, improve	Creutzig et al.,[66] Grubler et al.,[67] van Heerden et al.[68]
	efforts to explore the demand focused narratives, where access to core services rather than GDP growth is the core objective	Grubler et al.,[67] Doelman et al.[69]
	demand-side solutions, changes in consumption patterns, as well as technological innovation	Edelenbosch et al.,[59] van van Heerden et al.[61]
Institutional constraints and the feasibility of how certain interventions can be implemented is not well covered[70] 	feasibility constraints and institutional factors	Bertram et al.[71]
A “nexus” approach that looks at integration across sectors in a multi-sectoral approach is missing[72] 	integration of impacts and food, water, and biodiversity dimensions of SDG	Doelman et al.,[69] Schmidt Tagomori et al.,[73] Vinca et al.[74]
	food systems approach	Bodirsky et al.,[75] Fujimori et al.[76]
	food, water, and land interconnections	Fuhrman et al.[77]

(*Continued on next page*)

Table 3. *Continued*

Limitation	Area of focus	Selected references
Centering all forms of justice and the implications of an equity approach to solutions is not well documented[78–80] 	extension of pathways with quantification of fair finance transfers	Pachauri et al.[81]
	fairness, justice, and access to services	Zimm et al.,[82] Dekker et al.,[83] Emmerling et al.,[84,85] Kikstra et al.[86]
	differentiated responsibilities	Motlaghzadeh et al.[87]
	financial transfers and differentiated carbon pricing	Bauer et al.[88]
The needs for development and diverse geopolitical configurations are not well accounted for[89] 	inclusion of trade and geopolitics	Daioglou et al.,[90] Mandley et al.,[91] Mercure et al.[92]
The inclusion of non-scientific ways of knowing and more participatory processes prior to scenario explorations is a methodological gap[93] 	starting with participatory, qualitative scenarios across global regions before translation into simulation modeling; combining modeling and artistic practices	Muiderman et al.,[93] van Beek et al.,[94] Vervoort and Gupta,[52] Vervoort[95]

This table highlights some of the main critiques of IAMs in the literature and how these limitations have been addressed with reference to some examples.

note that existing post-growth scenarios tend to fall short of considering, let alone implementing, these key elements, and it is evident that advances in post-growth research, alongside international calls for mitigation rooted in fairness and equity, make a strong case for a holistic development of post-growth scenarios.[97]

Second, most 1.5°C scenarios rely heavily on negative emissions technologies, particularly bioenergy with carbon capture and storage (BECCS), despite significant uncertainties about their feasibility and impacts.[98,99] Although some of these concerns have started to be addressed,[62,100] the impacts of these technologies on, for example, biodiversity make their deployment difficult to reconcile with the other planetary boundaries.[101,102] The IPCC AR6 WGIII report has two clusters of scenarios of how to achieve 1.5°C, one without or limited overshoot (C1 scenarios) and one with high overshoot (C2 scenarios), and a rapid return that relies significantly on carbon dioxide removal (CDR) at unprecedented scales in order to sequester the residual emissions.[103] While IAM scenarios stress the need for overall decarbonization, technological dependence on CDR may create a perverse incentive to delay emission cuts while risking biodiversity loss, food security, and human rights.[104,105] The low energy demand (LED) scenario stands out as the only IAM pathway that achieves 1.5°C without geological carbon storage, demonstrating the possibility of alternative approaches through demand-side solutions.[67] The scenario shows how highly efficient systems of service provision can enable an increasing convergence of living standards between the Global North and Global South, reducing global development inequalities, despite rises in population, income, and activity. An innovation in the LED scenario is that it focuses on demand-side solutions (impacts of digitalization, sharing economy, and behavioral change) rather than supply-side technological fixes, which have been developed and expanded further in the next section. However, all these assumptions should be treated with caution because the assumptions of demand-side changes may be as implausibly optimistic as those driven by technological optimism.

Assumptions such as those around CDR and BECCS that are baked into many scenarios, combined with unaccounted trade-offs between climate solutions and other priorities such as development, food security, and biodiversity protection, can enable arguments for delayed fossil fuel phaseout[8,64,106] and emphasize potentially harmful, inequitable, and unjust interventions to achieve climate goals at the expense of people and biodiversity.[65,78,107,108] This is problematic because it can send a signal not to change societal reliance on fossil fuels and allows for the option of continuing to delay a transition, despite the fact that

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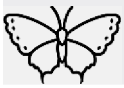
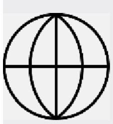
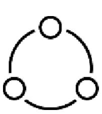
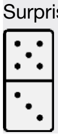
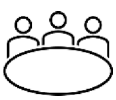
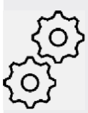
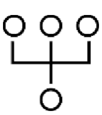
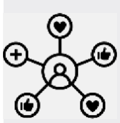
Table 4. Remaining gaps in scenarios and models

Thematic area	Selected references
Positive outcomes for biodiversity 	Kim et al.,[154] Kok et al.,[114] Pereira et al.,[49] Rosa et al.[34]
Diverse knowledge systems—including Indigenous knowledge—and epistemic justice 	Cheok et al.,[155] Chibwe et al.,[156] Milanez et al.,[157] Terry et al.[5]
Integrated marine-terrestrial systems 	Chaplin-Kramer et al.[158]
Diverse forms of justice 	Keys et al.,[79] Zimm et al.,[82] Venier-Cambron et al.[80]
Socioeconomic development and diverse geopolitics 	Moyer[89]
Alternative economic paradigms including post-growth and non-capitalist economies 	Hickel et al.,[51] Moranta et al.,[130] Vervoort and Gupta[52]
Making space for ecocentrism and other alternative framings of human-nature relationships, including relational values 	Borg and Skelton,[113] Chan et al.,[159] Pereira et al.[24]
Overshoot and return 	Allen et al.[131]
Surprise, tipping points, and cascading failures 	Clark-Wolf et al.,[152] Pereira et al.,[26] Puma et al.,[160] Richardson et al.[161]

(*Continued on next page*)

Table 4. *Continued*

Thematic area	Selected references
Climate mitigation and adaptation, including "maladaptation" and the limits to adaptation 	Dow et al.,[162] Pirani et al.,[163] Schipper[164]
Inequality, governance quality, conflict and security, and cultural values 	McElwee[64]
Inclusion and participation as an underpinning methodology 	IPBES,[165] Pereira et al.[24]
Improving diverse forms of innovation 	Herrero et al.,[166] Mason-D'Croz et al.[167]
Norms and plural preferences 	Bechthold et al.[168]
Grounding in diverse, interdisciplinary theories of societal transformation, transformation research and sociology 	Rutting et al.,[169]

This table outlines the remaining modeling gaps as outlined in the literature.

CCS/CDR technologies are not in place at scale and that natural carbon sinks are either uncertain or diminishing in capacity.[109] The UNFCCC COP28 President's controversial claim about the lack of scientific support for phasing out fossil fuels to reach the 1.5°C Paris target highlighted this critical issue in climate science communication,[110] which has continued to surface in negotiations at COP29 and COP30. Studies show that institutional constraints, which are often not accounted for in scenarios, are key drivers of feasibility concerns and that there are clear intertemporal trade-offs: early mitigation is more disruptive but prevents higher and persistent feasibility concerns produced by postponed mitigation actions later in the century.[70] Finally, a lack of alternative options opens the door for some advocates of climate engineering and "techno-fix" solutions such as solar radiation management to argue that these need to be researched, as they will be the only way to address the long-term impacts on Earth's systems from the lag effect in the climate,[111] despite their huge uncertainties and the potential for catastrophic unintended consequences.[112]

Evolution of current climate scenarios and models

Significant efforts have been made to use and expand the SSP-RCP matrix to explore broader scenarios and model configurations using IAMs and other models in order to overcome these shortcomings (Table 3), although some fundamental constraints remain.[113] Improvements have included efforts to elucidate the role of coupling IAMs with more detailed sectoral and spatial models, or impact indicators[114,115] and complementing scenario analysis with qualitative methods.[70,71,116] There have been updates to the SSPs to make them more relevant to different contexts, for example, a set of regional European SSPs[117] and local SSP extensions.[118–120] A recent paper outlines a new set of

SSPs in Europe that extends current narratives to capture interlinkages between climate and biodiversity across multiple sectors spanning energy, food, health, water, and transport.[121] IAMs were used in the co-created "sustainable development pathways" (SDPs), a set of three scenarios, each presenting alternative narratives and worldviews that lead toward achieving multiple sustainable development goals.[57,122] These narratives covered techno- and market optimism, post-growth sufficiency, and institutionalism. In these scenarios, IAMs were not used as exploratory devices, and the economic "driver" of the models was downplayed, with the models instead driven by the provision of social and environmental services (decent living, access to food/energy/water, biodiversity conservation, etc.), presenting target-seeking scenarios. By presenting three alternative narratives and scenarios, all reaching similar endpoints concerning SDGs, the scenario set presents a broad range of possible solutions and the different synergies and trade-offs across human and environmental systems. In addition, the SSP Extensions Explorer collects quantifications of different indicators (e.g., inequality, human development index, migration, and employment).[123]

The development of adaptive emission pathways offers an approach for achieving temperature targets. As demonstrated by Terhaar et al.,[124] such pathways can adaptively adjust emission reductions every 5 years based on observed temperatures and forcings, providing a more robust way to reach climate goals under uncertainty. This approach mirrors the Paris Agreement's ratcheting mechanism and could help in updating nationally determined contributions (NDCs) and supporting legislation, strategies, and plans. The next generation of scenarios should continue to improve the representation of adaptation dynamics and capacities,[125] alongside improved integration across physical climate science, impacts, and socioeconomic dimensions.[126] The IAM community is working toward more systematic exploration of transition pathways and policy-relevant futures[127] while enhancing treatment of uncertainties and climate system feedback.[47,128]

These adjustments to modeling and the SSP-RCP scenario matrix account better for more diverse areas of interest—for instance, food system transformation pathways toward 1.5°C that have environmental and social improvements.[129] But the applicability of these IAMs and scenarios to unpack the transformations required for broader sustainability remains limited, as their underlying narratives are dominated by the original climate objective to demonstrate future responses to climate change mitigation and sometimes adaptation challenges. The SSP-RCP framework inadequately represents the diversity of potential sustainable trajectories and, in particular, fails to capture diverse political systems and the compounding impacts of growth-oriented economic models on people and nature.[51,130] Some of their embedded assumptions, such as a growth-oriented economic paradigm,[51] have also been critiqued for being overly narrow, even though degrowth model runs have now been accomplished. This becomes more challenging when attempting not only to model potential future warming based on a set of assumptions about how the world works now but also to target a specific endpoint and model how to get there, i.e., achieving 1.5°C. There is growing concern that an overshoot of 1.5°C is fast becoming inevitable in the near term, as well as concerns regarding the feasibility of bringing temperatures back down again through net-negative emissions[131] after what is expected to be several decades of overshoot above 1.5°C.[132,133] The gap that needs to be addressed is therefore less about continuous adjustments of existing models, but rather employing a variety of different methods and tools to develop new scenarios and narratives that can push the models into new territories, potentially even into an "unmodelable" place. From this, we can start to learn from the assumptions embedded in the storylines and constantly iterate in a more flexible manner that can allow for a broader range of topics, perspectives, and solutions to be unpacked, potentially including the development of new models as needed.

For instance, there is value in prioritizing participatory scenarios developed in local or regional contexts first and using this participatory work to frame simulation modeling work. In the Scenarios Project of the CGIAR Climate Change, Agriculture and Food Security (CCAFS) program, scenarios were developed together with stakeholders representing governments, civil society, business, and researchers across 7 global regions in the Global South.[134] These scenarios then formed the framing context for simulation modeling based on the SSPs and RCPs, in terms of regional politics, cultural pathways, socioeconomic development, and more.[135,136] The benefit of this approach is that the framing of "what should be considered" regarding the future comes from local and regional experts and perspectives first, before the involvement of simulation modeling. However, the connection to global models and to globally dominant foresight practices more generally still made it challenging to escape dominant conceptions of the future.[93,137] This led to experimentation with scenario development based on existing, radical "seed" practices that focused on breaking the power of current regimes,[138,139] a process that has been widely documented in other participatory scenario processes[140–144] but has not yet been linked to modelable outcomes. Such innovations demonstrate that while challenges remain, there are methodological responses available and that broader collaboration across disciplines is required to weave them together.

Beyond the axis of "top-down" or expert-led scenarios (such as the SSPs) versus "bottom-up" or participatory scenarios (such as CCAFS),[26] there have been explorations of what an integrative reflective practice between artists and modelers would look like[145] and how modeling and game design can be integrated to create more dialogue and engagement, even in complex phenomena such as tipping points.[94] Yet, overall, there remains much work to be done regarding the role that scenario modeling plays in societal future-making processes[146,147] and the way it can make collective sensemaking about the future less accessible and relatable, with abstract and technocratic, modernistic considerations dominating the analysis.[148] There is a need for much more plurality in terms of incorporating ways of knowing and in terms of the design of processes of science-society engagement.[149] This is even more critical in the context of scenarios and model outputs used for decision-making because the room for (deliberate) misinterpretation (as showcased during the COP28 negotiations) is clear.

GAPS TO ADDRESS

While the efforts outlined above have focused on addressing various critiques of IAMs and scenarios, important gaps remain

(Table 4). Even from the climate science perspective, better Earth system analysis is increasingly needed to explain and predict extreme events, such as the unprecedented heatwaves in 2023, which have highlighted gaps in our understanding of climate system responses.[150] The scientific community needs improved observational networks and data collection systems to validate, improve, and complement ESM predictions. This has become particularly evident as conventional models struggle to explain recent temperature anomalies and their underlying drivers. Furthermore, Earth system tipping points have the potential for disruptive and cascading negative impacts that could undermine the good intentions of environmental policy.[151] Anticipating these "surprise" events can build resilience into decision-making frameworks to achieve positive, transformative outcomes as well as avoid negative ones. While current investigations of tipping points in ESMs (e.g., via TIPMIP [Tipping Points Model Intercomparison Project] experiments) focus on a systematic assessment of likelihood and impacts for stylized forcing scenarios, future iterations should be guided by storylines that explore the impacts of lower probability but very high-risk tipping events.[152] Understanding the impact of these events across sectors and society will be required to mobilize governance arrangements to mitigate the most disastrous outcomes (or to leverage the potential for positive tipping points), an essential aspect for the governance of complex systems toward transformative change.[153]

A further gap in the holistic modeling of biodiversity and nature's contributions to people (NCPs) lies in bridging marine and terrestrial systems through integrated scenario analysis. While significant advances have been made in marine modeling, including atmosphere-ocean circulation, climate-ecosystem dynamics, and projections of fisheries and aquaculture futures[170–173]; these developments often remain siloed from terrestrial land-use and food system models. From the perspective of the food-climate-biodiversity nexus, this disconnection undermines our ability to assess trade-offs and synergies across domains that are tightly interlinked. For instance, marine aquaculture offers alternative pathways that could alleviate pressure on wild fish stocks; its potential demand for land-based inputs may exacerbate land-based agricultural expansion to meet food demand, drive biodiversity loss, and increase emissions. Yet, without linked modeling frameworks, such cross-realm interactions remain poorly captured. Closing this gap is essential to inform transformative solutions that advance integrated goals for climate mitigation, biodiversity conservation, and food security by showing multiple pathways to bend the curve for biodiversity and NCPs, recognizing the multiple values of nature.[114,174] Future biodiversity modeling must better integrate the ocean, economics, and other social-ecological systems to create truly comprehensive scenarios, as recommended by Chaplin-Kramer et al.[158]

It is clear that the role and potential of alternative economic paradigms, social organization, regulatory frameworks, and changing cultural and societal norms and values remain underexplored, lacking clear actionable advice and a full exploration of synergies, trade-offs, enabling conditions, and lock-ins. The existing scenario paradigm explores what is technically possible but not what is socially feasible or desirable and provides limited to no insight on the role, motivation, or deterrence of different actors or networks in the required transformation. Getting out of the cognitive lock-in of the present is a key aspect to overcome in the next generation of scenarios and models and is the starting point for addressing these gaps in a more holistic manner.

Getting out of locked-in narratives of the future

If scenarios are to help us break out of dominant narratives of the future and open up new pathways, there needs to be an awareness of what those dominant narratives are in the first place and what makes them dominant. The notion of "imaginaries"—images of the future that are collectively held, institutionally supported, and publicly performed[175]—is helpful for this. Technocratic imaginaries from the Global North, such as "sustainable development," have long been dominant in scenario development.[93] In recent years, antidemocratic and authoritarian imaginaries have gained power.[176] An analysis of how scenario processes succeed or fail to break out of these dominant imaginaries is valuable for making such processes more politically and societally reflexive.[137] As outlined above, global environmental decision-making has been a dominant approach of SSP-related storyline development that is modeled in IAMs to inform its deliberations. While significant strides have been made to make these more inclusive and to address many of their earlier limitations, the primary starting point of climate change makes it difficult to incorporate other issues of concern. There is much to be built on from the developments in degrowth modeling and the inclusion of the SDGs and geopolitics, but there remains room for improvement in developing scenarios using different methods (including participatory and arts-based methods) and in expanding the integration with other models.

Furthermore, the single "good road" pathway (SSP1 x RCP2.6) is, in many respects, no longer feasible and does not actually show us how to achieve a future that is both "safe" within biophysical limits and "just" in terms of minimizing harm while ensuring the needs of people and nature are met now and in the future. There is a growing body of literature on what transformations are needed to achieve a more equitable and sustainable future. These include addressing the underlying drivers of biodiversity loss: (1) the concentration of power and wealth, (2) the prioritization of short-term, individual, and material gains; and (3) the disconnection from and domination over nature and people.[12] However, we currently do not have any global scenarios and models that can deal with the transformative changes that societies need to address the climate-nature-equity polycrisis, i.e., that achieve the objectives of both the UNFCCC and CBD, as well as the SDGs, through a justice lens while highlighting non-linearities,[177] acknowledging trade-offs, and finding opportunities for co-benefits.[178] This will require addressing the gaps laid out in Table 4, as well as a more emergent collaboration to bring multiple schools of thought together (Figure 3). In particular, the inclusion of justice and equity concerns remains limited both in terms of global imaginaries and how those translate into scenarios, although there is a growing body of literature on transformation pathways,[9] the role of scientists in building scenarios that contribute to transformative change,[179] and diverse visions of alternative futures in the Anthropocene.[180]

Justice considerations present unique challenges for modeling efforts, particularly as there may not be agreement

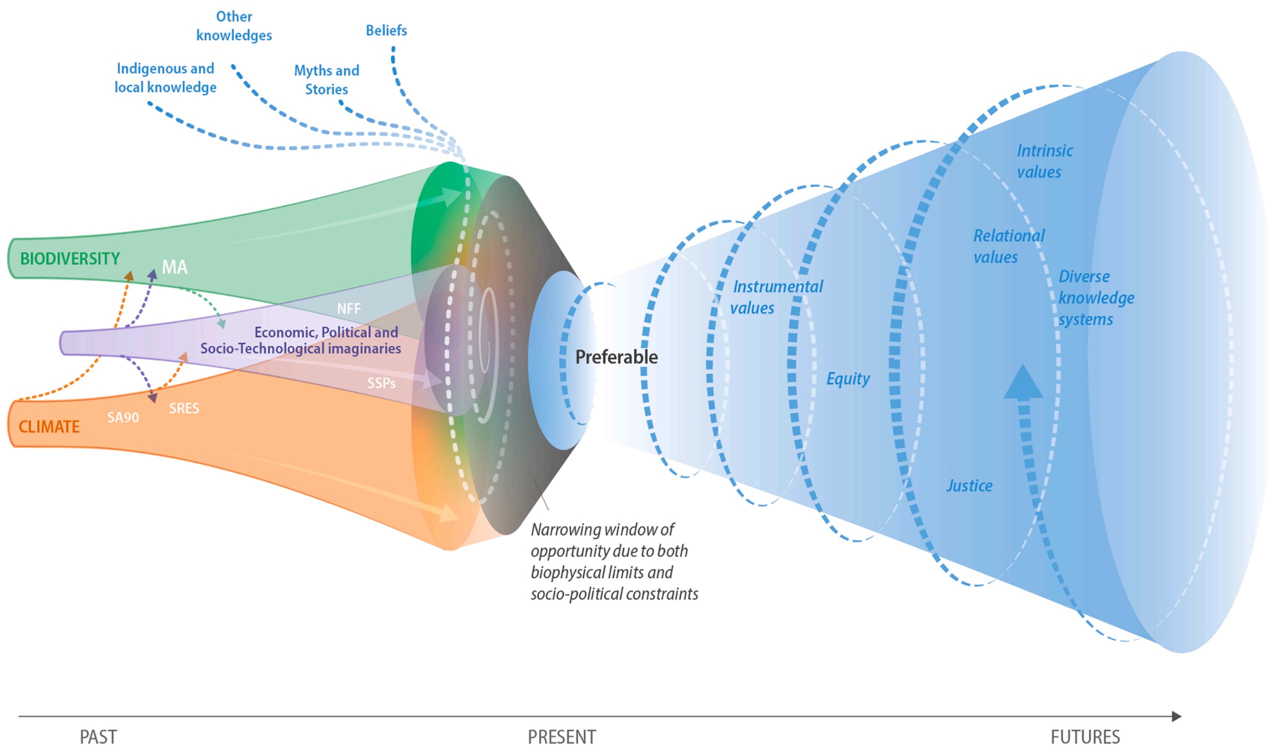


Figure 3. Futures cones representing diverse knowledge systems and disciplines
From left to right, futures cones inspired by Sardar and Sweeney,[25] representing the range of climate, biodiversity, and socioeconomic imaginaries expanding over time and starting to interconnect and influence each other. However, these tend to exclude other knowledge and belief systems that are important in imagining what transformative futures could look like. By coming together in the present, with a narrowing window of opportunity to act resulting from both biophysical constraints and socio-political and economic realities, these imaginaries must open up to embrace what transformative futures that meet climate, biodiversity, and equity needs could look like.

on which concept or theory of justice is being deployed[181]; thus, commitments to disclosure and clarity over normative assumptions are required.[182] Further, tensions between environmental sustainability goals and justice goals may arise; for example, the desire to extend improved mobility to underserved communities may conflict with sustainability if it prioritizes the use of private cars.[183] Further, across the three most cited dimensions of justice—distributional, recognitional, and procedural—there are additional definitional and technical challenges. Distributional justice concerns who benefits and who bears the costs from both climate impacts and policy responses.[184,185] Most people willingly sacrifice efficiency for fairness[186] and are more likely to accept climate policies they perceive as fair.[187] New economic approaches need to add these welfare-enhancing trade-offs. The integrated assessment modeling community is making concentrated efforts to explore justice considerations both conceptually[82,188] and through, for example, direct model implementation, such as differentiating responsibilities of states using an equity lens[87] while recognizing that models can only capture limited scopes of justice.[181]

While models can reveal regional or country-level trade-offs,[189] many winners and losers emerge at local levels,[190] requiring various solutions such as basic income provision.[191] Although IAMs struggle with procedural justice (i.e., ensuring affected parties participate in decision-making), they can help calculate fair investment flows for cost-effective mitigation and derive “fair-share” regional contributions, accounting for some elements of corrective justice,[81] albeit within limits given the need for aggregation.[192] Unequal consequences are amplified by unequal responsibilities, with those least responsible for environmental harm often most vulnerable to impacts. This limitation of models demands careful caveats about what they cannot represent, alongside complementary measures to recognize those bearing special burdens, including Indigenous peoples and future generations.[193,194] Various approaches have been proposed to improve intergenerational benefit distribution.[195,196]

Recognitional justice—acknowledging who is affected and how, particularly regarding cultural and social differences—connects to epistemic justice, which legitimizes diverse knowledge systems beyond science. While quantitative modeling cannot fully bridge these knowledge systems, scenario storylines can incorporate diverse worldviews, particularly through decolonizing practices of storyline creation.[5] The limitations of numerical representations for capturing human values and worldviews must be clearly acknowledged in model framing and interpretation. Procedural justice concerns who is included in processes of change, whether in model making, scenario building, or implementing new pathways and future trajectories. In this, the research community is making advances in more participatory scenario development and in the inclusion of Indigenous knowledge and futures thinking.[155,197–201]

Finally, intergenerational justice is a particular challenge to address yet crucially important as it relates to pathways, as burdens and benefits that are pushed off to future generations should be accounted for. Key factors to be included in IAMs to address these concerns have been identified by Jafino et al.[192] as (1) fair representation of future generations, (2) fair assessment of the distribution of impacts historically, (3) temporal dimensions to understand future benefits and burdens, (4) how policy lock-in may reduce future choices, and (5) exploration of plausible future value changes. Examples of how intergenerational justice concerns have been incorporated into scenarios and models include youth participation in scenario development,[202,203] thus also addressing procedural justice,[199,204] or the use of dynamic adaptive policy pathway (DAPP) approaches to evaluate and avoid policy lock-in.[205]

Across all concerns raised regarding justice, key solutions include greater incorporation of interpretive social sciences, a commitment by the research community to increase efforts toward holism, a stronger focus on descriptive narratives rather than quantitative aggregation, and heightened reflexivity regarding model inputs and outputs.[188,206] With the upcoming IPCC AR7 and IPBES's second global assessment, it is time for the scientific community to leverage existing work and bring the full diversity of their expertise to bear in developing more emergent processes to address this existential challenge of how to enable a more just and sustainable future for the planet. Therefore, we now lay out initial steps building on these existing indications of improvement.

APPROACHES TO TRANSFORMATIVE CLIMATE-NATURE-EQUITY SCENARIOS AND MODELING

As the previous sections outlined, a lot of progress has been achieved over recent years in enabling more integrated analysis of futures for climate, biodiversity, and society. However, the biggest gap remains in the silos within which researchers have been working—biodiversity and food system modelers incorporating new indicators and interventions, climate specialists and the IAM community working to address critiques of their new outputs, and participatory scenario experts innovating new methods for incorporating diverse perspectives and knowledge systems into storylines. There is still a disconnect between these processes and a true integration across expertise, especially as, over time, we have a narrower set of options for achieving preferable futures (Figure 3). The scientific consensus on urgent climate and biodiversity action requires "transformative change," but enabling such change remains our greatest challenge, as growing evidence shows that "business-as-usual" or status quo trends will largely miss global climate and biodiversity targets.[207] The scientific community can provide various scenarios of sustainable futures showing trade-offs and enabling conditions for decision-makers while emphasizing that multiple pathways exist to accommodate diverse perspectives and value systems.[208] This work can also help share and inspire more diverse imaginaries and discourses in our societies about how to move forward.[209] However, this plurality requires unprecedented collaboration across research communities to inspire more diverse societal discourses.

Moreover, it requires a different conceptualization of the role of science as simply providing knowledge for rational policymakers to use. The transformative impact of future visions occurs, in large part, because they offer support for truly inspiring narratives of the future, which are amplified by those who champion them: societal movements with clear messaging that speaks to and activates the values and concerns of diverse societal groups.[210,211] Scenarios alone cannot ensure such success—but they can contribute to it by connecting to alternative imaginaries of the future that hold the potential to activate and mobilize societies. The first task is to understand what these imaginaries and their underlying logics are.[137] The second task is to find ways to use simulation to investigate what is needed to achieve the change proposed as part of these imaginaries.

Existing scenarios and models are hamstrung by specific assumptions about what changes are "feasible" and how change happens. Creating a set of scenarios and models that demonstrate how climate change can be addressed in multiple ways (e.g., through reconfiguration of the economy and industries, redirecting finance, changing consumption patterns, appreciating diverse values, and improving energy efficiencies) is critical, in particular, taking into account other focus areas such as biodiversity, equity, and human well-being. While there has been movement on alternative economic scenarios, the ease of quantification makes these easier than some of the more relational and politically complex reconfigurations that might also be needed. For example, incorporating rights-of-nature legal frameworks, Indigenous ways of seeing and acting in the world, or even how time is dynamically conceptualized[5,212–215] needs to be done in the underlying scenario development process. At the same time, significant work remains to bridge gaps between different modeling communities, for example, between terrestrial and marine systems,[216] between climate and biodiversity modeling,[217] and between economic and biophysical domains. Some progress has already been made in this direction, for example, in using the HARMONEY model[218] and the FRIDA model.[219] In this section, we outline some of the cutting-edge research that could be leveraged and developed to address these gaps and build on the inroads that have already been made.

Nature and climate: Multi-target seeking scenarios and plurality

Integrating both mitigation and adaptation strategies, reflecting the complex interplay required to address climate change comprehensively, remains a challenge.[163] Scenarios that combine mitigation efforts—such as transitioning to renewable energy and reducing emissions—with adaptation actions, such as enhancing coastal defenses, promoting climate-resilient agriculture, and preparing communities for extreme weather events, offer a more realistic framework for planning, especially in the context of making progress toward the global goal on adaptation in the Paris Agreement. In these scenarios, it is also critical to include the "limits to adaptation" and "maladaptation."[162,164]

Integrated scenarios can provide policymakers with a clearer understanding of the synergies and trade-offs involved in simultaneous mitigation and adaptation efforts, thereby helping to prioritize actions that yield both immediate resilience benefits and long-term emission reductions. Developing these dual-focused scenarios is essential for creating policies that address not only the root causes of climate change but also the urgent need to protect vulnerable systems and communities from ongoing climate impacts. Innovative approaches for integrating adaptation in management plans by examining how climate-related changes might affect local ecosystems and livelihoods are emerging, e.g., in future-proofing conservation[220] and scenario-based decision analysis.[221] Similarly, scenarios modeling nature's contributions to adaptation can help decision planners to quantify biophysical and social-ecological processes that contribute to future climate change adaptation services.[222] While climate adaptation frameworks and methodologies have proliferated, significant challenges remain in reconciling place-based adaptation pathways with global scenarios.[223] A frontier challenge lies in reconciling the scales of largely place-based adaptation pathways with global social, economic, ecological, and climatological scenarios.

There is a growing body of integrated scenario narratives that center nature and climate but in the context of diverse societal aspirations. The first step in this was the development of the NFF under the IPBES Task Force on scenarios and models that sought to shift away from climate-focused storylines to incorporate diverse relationships with nature.[24] From this process emerged six illustrative scenarios that provide a foundation for integrating biodiversity and climate considerations.[224] These scenarios, while not yet fully quantified, offer guiding principles for modeling that go beyond traditional approaches. Initial modeling efforts that apply NFF assumptions to land-use change in Europe have demonstrated better outcomes than those from SSP1, particularly in balancing material and non-material ecosystem services and NCPs.[225] Similar results emerged from global analyses, which revealed that SSP scenarios systematically favor material ecosystem services over relational and intrinsic nature values.[226]

A key benefit of the NFF is that it addresses issues of operating across multiple scales and can be used in participatory processes that foreground diverse knowledge systems, for example, by weaving Indigenous and local knowledge with values-based consideration of conservation options in the context of climate change[227,228] as well as looking at how finance connects to nature. There are a growing number of case studies using the NFF across different ecosystems from coral reefs[229] to urban systems[230] and across scales from the Dutch dunes[140] to Europe[231,232] and the high seas.[143] In some cases, the NFF has been useful in incorporating Indigenous knowledge systems into futures outputs[201] and has been crafted into speculative fiction stories.[233–236] Another example is of work that aims to initiate a conversation between science and literature through situating, relating, and comparing contemporary climate change fiction, for example, to the five SSPs[237] and in the form of climate fiction.[238,239]

Weaving these place-based aspirations into global narratives supports adaptive pathway frameworks that can better account for local contexts while maintaining global consistency. While still a work in progress, the next critical step is in translating these narratives into scenarios that can be operationalized in models for the next round of simulations for upcoming assessments under the BES-SIM2 program. From the climate change perspective, there is recognition of the need for more inclusive narratives,[240] and ongoing work on scenario frameworks[163] is working to address these challenges through improved integration across domains and scales while maintaining policy relevance. Finally, a new set of sustainability pathways for the oceans has also been developed,[241] the ocean sustainable pathways (OSPs), drawing from the SSPs but also expanding to include the NFF. The EU-funded INSPIRI project takes this a step further by combining a participatory NFF visioning process with a range of modeling techniques (including using OSMOSE, Ecopath with Ecosim, and agent-based models) for the Mediterranean, Baltic, and Atlantic basins. These could provide the first stepping stones toward more integrated marine-terrestrial modeling.

Examples of combined multi-target scenarios, multi-scale modeling, and participatory processes

The following examples highlight how it is possible to model multiple targets based on inclusive processes. Starting with the development of the NFF framework that allows for consistent scenario development but across multiple scales and valuing diverse perspectives and aspirations, through projects such as BIONEXT and FABLE (food, agriculture, biodiversity, land, and energy project) that have adaptive models that can account for the diverse requirements of these participatory processes and the various interventions that they suggest. These examples showcase what is possible when nature and climate targets are combined with diverse stakeholder engagement processes.

In the BIONEXT[242] project, a nexus modeling framework has been developed to simulate transformative pathways to nature-positive futures, drawing from participatory scenario development using the NFF.[231] Transformative scenarios require integrated models and strategies to resolve key trade-offs associated with ambitious climate and biodiversity actions. In this case, the modeling framework consists of three complementary models, which collectively capture interlinkages between the seven "nexus elements" of biodiversity, climate change, water, food, energy, transport and health: (1) a regional integrated model (IAP2),[243] (2) an agent-based model (CRAFTY-Europe),[244] and (3) a systems dynamic model (JUNIPER). The use of different but complementary models enables an improved quantification of impacts, risks, and vulnerabilities, as well as cross-sectoral benefits, synergies, and trade-offs under a wide range of direct (e.g., climate change and land-use change) and indirect (e.g., socio-cultural, demographic, technological, economic, and governance) drivers. The framework also enables the assessment of the effects of transformative actions, such as the emergence of new social and economic structures, by representing transformative processes and adaptive learning between agents and institutions in some of the models. While focused on the EU level, BIONEXT provides a cutting-edge example of what could be managed at the global level to develop narratives and model outcomes for transformative futures. It provides a clear example of the solutions in Figure 2, notably by opening up the scenario space (solution 1) and through improved model linkages and interactions (solution 2).

FABLE provides another example of integrated participatory processes with rigorous modeling. Deep transformation of the food system is essential to address habitat loss, pollution, and environmental degradation—the primary threats to biodiversity and key drivers of climate change.[245] However, modeling this at the global scale remains a challenge. The FABLE Consortium offers guidance through a flexible, collaborative modeling framework that fosters the development of national pathways by local research teams and their integration on a global scale.[246] In such an approach, local researchers customize national models and co-create pathways with stakeholders to transition their national food and land-use systems toward food and nutritional security, climate stability, and environmental integrity.[247] An online platform then connects the national models, iteratively balances global exports and imports, and aggregates results to the global level.[248]

Integration of justice and equity

Justice is a core challenge for the foresight community to center as a key goal of scenario and model outcomes, not just a factor or a trade-off against other outcomes. A core aspect is that new economic pathways must better represent poverty and inequality dynamics, which remain difficult to capture in climate change risk modeling[249] but are fundamental to establishing not only a more sustainable but also a more equitable future.[189,250] Changes and further development of the economic models at the core of the IAMs can help explore the implications of post-growth developments. Recent developments, such as degrowth modeling at the national and sectoral levels, show promise alongside scenarios that aim to meet multiple SDGs.[57] The recent SDPs described in Soergel et al.[122] provide a starting point for exploring multiple possible futures that achieve various SDGs. Outside of IAMs, progress has also been made on how to meet human needs while using minimal energy.[251,252] However, a bigger constraint to modeling around questions of equity and justice is that most of the global models are pretty coarse in both their temporal scale and in their representation of social agents, often having a single representative consumer/producer without an easy way to capture distributional outcomes.[41,253]

A new economic paradigm

Modeling economic innovations requires several fundamental shifts. Current measures of growth through gross domestic product (GDP) ignore natural capital depreciation and social external costs of ecosystem degradation and lost services.[254] More comprehensive metrics of economic progress could improve analysis,[255] with recent estimations of gross ecosystem product[256] representing important progress in monetary valuation of ecosystem goods and services. Multi-model studies could better capture different aspects of diverse "worlds," while improved behavioral foundations could better reflect how humans actually make decisions. The SLIM (Sustainable Living in Systems Change) scenarios on lifestyle change with an equity component demonstrate progress in this direction.[257]

One key way to address paradigmatic concerns is through the development of new narratives that break the dominant economic growth-oriented paradigm and reconfigure it in different ways. For example, new socioeconomic pathways are being developed under the NEWPATHWAYS project.[258] There is also a specific outline for how to co-design post-growth pathways, in combination with the NFF, to look at the impacts of economic shifts on biodiversity.[96] Following from the 2025 scenarios forum, there is also now a post-growth modeling community that is working on both new post-growth narratives as well as reconfiguring some basic elements (such as GDP growth projections and labor distribution) within the existing SSP framework. Although there is a gap in linking these to biodiversity outputs, the BEYONDS synthesis project under CESAB (French Centre for the Synthesis and Analysis of Biodiversity) aims to do this.[259] Finally, a group of EU-funded research projects (SPES, ToBe, WISE Horizons, and REAL) are developing and assessing new models and scenarios for sustainable and inclusive well-being.[260]

A focus on justice

The representation of justice in IAM scenarios remains narrow, with conventional scenarios often prioritizing cost-efficiency, technological feasibility, and aggregate welfare, neglecting distributional consequences, historical responsibility, and intergenerational equity. As a result, models may produce pathways that are technically plausible but socially less acceptable in many parts of the world, particularly the Global South. The challenge of justice inclusion in IAMs is therefore both conceptual—relating to the ambiguity and plurality of justice principles—and methodological—relating to the operationalization of these principles within quantitative modeling frameworks.

The Justice Model Intercomparison Project (JustMIP)[261] responds by embedding justice considerations into scenario design, model implementation, and intercomparison—as opposed to treating justice as an ex-post-evaluative criterion. JustMIP builds upon a structured justice framework that articulates multiple dimensions of justice—including distributional, procedural, recognitional, corrective, and transitional justice—across temporal, spatial, and interspecies domains. Its protocol requires modeling teams to specify which dimensions they address, incorporate justice-relevant objectives (e.g., universal access to decent living and energy services), and transparently report normative assumptions. This enhances procedural justice and accountability while enabling systematic comparison across models. By expanding the scenario space to include justice-sensitive pathways, JustMIP allows models to explore how different justice principles reshape system transformations, mitigation costs, technological reliance, distributional outcomes, and the feasibility of meeting climate goals. By bringing together multiple modeling teams of the Global South and North under a common protocol, JustMIP represents a major step toward pathways that are both climate ambitious and socially robust.

Epistemic and regional inclusivity through creative practice

Building on the need for more diverse and pluralistic modeling practices and the epistemic justice concern of including more diverse knowledge systems in modeling processes,[157,262] there is a great opportunity to integrate and hybridize modeling work with other forms of sensemaking. We have discussed work that starts with participatory scenarios as a bridge between local and regional perspectives and global models.[134,263] But when participatory scenario methods diverge further from the type of narrative that easily fits into simulation modeling inputs, such as scenarios based on the recombination of various innovative "seed" practices,[264] new modeling approaches could try to follow the conceptual underpinnings of such bottom-up approaches. Beyond this, the interaction between modeling and creative practices offers significant potential, such as the involvement of artists in sensemaking,[145] modeling, and game design.[94] Creative practices offer unique possibilities for making the exploration of potential futures truly engaging and co-productive.[265] This can be especially powerful when the involvement of creative practitioners and creative methods is used as more than a communication arm of the modeling but allows the creative practices to critique and question the modeling practice as well.[145] There is even scope for scenario developers and modelers to engage more with mainstream creative media, such as games and film, and help shape large-scale imaginaries.[266]

From an epistemic inclusivity perspective, these methodological innovations could be adapted to improve ethical connection with diverse knowledge systems. The work conducted under IPBES through the Task Force on Indigenous and Local Knowledge and in collaboration with the Scenarios and Models Task Force illustrates the need for more in-depth and long-lasting practices that can truly weave diverse knowledge systems into thinking about the future.[165,267] While there is evidence of individual research projects and programs addressing this gap, there is a need to bring these efforts together holistically. Methodological innovations, using creative and other practices, are one key example of how these diverse worldviews could intersect more closely.

OUTLOOK

Achieving safe and just futures requires radically diversifying who is involved, what is represented, and how scenarios and models are operationalized. What would it look like to have a global modeling community that embraced truly diverse ways of knowing, diverse views of human-nature relationships, diverse conceptions of economics, social change, and more? This perspective identifies where such solutions are already emerging. Here, we propose a research agenda that can bolster the connection between these initiatives to answer the demands of policy for truly integrative transformation pathways, centered on three key steps.

First, establish a scenarios secretariat based in the Global South that could ensure stronger South-South collaborations around narratives and storylines for the IPCC, the IPBES, and other scientific bodies. This would improve coordination across the climate and biodiversity communities within the Rio Conventions[268] and improve coordination around narratives and storylines for the IPCC, the IPBES, and other scientific bodies. This body could help shape more inclusive scenario processes, with greater representativeness of voices from the Global South while still acknowledging and building on the extensive work that has so far been done by researchers largely based in the Global North. This would also foster a long-term commitment to more inclusive research praxis.

Second, develop a new generation of models from the ground up. This could include flexible and modular IAMs developed in underrepresented regions such as Africa, which remains the only global region without an IAM. This undertaking would require substantial investment but could have a significant impact in terms of model outputs that are fit for purpose for developing country contexts and that could go beyond a climate-energy focus, bringing in diverse nature values and livelihoods and alternative economic thinking.

Third, coordinate efforts to advance transformation pathways toward safe and just futures. A growing body of work, including the cases outlined above, and international efforts, such as the Earth Commission, have started to make an initial attempt at developing global scenarios that take into account existing participatory processes and aspirations within the context of pathways that can be modeled at the global level.[269] However, for the needs of decision-makers, there is a need for a more inclusive and coordinated effort toward aligning these efforts—in a similar vein to how the NFF has become a heuristic tool for biodiversity-related scenarios and models.[24]

CONCLUSION

A core element of the Paris Agreement on Climate Change's architecture is the global stocktake that is carried out every 5 years—the outcome of which countries are required to consider when they update their climate plans (NDCs). The first stocktake concluded in December 2023 and included strong text on, *inter alia*, the need to transition away from fossil fuels (1/CMA.5 para. 28) in energy systems and the importance of conserving, protecting, and restoring nature and ecosystems to support the global temperature goal (UNFCCC 2023, 1/CMA.5 para. 33). While the political outcome decision of the stocktake stayed short of calling for system transformation, the synthesis report of the technical phase of the stocktake had as one of its key findings the need for systems transformations to mainstream climate resilience and low emissions development (UNFCCC 2023, FCCC/SB/2023/9). Similarly, the CBD established a transparency and accountability mechanism (2022, 2025) with a global stocktake and review process taking place to inform future action. While still in its infancy, similar to the climate stocktake, information on pathways to meet biodiversity goals will be needed.[270] The recent acceptance of the IPBES Transformative Change and Nexus Assessments by governments in December 2024[12,271] further highlights the critical need to engage meaningfully with integrated transformative scenarios that explicitly incorporate social justice and equity in grappling with the climate and biodiversity crises.

To support sustainability policy and decision-making effectively, research needs to showcase clear options that allow the world's societies to achieve not only the 1.5°C target but also the internationally agreed biodiversity targets while achieving the SDGs. This is no easy task, but it is among the most pressing requirements of our time. This challenge underscores an urgent need to formulate and adopt diverse, alternative narratives of transformative change. There is growing visibility of wildly unreasonable scenarios put forward by the world's "tech-bro billionaires": either the techno-optimism of colonizing space by Elon Musk or the environmental antichrist narratives of Peter Thiel. Alternative scenarios that are embedded with the aspirations of "living in harmony with nature" or "leaving no one behind" must be developed to counter these dystopian futures and inspire public mobilization and policy action. This is the broader context within which this perspective is situated.

There is a critical role for researchers from diverse disciplines to come together to develop a broad set of actionable options for decision-makers and to make the uncertainties and assumptions of these future scenarios much more explicit. The world requires clear options grounded in local realities in order to chart a path to a more sustainable trajectory. More inclusive science that foregrounds equitable solution pathways is essential—i.e., alternatives cannot just showcase technological developments or lifestyle changes but must also show how to address systemic inequity and injustice. Science can and must rise to the challenge of building a more sustainable and equitable future for all by clearly demonstrating what needs to be done, by whom, and where, to avert a climate catastrophe and mass extinctions.

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DECLARATION OF INTERESTS

The authors declare no competing interests.

SUPPLEMENTAL INFORMATION

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